Design of Environmental Performance Measurement Systems for Agriculture

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Certificate of original authorship

I certify that the work in this thesis has not previously been submitted for a degree, nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

The research question addressed in this thesis is: how can Environmental Performance Measurement Systems (EPMS) be *designed* and *used* in an agricultural setting to support managers in water and economic sustainability-related decision making and control.

Sustainability and the increasing scarcity of natural resources such as freshwater are of growing social interest. Agriculture has a significant impact on the sustainability of freshwater at both global and local levels. As agriculture is economically and socially significant in meeting human needs for food and clothing, it is surprising that there has been very little management accounting research conducted within an agricultural setting and almost none on its role in environmental sustainability.

Extant EPMS research manifests two underlying theoretical problems, which are also reflected in broader performance measurement systems research. First, the research provides little insight into how to design *valid* environmental performance measures which could provide managers with precise information to enable decision making and control over environmental sustainability. I argue that there are two key reasons for this: that theories from natural science are yet to inform EPMS design; and that while environmental management typically occurs at an operational level, EPMS typically reside at the organisational level. The second theoretical problem is the lack of existing research that considers how environmental performance standards can be developed for use as *targets* to support managers in improving sustainability-related decision making and control.

I address these two problems with a new theoretical construction of a multi-level decomposition EPMS model - which I label, Water and Economic Sustainability Performance Measurement (WESM). The model integrates science into an accounting framework. This design overcomes the two key challenges with EPMS validity. I subsequently examine how the WESM model can be used to support managers in improving sustainability-related decision making and control using a two- phased crop production simulation modelling approach. The simulation results provide significant implications for the cotton industry (and agriculture more broadly) with the potential to save hundreds of gigalitres of water and increase profitability by tens of millions of dollars per crop season for cotton farming in Australia.

The research also makes a theoretical contribution to the accounting literature by developing and applying theory from science to overcome inherent validity and target setting problems in PMS design. In addition, I demonstrate the usefulness of simulation modelling as a research method, which has yet to have a great deal of application in accounting research designs beyond few costing studies.

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Chapter 1. Introduction

1.1 Research objective

The objective of this research is to examine how an Environmental Performance Measurement Systems[1] (EPMS) can be designed and used[2] in an agricultural setting to support managers to improve their environmental and economic sustainability-related[3] decision making and control. This thesis examines environmental sustainability performance management of one particular natural resource in the Australian crop agricultural industry – water.[4] Further, while issues of sustainability and their impact on organisations' performance have received growing attention from management accounting (MA) researchers, little is known about how EPMS can be designed and used to support managers to better manage sustainability issues arising from activities at the operational level[5] and to improve the organisation's economic and environmental performance, which is the focus of this thesis.

1.2 Motivations for the research

1.2.1 Motivation 1 – Management accounting research

Since the late twentieth century global environmental issues, such as shortages of natural resources, have drawn increasing attention from scientists, politicians, economists, and the international community (Intergovernmental Panel on Climate Change 2013; The Economics of Ecosystems and Biodiversity 2014). A number of global resource analyses reveal that

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[1] A performance measurement system is defined as "*the set of metrics used to quantify both the efficiency and effectiveness of actions"*(Neely, Gregory & Platts 1995, p. 81). More specifically, in this thesis, the term 'environmental performance measurement system' is used to indicate the inclusion of environmental performance indicators into a traditional performance measurement system (which comprises financial and non-financial indicators) (Henri & Journeault 2008).

[2] In the context of this study, I am not studying whether farmers/crop managers adopt and use the model. What I am studying is whether it would be useful for farmers/crop managers and how it would be useful for them if they need to make decisions around changing water management practices and how the decisions would impact their crop economic and environmental performance.

[3] At the operating level, this thesis adopts the concept of sustainable development defined by Elkington (1997, p. 70) as development that "*requires dramatic changes in organizations' performance against the triple bottom line, which focus on economic prosperity, environmental quality and social justice*". In particular, the thesis focuses on the environmental and economic aspects of an organization in terms of its sustainability performance. In the theory development contained in Chapter 2, the Brundtland Commission (1987, p. 1) definition is used as the departure point where sustainable development is characterised as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*".

[4] In this thesis water sustainability primarily focuses on environmental and economic sustainability of water. The concept of water sustainability is developed in Chapters 2 and 3.

[5] This thesis adopts the organisation's operational level concept defined by Scherer (2001, p. 5679) as "*the level at which hands-on knowledge and responsibility for implementation are present*". Accordingly, the organisation's operational level discussed in this thesis refers to the level at which organisational activities that relate to the organisational production processes are conducted.

several key natural resources, including freshwater and fossil fuels, will become increasingly scarce over the next few decades (Moore 2013; Raskin et al. 1997; Rijsberman 2006; The Economics of Ecosystems and Biodiversity 2013). At the macro level, the concept of sustainable development was introduced by the Brundtland Commission[6] (1987, p.1) as development that "*meets the needs of the present without compromising the ability of future generations to meet their own needs",* in part to raise public awareness of global environmental issues arising from industrialization and growth. Despite increased awareness of many factors which impede the development of human beings in the long-run, many of the key issues of sustainability remain unsolved.

Scientific evidence demonstrates that global environmental sustainability issues have arisen partly from organisational activities which involve the exploitation and use of natural resources and the discharge of waste into global ecosystems (The Brundtland Commission 1987; The Economics of Ecosystems and Biodiversity 2013). Therefore, while we need to resolve the broad sustainability question at the society level, it is critical to examine environmental sustainability performance at the level *where environmental sustainability issues actually arise – the organisation's operational level*. Measuring environmental performance at the organisational level allows for information to be aggregated at higher levels, enabling the evaluation of sustainability issues at the industry, regional, national and global level (Chenoweth, Hadjikakou & Zoumides 2013; Henri & Journeault 2008).

Environmental performance measurement systems (EPMS) research emerged more than a decade ago, often examining environmental performance in the context of more traditional organisational performance and integrating concepts from environmental management (Burritt & Schaltegger 2001; Burritt, Hahn & Schaltegger 2002; Burritt & Saka 2006; Epstein & Roy 2001; Figge & Hahn 2013; Henri & Journeault 2008, 2010; Schaltegger & Synnestvedt 2002; Wagner & Schaltegger 2004; Wei, Roger & Gary 2011)[7]. While EPMS research has received growing attention from management accounting researchers, much of it

[6] The Brundtland Commission is also formally known as the World Commission on Environment and Development (WCED).

[7] EPMS literature is a subset of the broader sustainability accounting literature (Bartolomeo et al. 2000; Bebbington & Larrinaga 2014; Bebbington & Thomson 2013; Burritt & Schaltegger 2010; Gray 1992, 2010; Herbohn 2005; Hopwood 2009; Lamberton 2005; Milne 1996) and environmental management control systems (Brown & Sundin 2016; Henri & Journeault 2010; Pondeville, Swaen & De Rongé 2013). The thesis focuses on a particular issue that sits in the EPMS literature - validity measurement of EPMS - which is underpinning the entire infrastructure of environmental sustainability performance and management.

has focused on the examination of the role and use of EPMS in driving environmental and economic performance within organisations (Henri & Journeault 2008, 2010; Pondeville, Swaen & De Rongé 2013) or the relations between environmental disclosure, environmental performance, and economic performance (Al-Tuwaijri, Christensen & Hughes Ii 2004; Clarkson et al. 2008; Patten 2002)[8].

Though this research contributes to MA literature in creating an understanding of how existing EPMS may have some influence on organisations' environmental and economic performance, little is known about how the examined EPMS are (or could be) *designed* in a way that more precisely capture the concept of economic and environmental sustainability at the organisational level. Furthermore, there are problems that emerge due to this lack of focus on EPMS design in studies which investigate EPMS. If the EPMS studied do not provide measures that capture and quantify the performance of an underlying phenomenon, activity or system, then studies evaluating how the EPMS are used to support decision making and control seem unlikely to provide meaningful outcomes/implications.

The roots of EPMS lie in performance measurement systems (PMS) - a subset of management control systems (MCS), which are traditionally defined as the systems that provide financial and non-financial information that is intended to be useful to managers for decision making and control to ensure the attainment of organisational objectives (Franco-Santos et al. 2007; Ittner & Larcker 2001; Malmi & Brown 2008; Otley 1999). The theoretical roots of how PMS design enable control are in cybernetic[9] control theory[10] (Fisher 1995; Flamholtz, Das & Tsui 1985; Green & Welsh 1988) with PMS operating as a cybernetic control system when it possesses five characteristics (Malmi & Brown 2008). The first characteristic is the ability to provide measures that more precisely capture the performance of an underlying activity or system. Second is the ability to create standards of performance, which could be a target to guide managers on what to achieve or aim for. Third

[8] I recognise that there is a broader debate in the accounting literature about business cases for sustainability (Brix-Asala, Hahn & Seuring 2016; Dias, Vianna & Felby 2016; Haslam et al. 2014; Jones & Corral de Zubielqui 2016; Kang, Ryu & Kim 2010; Salzmann, Ionescu-somers & Steger 2005; Schaltegger & Burritt 2010; Weber 2008). However, it is beyond the scope of the thesis

[9] Cybernetic is defined as a process in which a feedback loop is represented by using standards of performance, measuring system performance, comparing that performance to standards, feeding back information about unwanted variances in the system, and modifying the system's components (Hofstede 1978).

[10] Green & Welsh 1988 define control as "*a cybernetic, regulatory process that directs or contains an interactive activity to some standard or purpose*" (p. 289).

is a feedback process which involves quantifying the actual performance of the activity or the system and comparing it with the targets (the expected performance). Fourth is the ability to perform variance analysis, which involves examining and identifying the key factors of difference between actual and expected performance (if any) that are examined in the feedback process. Fifth is the ability to modify the underlying activities or systems to enable improvement in their performance in the next activity cycle. Among the five characteristics of the cybernetic control systems, the first and second relate to the design of the systems whereas the later three relate to the use of the systems as a cybernetic control tool for decision making and control.

PMS literature has recognised the crucial role of the design phase among the three phases of PMS development (system design, system implementation and system use) laying out the theoretical foundation for the studies of the later phases of the PMS cycle (Artz, Homburg & Rajab 2012; Bourne et al. 2000; Ferreira & Otley 2009; Neely et al. 2000; Neely et al. 1997). However, from the research to date, in the relatively few studies on the design of EPMS (Figge & Hahn 2013), two broad problems were identified: first, the validity of EPMS design and second, target setting in EPMS design.

1.2.1.1 Validity issue of EPMS design

The first problem in this line of research relates to the validity of EPMS in relation to designing performance measures. Validity is defined as *"the extent to which a metric succeeds in capturing what it is supposed to capture"* (Ittner & Larcker 2003, p. 92). Accordingly, there are two questions that need to be considered when designing performance measures; what is supposed to be captured, and how can a measure(s) be designed to successfully capture this.

Extant PMS research has long addressed the validity issue of traditional performance measures (Bhargava, Dubelaar & Scott 1998; Dubelaar, Bhargava & Ferrarin 2002; Flamholtz, Das & Tsui 1985; Ittner & Larcker 2003; Nørreklit, Nørreklit & Israelsen 2006; Otley 1999). However, in the context of EPMS, the validity issue of environmental performance measures appears even more of a challenge to researchers with the need to understand natural science (particularly environmental science) and the integration between environmental performance measures and traditional financial performance measures. Since designing measures that capture the performance of an underlying activity or system is the

first and essential step of PMS design, which is then used as a cybernetic control for better decision making and control, invalid environmental sustainability measures will prevent organisations from improving their environmental and economic performance.
Extant EPMS research reveals that validity, one of the most important properties of sustainability measures, is generally missing in many environmental sustainability reporting and management practices (Burritt & Schaltegger 2010; Epstein 1996; Gray 2010). More specifically, Gray (2010) argues that most environmental sustainability reporting shows little implications of organisations' actual sustainability actions and emphasizes that *"Only on those rare occasions when the indicators capture the key issues – and the issues are equally key to all parties – can the range of indicators necessarily be said to provide a full narrative"* (Gray 2010, p.51).

The gap in our knowledge about validity of performance measures in extant EPMS research is due to three main reasons. First, there is still little work on the integration of PMS and environmental science (Bebbington & Thomson 2013). This means that the EPMS researchers do not always have a good understanding of the environmental science behind the phenomenon they study. In recognition of this kind of problem, Bebbington and Thomson (2013) call for more engagement and/or stronger interactions between the natural environment and sustainability oriented management accounting studies. In his study of the development of a framework for performance management, Otley (1999, p. 381) articulates a widely accepted concept which is relevant for EPMS, that "*attempting to design control systems without having a detailed knowledge of how business works is likely to prove a recipe for disaster*". In respect to EPMS, this means attempts to design applicable environmental sustainability measures without a detailed understanding of the science behind the environmental issues being examined is unlikely to lead to valid measures, and hence improved organisational performance and/or meaningful practical implications associated with the use of the designed EPMS.[11] Two key components of the question of whether an

[11] For example, in their more recent study of improving the efficient use of environmental resources, Figge and Hahn (2013) provide an empirical analysis of the carbon-efficiency of international car manufacturers, which is not consistent with their theoretical framework of corporate eco-efficiency. The problem lies in the confusion between natural resources efficiency and CO_2 efficiency, which capture two different aspects of environmental sustainability. While the former relates to the degree of natural resources used for production processes, the later relates to the degree of pollution due to the discharge of wastes (gaseous, liquid or solid wastes) from the processes. This illustrates that while the authors have made a good attempt to integrate natural science into their study, there is still lack of good scientific understanding of the environmental science behind the phenomenon they study.

environmental sustainability measure(s) is valid are: (i) what is supposed to be captured in respect to environmental sustainability, and (ii) which measure(s) can capture this.

From the MA research to date there is still little understanding of what environmental sustainability means and how to account for environmental sustainability and its impact at the organisational level (Bebbington & Thomson 2013; Gray 2010; Gray 1992)[12]. For example, extant EPMS research mainly considers eco-efficiency or environmental resource use efficiency as a sustainability measure for businesses (Figge & Hahn 2013). While these measures reflect economic return on the use of an environmental resource, the broader concept of sustainable development, which includes consideration of environmental impacts (among other things) of businesses on the environment, is largely ignored. As discussed previously, scientific evidence also shows that many sustainability issues (including unsustainable water use) have arisen due to organisational activities (The Brundtland Commission 1987; The Economics of Ecosystems and Biodiversity 2013). This is manifest in two ways. First, organisations may operate in an inefficient manner (i.e., not using natural resource efficiently and effectively) resulting in inefficient use of Earth's limited natural resource capacity and increased costs. Second, even under conditions of efficiency, continuing withdrawals of natural resources from the environment will lead to the reduction of non-renewable resources or cause imbalance of the ecosystems. Consequently, one way to solve the sustainability issues at the global level is to manage the sustainability issues at the level they happen -the organisational level – by improving natural resource use efficiently and minimising interference in the natural environment[13].Therefore, in order to deal with the validity issue of EPMS, it is of crucial important to incorporate environmental science into the first step of PMS design.

The second reason in relation to the validity of measures used in EPMS is that EPMS researchers typically do not look at the detail in the operational level of organisations when

[12] This is a long-standing problem in environmental management accounting, and its most evolved form – sustainability oriented management accounting. More than two decades ago, Gray (1992) raised a concern of failures of conventional accounting with regard to its ability to deal with accounting for environmental issues and/or answering the questions of how and why we need to account for sustainability. Nearly twenty years later, Gray (2010) raises another concern in relation to accounting for sustainability, which is whether accounting for sustainability is actually accounting for sustainability and how we would know.

[13] For example, in the context of crop water sustainability, for a crop business to be sustainable, it is not just about reducing the amount of water used to produce a crop but also about reducing organizational impacts on the natural environment. The thesis focuses on how to reduce as much water abstracted from the environment (which is irrigation) as possible, and from that I come up with my definition of water sustainability and crop water sustainability measurement which is discussed in more details in Chapters 2 and 3.

studying EPMS design. Due to focusing primarily at the organisation level, researchers know little about the design of EPMS at the level where environmental issues need to be managed. Scientific evidence shows that some of the key global environmental sustainability issues, such as the depletion of natural resources and the degradation of ecosystem services, have arisen directly from organisational production processes and activities, through the consumption of physical resources and the discharge of gaseous, liquid and solid waste into the natural environment (Intergovernmental Panel on Climate Change 2011; The Economics of Ecosystems and Biodiversity 2010). Therefore, in order to gain insights into environmental sustainability issues within organisational research, the focus must be on the level where organisational production processes and activities are carried out and, thus, environmental sustainability issues actually occur – the operational level of an organisation. By doing this, the question of what needs to be captured in respect to an organisation's environmental sustainability could be resolved.

However, one of the most common approaches that MA researchers adopt in EPMS studies is focusing on the corporate level or business level of an organisation and analysing financial and environmental data stemming from annual and environmental reports published by the companies under analysis (Figge & Hahn 2013; Pondeville, Swaen & De Rongé 2013). While EPMS studies at the higher organisational levels provide aggregate information about environmental performance of an organisation, the aggregate, high level information may not capture the underlying phenomenon being examined. In contrast, the examination of EPMS at the operational level will provide disaggregated and detailed information in relation to environmental sustainability that allows us to better understand the actual drivers of environmental performance of the organisation.

The third reason is that there is still a lack of a theoretical connection between summary performance measures, which sit at the organisational level, and environmental-related activities happening at the organisation's operational level – the level at which environmental issues occur and need to be managed. On the one hand, valid summary performance measures representing the overall (environmental and economic) sustainability performance of an organisation are an important measure that allow high-level managers to have more informed sustainability-related decision making and control. On the other hand, environmental-related activities and their performance can be managed and improved by operational level managers. A higher-level manager cannot assess the overall sustainability-related performance of their organisation unless they see clearly the impact of management practices and/or management decisions at the operational level. Therefore, it is necessary to establish stronger and theoretical connections between these two levels to enable MA researchers to gain better and valid understanding of the routines, actions and outcomes of sustainability-related management and accounting activities within organisations.

In summary, in order to deal with the validity issue of EPMS design it is important for PMS researchers to integrate environmental science into PMS theory, examine environmental issues at the organisational operational level, and build a theoretical connection between the summary measures sitting at the organisational level and environmental-related activities capturing environmental issues at the organisation's operational level. This will enable MA researchers to gain more insights into what is supposed to be captured and which measures can successfully capture this in relation to environmental sustainability performance of an organisation.

1.2.1.2 Target setting issue of EPMS design

The second problem in this line of research relates to target setting of EPMS design. Target setting refers to a process of developing targets (e.g. baselines, standards or goals) for performance measures to assist managers in identifying what to aim for and directing organisational change (Dekker, Groot & Schoute 2012; Ittner & Larcker 2001). In respect to EPMS research, target setting relates to a process of developing sustainability targets to support managers in improving organisational sustainably performance and/or moving towards sustainability.

Extant MA research has addressed the important role of target setting in managing and directing organisational performance (Dekker, Groot & Schoute 2012; Ittner & Larcker 2001). Furthermore, as discussed above, in EPMS design, setting of performance targets is the second step in designing a cybernetic control tool (Green & Welsh 1988). There is a considerable literature in accounting on target setting that spans topics such as, managerial and supervisory influences on targets (Bol et al. 2010), participation in the target setting process (Anderson, Dekker & Sedatole 2010), the relation between incentives, ratcheting and target setting (Aranda, Arellano & Davila 2014; Indjejikian, Matějka & Schloetzer 2014) performance level and effort (Fisher et al. 2015), and target difficulty, flexibility and performance (Arnold & Artz 2015). However, little attention has been paid to the methods of determining performance targets with it being identified as being a topic that has been under-researched (Bol et al. 2010; Dekker, Groot & Schoute 2012; Ittner & Larcker 2001).

A number of PMS researchers have raised concerns about a lack of appropriate methods for target setting in the MA literature (Dekker, Groot & Schoute 2012; Ittner & Larcker 2001). The target setting research to date has mainly focused on two main methods to establish goals for future performance measures: (i) historical results based target setting and (ii) benchmarking based target setting (Ahmed & Rafiq 1998; Dekker, Groot & Schoute 2012; Elnathan, Lin & Young 1996; Figge & Hahn 2013; Ittner & Larcker 2001; Josée & Louis 2004). There are three limitations to the two methods. First, historical results and benchmarking methods do not always provide theoretically justified or reliable targets that organisations can aim for in the long-term. This is largely because they are either based on a firm's historical or past performance (under the historical results based target setting method) or rely on the performance of others within the industry to establish goals for future performance; none of which are a theoretically or scientifically justified maximum level of performance that a firm should aim for. Second, in relation to the benchmarking based target setting method, most companies do not have performance data from outside entities, such as their competitors (Dekker, Groot & Schoute 2012). Third, data that are publicly available[14], might not be reliable, comprehensive or valid (Dekker, Groot & Schoute 2012; Ittner & Larcker 2001).

One way to overcome the limitations of the two methods mentioned above when studying organisational performance and target setting is applying analytical and simulation[15] modelling methods to determine optimal performance (Balakrishnan & Sivaramakrishnan 2002). For example, a small body of relevant costing, product pricing and capacity planning decisions research applies analytical and simulation modelling methods to approach questions that relate to optimization of decisions and performance (Balachandran, Balakrishnan & Sivaramakrishnan 1997; Balakrishnan & Sivaramakrishnan 2001, 2002; Christensen & Demski 1995; Dhavale 2005; Hansen & Banker 2002; Kaplan & Thompson 1971; Labro &

[14] Including surveys conducted by either third parties, such as consulting firms, or researchers.
[15] Balakrishnan and Sivaramakrishnan (2002, p. 24) define that "*To simulate is to attempt to duplicate the features, appearance, and characteristics of a real system. Scientists often use physical models to investigate phenomenon (e.g., airplane wind tunnel simulations). In a similar manner, accounting researchers use computational experiments (with mathematical models) to estimate the effects of various alternatives. The idea behind simulation is to model a situation mathematically, use numerical methods to study its properties, and to draw conclusions and make decisions based on the results of the simulation*".

Vanhoucke 2007; Noreen & Burgstahler 1997). Compared to the analytical method, the simulation method is an appropriate method to investigate the efficiency of various decision rules (i.e. cost-based decision rules), and characterise the performance of various planning rules (i.e. capacity planning rules or analyse trade-offs between performance measures) when dealing with a complex environment, as the complexity of the phenomenon or problem makes it difficult to mathematically compare performance (Balachandran, Balakrishnan & Sivaramakrishnan 1997). However, the analytical and simulation modelling methods have still not been widely used in PMS research; perhaps due to a paucity of appropriate/relevant simulation models and technical expertise.

In the development of EPMS, issues related to appropriate target values for performance measures become an even greater challenge as decision-makers have to deal with a more complex environment where economic and environmental performance aspects are simultaneously taken into consideration.[16] The limitations of historical results-based and benchmarking-based target setting methods discussed above make them problematic choices in setting targets for improving organisational sustainability performance. More specifically, in respect to environmental sustainability performance, the two methods mentioned above are limited in their ability to provide insights into which current management areas/practices need to be changed and to which extent to minimise the environmental issues occurring at the organisation's operational level in order to improve the overall organisational sustainability performance. For example, in one of the most recent studies on energy sustainability performance using benchmarking based target setting method, using the average performance of the car industry sector as the benchmark, Figge & Hahn (2013) admit that this approach does not provide insights into the level of sustainability of the sector or help understand how firms can move from the status quo to a more environmentally sustainable performance. In addition, while one way to improve organisations' performance is to estimate and evaluate the effects of various alternatives, the effect of a particular decision choice on performance of a business cannot be studied if it has not yet been used in practice, especially when a long-term effect which links to the sustainability concept is considered.

[16] For example, in their study of energy efficiency, Virtanen, Tuomaala and Pentti (2013, p. 401) raise a concern that setting targets for energy efficiency is problematic due to the complexities involved in the measurement and management of the efficient use of energy.

In summary, while setting target is the second and necessary step in designing EPMS to be used as cybernetic control, there is still little research on how to develop appropriate targets for sustainability performance measures that can help organisations improve their sustainability performance. There are two main reasons for this. First, valid sustainability measures need to be designed. Second, most studies on environmental- related target setting in extant EPMS literature focus on historical results-based and benchmarking-based target setting methods which as discussed do not always provide theoretically justified and reliable targets that organisations can aim for in the long-term.

1.2.2 Motivation 2 – Agriculture research

The agricultural sector is a potentially fruitful setting to investigate EPMS and water management in particular for three main reasons. First, from an economic perspective, the agricultural sectors play an important role in the global economy. Agriculture is the third largest contributor to the global GDP (after services and industry) (FAO 2013) and the value-added of world's agricultural production is estimated at US$ 2 trillion as of 2013 (FAO 2013; UNCTAD 2014). In 2010-11, the Australian agricultural sector, with approximately 134,000 farm businesses (99% of which are family owned and operated), contributed around AU$48.7 billion to the Australian economy (at farm-gate) (National Farmers' Federation 2012). Moreover, when post-farm gate value[17] is added, the Australian agricultural sector contributes around AU$155 billion, or 12%, each year to the GDP (National Farmers' Federation 2012). In addition, the Australian agricultural sector provides about 300,000 jobs at the farm gate, and 1.6 million jobs across the agricultural supply chain, to the Australian economy. In the US, the agricultural sector accounts for approximately one-fifth of national economic activity (US Department of Homeland Security 2013). It is estimated that the US agricultural sector consists of 2.2 million farms, and impacts more than 400,000 food manufacturing, processing, and storage facilities, and 900,000 restaurants (US Department of Homeland Security 2013).

Second, from a social point of view, agriculture is of crucial importance to the existence and development of human beings as it provides food and fibre to meet two of the most essential needs of human beings (Henzell 2007).[18] Jack (2005, p. 60) emphasizes that "*this is one industry that has every single person as a stakeholder, relying on it for food and clothing*".

[17] Value of all economic activities supporting farm production processes of food and fibre from the farm-gate.
[18] Agriculture also provides critical inputs for bio-fuel, which is also of importance.

One-third of the world's population still obtains its life-essential income from agriculture (FAO 2013). Due to population growth and rising per capita income, it is projected that the world annual agricultural production needs to further increase by approximately 60-70 percent in order to satisfy the future demand (Alexandratos & Bruinsma 2012; Conforti 2011). Australian farmers produce food for an estimated 60 million people. Of its total agricultural production, 40% is for Australia's daily food supply and 60% is exported (National Farmers' Federation 2012). The growth in world population since the 1950s requires substantial increases in global food and fibre production (Rijsberman 2006; van Ittersum et al. 2012). This means sustaining crop agriculture is critical to maintaining human society and the global economy.

Third, agronomic research shows that water is one of the key limiting factors to crop yield and quality (Cai et al. 2011; Hochman, Holzworth & Hunt 2009; Passioura 2006). While water plays an important role in improving crop yield and crop quality for sustaining crop businesses' profitability (Bange et al. 2010; Long et al. 2010), it is predicted that a water shortage will become a key constraint for agriculture in coming decades (Hamdy, Ragab & Scarascia-Mugnozza 2003; Jackson et al. 2011). Only 2.5 percent of the planet's water is freshwater, however only 0.76% can be considered as usable fresh water (Ibaraki, 2010). Increased human consumption has contributed to the severe stress and deterioration of the limited freshwater resources worldwide(WWAP 2009, 2012, 2014). Agriculture is the biggest contributor towards freshwater use - currently irrigated agriculture accounts for about 70 percent of freshwater withdrawals globally (FAO 2013). Furthermore, among the three main water consuming sectors (domestic, industrial and agricultural sectors), irrigated agriculture is the largest consumer of water (Jackson, Khan & Hafeez 2010; Rijsberman 2006; van Ittersum et al. 2012). In Australia, it is reported that agriculture consumes a large proportion of water resources (i.e. the agriculture industry accounted for 52% of national water use in 2009-10) (Pink 2012). Therefore, improvement of water management in agriculture is vital for global economic, social and environmental sustainability.

Despite the important role of water sustainability management in agriculture, the issues around how to design appropriate EPMS to support crop growers in improving their sustainable use of water are unresolved. One of the main reasons for this is a lack of theoretical framework of crop water sustainability performance at the crop business level. Extant research mainly focuses on water performance measures for improving the efficiency in water use[19] (Hochman, Holzworth & Hunt 2009; van Ittersum et al. 2012), without incorporating economic performance of a crop business; or considering the trade-off between water-related environmental and economic performance to provide a more complete picture of water sustainability. Moreover, literature which focuses on efficiency of water used by plants is plagued by inconsistent terminology in such areas as, the relationship between crop yield and water use, different terms for the water component and crop output, and differing concepts of water efficiency (Blum 2009; Cossani, Slafer & Savin 2012; Hochman, Holzworth & Hunt 2009; Igbadun et al. 2006; Liu-Kang & Hsiao 2004; Moore, Robertson & Routley 2011; Passioura 2006; Pereira, Cordery & Iacovides 2012; Tennakoon & Milroy 2003; van Halsema & Vincent 2012). The above challenges with validity of measures creates limitations on the capacity of researchers and growers to develop 'appropriate' targets to support crop growers in improving their crop water sustainability performance.

Though the development of crop simulation models since the 1980s provides opportunities for the simulation-based target setting approach to be adopted in crop science research (Hearn et al. 1981; Keating et al. 2003), this body of research mainly focuses on crop yield as the main output. This means that a number of determinants of environmental sustainability generally, and water sustainability performance particularly, are still missing in crop simulation models (Cheeroo-Nayamuth et al. 2000; Grassini, Hall & Mercau 2009; van Ittersum et al. 2012). Therefore, without a crop water sustainability framework coupled with crop water performance measurement, the question of how crop businesses can move towards water sustainability will remain unanswered.

1.3 Research question and approach

The above arguments outline three unresolved issues from extant research on EPMS design for crop agriculture. First is the lack of validity of EPMS to provide managers more precise environmental performance information about what environmental sustainability issues need to be captured and measured. Second is the lack of environmental performance standards that can be used as targets to direct managers as to what they need to do for better decision making and control. Third is the lack of a theoretical framework of crop water measurement

[19] Crop yield per unit of crop water use.

systems that can support crop managers and inform better water sustainability-related decision making and control[20].

Therefore, the core research question addressed in this thesis is:

How can Environmental Performance Measurement Systems (EPMS) be designed and used in an agricultural setting to support managers in water and economic sustainability-related decision making and control?

This question focuses on the concept of economic and environmental sustainability at the level of organisation, and more specifically, economic and water sustainability of crop production. In this context, there are two components to the research question. The first is how EPMS can be designed; the second is how the EPMS can be used to better support sustainability-related decision making and control.

1.3.1 The first component of the research question and approach

Chapters 2, 3 and 4 address the first component of the research question – relating to how EPMS can be designed. In order to overcome the first issue of EPMS design, which is the validity issue of EPMS, in Chapter 2, a set of water sustainability principles, based on water science and contemporary sustainable thinking, are developed to provide a theoretical foundation of what water sustainability means generally. Chapter 3 then provides a theoretical foundation for conceptualising water sustainability at the business level, in the context of crop agriculture, and developing some key environmental sustainability measures that capture the underlying crop water sustainability issues arising from irrigation management practices and activities. This is done through a number of steps. First, a crop water process model, based on crop science, is developed to lay out the inflow and outflow components of a crop production process occurring at the operational level of the crop business. Second, based on the water sustainability principles developed in Chapter 2 and the constructed crop water process model, four key water sustainability measures (including

[20] I recognise that there is accounting literature which deals with water sustainability and water accounting at an industry and higher levels (Chenoweth, Hadjikakou & Zoumides 2013; Gleick 2003; Ibaraki 2010; Rijsberman 2006; The Economics of Ecosystems and Biodiversity 2013) and political issues related water accounting (Bell & Quiggin 2008; Chalmers, Godfrey & Lynch 2012; Moore 2013; Ogden 1997; Tingey-Holyoak 2014). However, it is beyond the scope of the thesis. My thesis focuses on a technical issue of sustainability measurement which is dealt with at the organisational level.

water input efficiency, water resource efficiency, environmental index, and crop water use index), which capture sustainability-related activities/management practices occurring at the crop production level (the level at which water sustainability issues occur and need to be managed) are developed and theoretical links between crop water and crop production is established. Furthermore, a discussion of the theoretical value of some of the developed sustainability measures is included in this chapter to lay out theoretical target development for the second step of EPMS design.

In Chapter 4 I develop a Water and Economic Sustainability Measurement (WESM) model – a form of EPMS specifically for the context of water and economic sustainability performance measurement for crop agriculture. More specifically, I apply the decomposition ratio analysis approach – a way to present performance measures in a transparent, structured and hierarchical way[21]– to design a hierarchical decomposition model that has measures at the organisational level connecting down to the operational level. The design of the WESM comprises two main steps. First, by incorporating the economic aspect into the discussion of water sustainability developed in the previous two chapters, a theoretical summary measure of water and economic sustainability – the profit to water cost ratio – is developed. This measure is informative about both economic and water sustainability performance in one equation. Together with the four key water sustainability measures (water input efficiency, water resource efficiency, environmental index and crop water use index), I argue how this summary measure can be used to support managers in better sustainability-related decision making and control. Second, the profit to water cost ratio that sits in the highest level (e.g. the first level) of the WESM model can be decomposed into its key components (sitting in the second and third levels of the WESM model), and further decomposed into some of the key water sustainability measures developed in Chapter 3 (sitting in the fourth and fifth levels of WESM model) which link to water and crop production components of the crop water process model (through various water and economic measures sitting in the sixth and seventh levels of WESM model).

This application of the decomposition analysis approach allows the summary measure of water and economic sustainability and its drivers to be tied in a logical and structured way to

[21] One of the key features of the decomposition ratio analysis approach is that the aggregate measures can be decomposed into more detailed and specific descriptors of an organization's performance, and hence, changes in overall performance can be traced in terms of changes in specific aspects of the organization's performance (Penman 2003).

form the architecture of the WESM.[22] This also enables establishing of a theoretical and logical connection between the summary sustainability performance at the business level, and water sustainability-related activities/management practices occurring at the crop businesses' operational level. This allows us to better understand how the profit to water cost ratio will change as a result of a particular management decision at the operational level, and how the change translates into economic and environmental sustainability value/gain created for the crop business. The WESM provides a platform for the empirical work in later chapters of the thesis.

1.3.2 The second component of the research question and approach

The second component of the research question addressed in this thesis is how the designed EPMS can be used in an agricultural setting to support managers in water and economic sustainability-related decision making and control. This focusses on the target setting feature of the WESM, followed by the feedback process, variance analysis and system modification features of the WESM. This is addressed in Chapters 5, 6, 7 and 8.

First, Chapter 5 lays out the method applied in this thesis. The focus of the empirical work is on cotton production in Australia. This is for four key reasons. First, cotton is a crop of economic significance. Second, cotton provides fibre to meet one of the most essential needs of human beings - clothing. Third, cotton yield and quality is sensitive to water availability. Finally, cotton is a comparatively high user of water.

In relation to the research method, crop production simulation modelling is argued as the most appropriate approach, among three common methods that can be applied to collect crop data and information (field experiments, publicly available data and crop simulation modelling). This is due to the complexity of the phenomenon being studied and the lack of reliable, valid and specific crop data from public sources. Most importantly, crop simulation modelling allows model users to simulate a cropping system in response to various climate and soil factors, examine spatial and temporal variation, and evaluate management intervention through a wide range of management practices, which is not feasible (if not impossible) with field experiments or collection of historical and/or publicly available data.

[22] While this approach is similar to Penman styled ratio analysis (Nissim & Penman 2001; Penman 2003) or DuPont styled ratio analysis (Soliman 2008) in the financial statement analysis and security valuation literature, the set of variables in Chapter 4 extend beyond the information available in financial statements.

The Decision Support System for Agrotechnology Transfer (DSSAT) model with the CROPGRO-Cotton module[23] is applied for cotton production simulation modelling. The DSSAT system is selected as the most appropriate crop simulation model for this study; it is well-recognised and widely-used by researchers worldwide and proven to generate valid and reliable crop information which can facilitate the evaluation of water and economic sustainability performance of a crop business from various crop management decision choices. The DSSAT system provides a mechanism to simulate the real-world cropping system represented by the crop water process model. Accordingly, input data to DSSAT includes information about crop genotype (*G*), environmental conditions (*E*) and a set of management rules for crop production processes (*M*), whilst output data from DSSAT comprise crop water and production components of the crop water process model. Output data generated by the DSSAT model and accounting data are fed into the WESM model to allow quantification of key water and economic sustainability measures presented in the WESM model, as well as the effect of specific water management decisions/activities on the overall water and economic sustainability performance of a crop business.

Second, building on Chapter 5, Chapter 6 constructs a two phased-crop simulation modelling design which enables capture of a more comprehensive picture of a real-world cropping system. To do this, I first select furrow irrigation systems as an irrigation method applied in examining the use of the designed WESM in this thesis since furrow irrigation is currently the most common irrigation system applied in cotton production. Second, I address some of key limitations of the DSSAT model in simulating cotton production systems with furrow irrigation management practices. This leads to the need to incorporate a furrow irrigation simulation model, SIRMOD, into the DSSAT model to build a two phased-crop simulation modelling design with integration of two simulation modelling processes – furrow irrigation simulation modelling using SIRMOD and crop production simulation modelling using DSSAT. This approach enables generation of more accurate, valid, useful and higher quality information under various scenarios of G x E x M conditions, and over a long period of time, to better support sustainability-related decision making and control.

Given the development of a new EPMS (WESM) in the first part of the thesis which includes a range of new water and economic performance measures, the question of what the targets of

[23] CROPGRO-Cotton is the cotton specific module in DSSAT. In the thesis I will refer to this as being the DSSAT model.

these performance measures look like is difficult to answer as no data currently exists for this. In Chapter 7, the WESM model will be run the first time to enable me to create initial targets for the model. This relates to the second stage of the cybernetic control. More specifically, based on the designed two phased-crop simulation modelling method, a cropping system using current water management practice is simulated using data reflective of current practice in order to quantify performance. For each of the key water and economic sustainability measures presented in the WESM model, their simulated results reported in Chapter 7 represent the range of values that can be obtained under current operating conditions which provides some initial evidence on performance and guidance for target setting for the new WESM. This will then support the decisions related to how current water management practices can be changed to improve water and economic sustainability performance of crop businesses, which relates to the stage 5 of cybernetic control.

Chapter 8 then creates a scenario (Scenario 1) with 86 years of weather data (from 1924 to 2014 excluding four drought years in which no crops were grown) using the same cropping system as outlined in Chapter 7. Then for purposes of comparison, sets up a more advanced (improved) water management practice (Scenario 2) using the same cropping system. The simulated results over 86 years of weather data under Scenario 2 are compared against that of Scenario 1 and variance analysis is performed to examine and identify the driving factors of difference in the summary water and economic sustainability performance between Scenario 1 and Scenario 2. This represents the feedback process and variance analysis process which are the third and fourth features of a cybernetic control system. The average value over 86 years of weather data obtained from Scenario 2 can be set as the second stage of target setting for the new EPMS.

Chapter 8 also provides a test of the usefulness of the WESM model in supporting crop managers in making better sustainability- related decisions in order to improve their businesses' environmental and economic sustainability performance. More specifically, using the simulation method designed in this thesis, I provide evidence that there is a statistically, economically and environmentally significant difference when moving from the current water management practice to the improved water management practice.

Finally, Chapter 9 provides the summary, discussion, limitations, delineations and conclusions of this study and suggestions for future research.

1.4 Research contributions

Based on our knowledge gaps addressed in the motivation section, the thesis is expected to make three broad contributions to MA research and a contribution to crop agricultural research and practice.

1.4.1 Contribution 1

This thesis provides MA research with a new theoretical construction of EPMS design - WESM model - by building off PMS and cybernetic control theory along with agricultural science.

The WESM model is constructed based on science and accounting theories to deal with theoretical issues in EPMS design - validity issues - to improve quality of sustainability information to support better sustainability related decision making. It this respect, it provides a theoretical contribution to sustainability management accounting research. More specifically, the construction of WESM addresses the validity issues of EPMS design with regard to crop water sustainability measurement in three ways.

First, using an interdisciplinary approach and integrating crop science into PMS and accounting theories, this research provides insights into the science behind crop water sustainability to better understand the underlying water sustainability issues of the phenomenon (e.g. cropping systems) being studied and capture more precisely both environmental aspect and economic aspect of crop water sustainability. Furthermore, the thesis makes a theoretical and methodological contribution to MA research by demonstrating how to operationalise an interdisciplinary approach in sustainability-related MA research. This also responds to a call for broader cross-disciplinary study by Bebbington & Thomson (2013) who address a number of limitations that have arisen when MA research is treated as a stand-alone discipline in studying managerial approaches to sustainability.

Second, this research examines water sustainability issues at the operational level of a crop business (e.g. the crop production level). By undertaking this approach, I am able to identify the links between operational level decisions (i.e., irrigation method choices) and the overall economic and environmental sustainability performance of a crop business. The significance of this is that overall organisational decisions with regards to economic and environmental sustainability that are made at the business or strategic level are often distant from where the sustainability issues that actually arise and key operational or management decisions that are made and where environmental impacts occur. The research demonstrates the value of studying environmental issues at the level where environmental issues actually arise. The findings support the contention of Ittner and Larker (2001) that it would be fruitful to study MA at different organisational levels where the value drivers are more closely tied to the management action.

Finally, this research establishes theoretical links between sustainability measures at the organisational level and the operational level of crop businesses. By applying a decomposition ratio analysis approach, which is commonly used for financial statement and profitability analysis in financial accounting research, I articulate theoretical and logical links between the summary sustainability measure and operational level measures and tie those measures in a logical and structured way. This allows me to identify drivers of the summary sustainability measure (profit to water cost ratio) to gain better understand how profit to water cost ratio will change as a result of a particular management decision at the operational level, and how the change translates into economic and environmental sustainability value created for the crop business.

1.4.2 Contribution 2

The second contribution relates to the second problem of EPMS design identified in this thesis - developing appropriate methods for designing sustainability targets to steer managerial decisions towards sustainability. In this thesis, water sustainability targets will be developed based on a crop model simulation. By doing this, the thesis makes a contribution to sustainability- related management accounting research by providing a new method to set valid targets, the second feature of a cybernetic system, to support better sustainability-related decision making and control.

In MA research to date, most simulation studies have focused on cost accounting systems generally and activity-based costing particularly. It is anticipated that this study will be the first simulation study on sustainability performance measures and target setting.
The application of the simulation method to answer the question of how organisations' performance can be improved will provide opportunities to expand our research in performance measurement systems. Extant management accounting research discusses the

value of using a range of research methods to address the same research question (Atkinson et al. 1997; Ittner & Larcker 2001). It is proposed that opportunities to expand our understanding of the phenomenon being studied are created when "*researchers use the synergy that exists among research methods and across disciplines to study complementary issues*" (Atkinson et al. 1997, p. 81).

Furthermore, by designing a two phased-crop simulation modelling process, integrating two simulation modelling phases (furrow irrigation simulation modelling using SIRMOD and crop production simulation modelling using DSSAT), a more comprehensive picture of a real-world cropping system can be captured and hence the quality of simulated information can be improved to support better sustainability-related decision making and control. This is because by coupling SIRMOD and DSSAT together, it allows DSSAT to get pass a single point description of furrow irrigation and capture the key characteristics of furrow irrigation systems which is the non-uniformity of water distribution along the furrows. In this respect, I enhance the realism of cotton production simulation and improve the quality of crop information input to WESM.

Moreover, it is believed that the empirical results reported in this thesis are the first to be based on two-phase simulation modelling for studying how economic and environmental sustainability performance of a crop business can be improved by moving from the status quo. The results include how the summary water and economic sustainability measure changes as a result of the change in water management decisions and how the change can be translated into better environmental sustainability performance and, at the same time, increase economic value created for the crop business. In this respect, the designed WESM is a useful tool for quantifying, assessing and forecasting the impact of water management decisions at the operational and organisational level of crop businesses using simulation modelling.

1.4.3 Contribution 3

The third contribution relates to the setting selected in the thesis – the agricultural sector. Much of the research in environmental management accounting to date focuses on the manufacturing sector (Figge & Hahn 2013; Henri & Journeault 2008, 2010; Pondeville, Swaen & De Rongé 2013). In contrast, the agricultural accounting topic is still under-researched (Jack 2005), despite the vital role of agricultural sectors to global economic, social and environmental sustainability. Jack (2005, p. 60) argues that "*agricultural academics tend not to be interested in accounting and accounting researchers tend to stay clear of agriculture and related industries*". Argilés and Slof (2001) also raise concerns about the sparseness of accounting research in the agricultural setting despite the relative importance of agriculture in the economy of many countries. This study is one of the first to address in detail the design and use of PMS and more specifically EPMS in an agricultural setting. I provide science based theoretical development in relation to how EPMS can be designed and used in agriculture and empirical evidence on how water and economic sustainability performance can be improved. Insight is provided into how management accounting has a role to play in understanding how this important sector may move towards water sustainability. In doing so, a new avenue of investigation is opened up for studying environmental performance management in agriculture.

1.4.4 Contribution 4

The contribution to crop agriculture research broadly relates to the theoretical framework of crop water sustainability performance measurement systems at the crop business level. More specifically, I contribute to this agricultural research in two key areas. Both of these areas also have the potential to contribute to practice.

First, I contribute towards overcoming the ambiguity, inconsistency and validity issues associated with water use efficiency measurement in the extant literature (Cammarano et al. 2012; Igbadun et al. 2006; Pereira, Cordery & Iacovides 2012). I do this by developing (based on water and crop science) a set of key water sustainability measures that more precisely reflect water sustainability-related activities and management practices. These exist where water sustainability issues arise - at the crop production level. As part of this I also establish a clear theoretical connection between water coming into a cropping system and crop production coming out the cropping system. In addition, through building the WESM model I link the organisational summary measure (profit to water cost ratio) to its drivers across all levels of the organisation and in particular down to the operational level. To the author's knowledge, this study is the first study to provide a theoretical development of a comprehensive conceptual framework for crop water and economic sustainability performance, which is of interest to both agricultural researchers and practitioners.

Second, using the WESM model and drawing upon current water and crop simulation models, I develop a novel two-phased crop simulation modelling process. This contributes to the crop simulation modelling literature with a new approach by establishing an end-to-end connection between irrigation strategies and their economic and environmental outcomes, improving the quality of simulated information. This approach also contributes to literature and practice in the development of more valid and precise standards and targets for crop businesses' economic and environmental performance measures. This will enable researchers and crop businesses to evaluate actual performance against targets and identify areas for improvement in water and economic sustainability performance – including how to drive better economic and environmental performance simultaneously. Furthermore, this has the potential to provide crop growers greater product value post-farm gate by creating more transparent on-farm sustainability information to the supply chain downstream. As the demand for sustainability related information signals increases for product branding this will become an increasingly important issue.

Moreover, the developed model can provide crop growers with simulation ability for more accessible scenario analysis for crop production. This can translate to the regional level as the model has the capacity to establish how profitable a crop is in comparison to other crops in relation to water resources used. This has the potential to support growers and policy makers in relevant decisions related to water allocation under water constraints.

Chapter 2. Theoretical Discussion of Water Sustainability

2.1 Introduction

The first component of the research question addressed in this thesis is how EPMS can be *designed* in an agricultural setting to support managers in water and economic sustainability-related decision making and control. To answer this, the first issue considered is the development of sustainability measures that more precisely capture performance, both in terms of economics and water sustainability, of crop businesses. In order to do this, it is of crucial importance to have a clear understanding of what water sustainability means generally and how the concept of water sustainability at different levels (globally and locally) can be translated and applied to the individual crop business.

This chapter develops a theoretical discussion of water sustainability at the global and local levels, based on water science and contemporary sustainable thinking and discourse, which can be used as a foundation for conceptualising crop water sustainability at the business level in Chapter 3 and designing valid EPMS in Chapter 4. Section 2.2 reviews the Brundtland Commission's definition of sustainability; this is followed by the review of global hydrological cycle and water mass balance concepts in Section 2.3. Based on this, some of the key issues related to water sustainability at the global and local levels are addressed and a number of key water sustainability principles are developed to provide a theoretical foundation for discussion of water sustainability for crop production in the next chapter of the thesis.

2.2 Sustainability definition

2.2.1 The Brundtland Commission's definition of sustainable development

In an attempt to raise public awareness of global environmental issues arising from industrialization and growth, the Brundtland Commission[24] developed and published a broad concept of sustainable development, defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (The Brundtland Commission 1987, p. 1). This definition of sustainable development has become

24 The Brundtland Commission is also formally known as the World Commission on Environment and Development (WCED).

one of the most commonly used definitions for sustainability research in both natural and social science (Ibaraki 2010).

The concept of human needs is at the heart of the Brundtland definition. The definition has as its emphasis that the main objective of sustainable development is ensuring adequate environmental capacity to satisfy human needs and aspirations (such as food, clothing, shelter and jobs), at present and in the future (The Brundtland Commission, 1987). In addition, the idea of social equity is inherit in the definition so as to ensure equitable opportunities for all people, both in developed and developing countries, to satisfy their basic needs and aspirations for a better life. There are three key aspects embedded in this concept:

(i) Human beings: The definition is anthropocentric, it sees human beings are the central species and more intrinsically valuable than animals and all the other non-human things on the planet (Brennan & Lo, 2010). This provides the underlying reason why humanity dominates and is the centre for the need to develop.

(ii) Capacity of the environment: This refers both to the availability of physical resources as well as the assimilative capacity of the environment, defined as the extent to which the natural environment is capable of receiving, degrading and converting waste matter to useful substances for ecosystems (Pearce, 1976), to allow human survival and development.

(iii) Time: This reflects on the extent to which environmental capacity still meets human needs. In addition, time can also be considered in terms of expected improvements in technology over time.

A number of key sustainability principles can be drawn from the first aspect of the Brundtland definition and the related discussion in the Brundtland Report (The Brundtland Commission, 1987). First, sustainability is about the relation between human needs and environmental capacity. Human development involves exploitation of natural resources (i.e. fossil fuels, minerals and freshwater) and discharge of waste into the environment. Human intervention in natural systems (either via withdrawing natural resources from or discharging waste into the environment) reduces the availability of natural resources and reduces the assimilative capacity of the natural environment, which in turn may constrain the ability of human beings to continue to develop (Greene 2010; Ibaraki 2010; Pearce 1976; The Brundtland Commission 1987; The Economics of Ecosystems and Biodiversity 2010, 2013). Therefore, the discussion of sustainability needs to be placed in the context of anthropogenic impact (human impact) on natural systems of the planet.

Second, due to human intervention in these natural systems, the capacity of the environment to absorb waste (solid, liquid or gas) will change over time. Scientific evidence shows that this capacity is currently a decreasing trend (Ibaraki 2010; Intergovernmental Panel on Climate Change 2011; Patzek 2004; Patzek & Pimentel 2005; Pearce 1976; The Brundtland Commission 1987; The Economics of Ecosystems and Biodiversity 2010, 2013). This trend is predicted to reach a critical level (i.e. at which natural resources become alarmingly scarce and waste residuals greatly impact on human health and hinder economic development) if no actions are taken in the near future (Pearce 1976). While several key natural resources (such as freshwater, fossil fuels, minerals) are still available at the present, some of them will not be available in the next several decades (Patzek 2004). The fact that Earth is still capable of receiving waste does not guarantee that the volume of waste residuals will not exceed the assimilative capacity of the natural environment in the near future (Patzek 2004; Pearce 1976). Therefore, a time dimension must be included in the discussion of sustainability.

Third, while its focus is to meet the present needs, the Brundtland definition also suggests that current generations owe a duty to future generations and other living beings to conserve natural capital (The Brundtland Commission, 1987). Even though human beings might be able to meet their needs at the present, if current generations continue to exploit and consume natural resources and emit waste to the environment at the current rate without implementing appropriate plans to preserve environmental capacity, future generations may not be able to meet their own needs due to a shortage of key natural resources and low quality of ecosystem services (Massoud et al. 2010; Patzek 2004; Pearce 1976; Schäfer & Beder 2006; The Brundtland Commission 1987; The Economics of Ecosystems and Biodiversity 2013).

2.2.2 The Brundtland definition in practice

Although the Brundtland definition is widely accepted, in part due to its appeal to principles of equity and self-preservation, it has two main of limitations – especially when applied to the sustainability of individual natural resources. First, as its focus is at the macro level (such as economy or society), the definition is too abstract and complex to provide an exact meaning of sustainability at an organisational level (Azapagic & Perdan 2000; Farrell & Hart 1998). Evidence shows that some of the key global environmental issues have arisen directly from organisational activities through their consumption of physical resources and discharge of waste into the environment (The Economics of Ecosystems and Biodiversity 2013). This means it is the organisation's operational level where human activities are actually carried in order to meet the needs of the present generation (Patzek & Pimentel 2005). Therefore, discussion of sustainability of natural resources needs have a focus at the organisation's operational level to capture the issues of sustainability actually occurring at that level.

Second, it is a challenge to persuade individual organisations to act in the "common interest" as addressed in the Brundtland definition. In addition, it is difficult to see how intergenerational decisions can be made efficiently by individuals. Furthermore, environmental and ecological interactions do not respect the boundaries of individual ownership and political jurisdiction. From a classical economics point of view, the goal of business is to maximise shareholders' value with the key objective being to increase productivity. However, in the contemporary business environment, organisations in many industries, such as agriculture, manufacturing or petroleum industries, have faced challenges of operating in a more efficient and more environmentally friendly manner in order to move towards sustainable development (Barney 1991; Hart 1995; Joshi, Krishnan & Lave 2001; Rainey 2010; Williams & Martin 2011; Wisner, Epstein & Bagozzi 2006). Therefore, the link between economic performance and environmental performance of a business needs to be demonstrated explicitly to encourage individual businesses to pursue an evolutionary trajectory towards sustainability.

In summary, while the Brundtland definition provides useful guidance in how to think about sustainability at a macro level, it's translation into a more meaningful, clear, rigorous and relevant definition at the organisational level still remains a challenge.

2.3 Water sustainability

2.3.1 Global natural water system

As discussed in Chapter 1, this thesis focuses on water sustainability for crop production. In order to gain an understanding of what water sustainability means and identify potential approaches to the sustainable use and management of water, both globally and locally, it is necessary to have a fundamental understanding of hydrology (Barth et al. 2010; De Wever 2010; Graedel & van der Voet 2010; Ibaraki 2010; Kanae 2010; Knepper & Ternes 2010; Lindner et al. 2010). This section reviews the water cycle and water distribution to provide background on global water flows and water stocks. This is used as a foundation for discussing issues related to water sustainability when considering human impact on the natural water systems.

2.3.1.1 Global water cycle

Water is considered one of the most important natural resources essential for human life (Ibaraki 2010). In addition, water resources are fundamental elements for economic development (including transport) and the maintenance of ecological systems (Ibaraki 2010) . Of the three main uses of water, including domestic, industry and agriculture, agriculture is currently the highest consumer of freshwater (i.e. for irrigation) (Kanae 2010).

Water can exist in three phases: gas (i.e. water vapour or moisture that exists in the atmosphere), liquid (water drops in a form of rain, surface water, groundwater or sea water) and solid (i.e. snow, ice), and can change from one phase to another in the hydrological cycle[25] (Ibaraki 2010). Figure 2.1 illustrates the hydrological cycle.

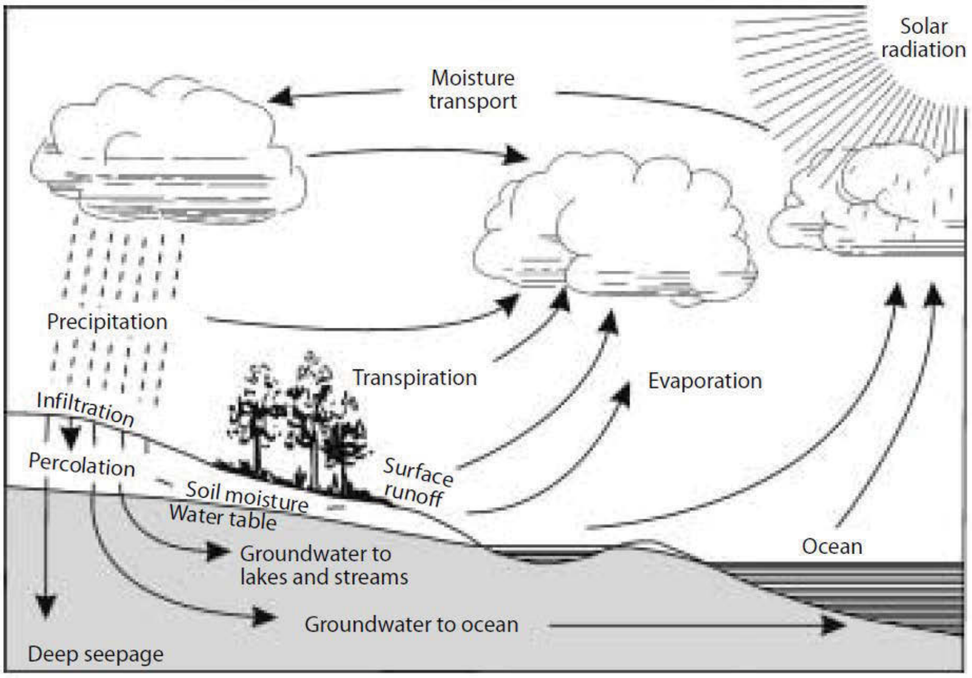

Figure 2.1 The hydrological cycle
Source: Zhang, Walker & Dawes 2002

[25] Water circulation that occurs naturally near the Earth's surface.

The hydrological cycle refers to water circulation that occurs naturally near the Earth's surface (Ibaraki 2010; Zhang, Walker & Dawes 2002). It is an endless recirculatory system that links water in the atmosphere, oceans and on the continents though several natural processes, including evaporation and transpiration (liquid water vaporized from the surface water or from plant stomata) (Avissar et al. 1985), precipitation and water run-off (Barth et al. 2010; De Wever 2010). The four key processes of the global hydrological cycle can be quantified as presented in Figure 2.2.

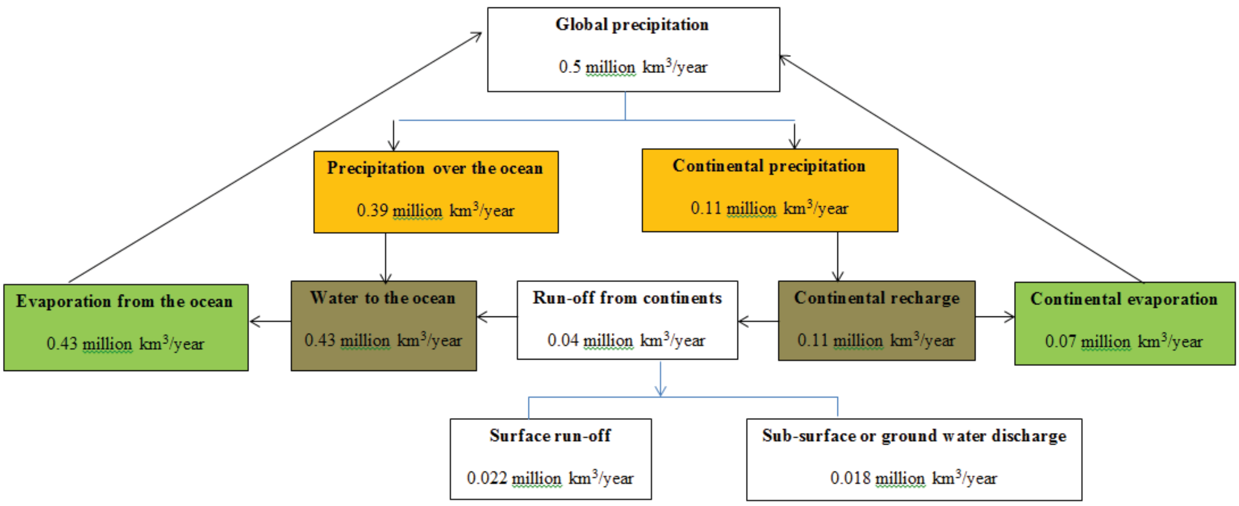

Figure 2.2 Annual global flux water cycle
Source: Barth et al. (2010)

Annual global evaporation (from both the ocean and the continents) equals the amount of annual global precipitation (to the ocean and the continents) (see Figure 2.2). This is the natural water mass balance at the global scale; in the natural hydrological cycle (the global-scale, closed system). Water does not disappear but moves from one place to another around the Earth surface in the hydrological cycle (Ibaraki 2010).

In addition, as the global hydrological cycle is a closed system, water does not disappear but changes from one phase to another by melting (solid to liquid), evaporating (liquid to gas), sublimating (solid to gas), condensing (gas to liquid) or freezing (liquid to solid) and moves from one place to another around the Earth's surface (Ibaraki 2010). Notably, water is unevenly distributed on the Earth, determined by a number of geographical factors such as gravity, energy (i.e. solar or wind energy), climatic conditions, and other forces (De Wever 2010).

2.3.1.2 Global water distribution

Understanding the distribution of freshwater and saltwater in the hydrological cycle helps us to quantify the availability of freshwater resources and examine water sustainability (Ibaraki 2010). Figure 2.3 shows global water distribution in the hydrologic cycle.

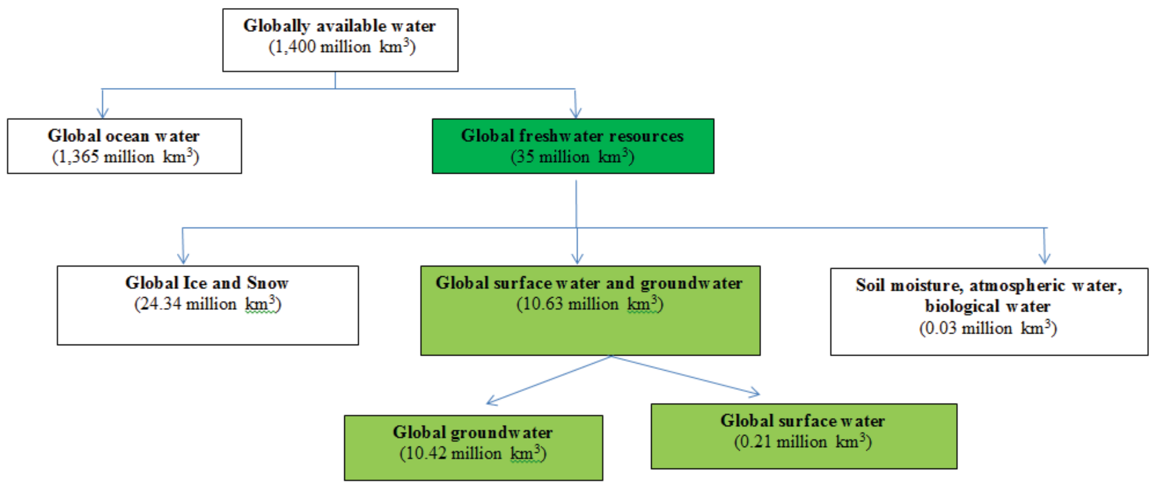

Figure 2.3 Global water distribution in the hydrological cycle
Source: (Ibaraki, 2010)

Global water distribution in the hydrological cycle reveals that, while only freshwater resources can be used for domestic, industrial and agricultural purposes, freshwater comprises only 2.5% of global water (see Figure 2.3). Furthermore, while glaciers and permanent snow cover, stored in polar and mountainous regions (i.e. Antarctica and Greenland), are the main components of freshwater (making up approximately 70% of global freshwater), groundwater (making up 30% of global freshwater) is the largest source of freshwater that is readily accessible. This means only 0.76% of global water resources, in the form of groundwater and surface water, can be considered as usable freshwater.

While it is evident that the amount of freshwater to meet all human water needs is limited (De Wever 2010; Ramankutty 2010), Barth et al. (2010) predict that demand for freshwater will increase with future population growth and associated agricultural and industrial development, in addition to the higher living standards (and consumption of water) in some parts of the world. Therefore, one of the main foci for water sustainability examination is groundwater, including its characteristics and its availability (in both temporal and spatial dimensions), and how it is being used and managed at the local level.

2.3.2 Local water systems

In order to evaluate the availability and sustainability of freshwater resources at a regional or local level, the application of the principle of conservation of mass to flows of water in a natural system (e.g. watershed, water basin) and change of its water storage volume is needed.

2.3.2.1 The principle of conservation of mass of water

The principle of conservation of mass of water is that the water mass that enters a system (within the *control volume*) must leave the system. Accordingly, the annual rate of water inflow (I) to the control volume must equal the annual rate of water outflow (O) from the system (Ibaraki 2010). Water balance in a natural system (i.e. watershed) can be expressed as follows[26]:

$$I = O \quad [2.1]$$

Or

$$I - O = 0 \quad [2.2]$$

Furthermore, by assuming that the density of water, therefore it's volume, is constant, under average conditions, water stored in a natural system does not change its volume significantly. Accordingly, dV/dt equals zero.

$$\frac{dV}{dt} = I - O = 0 \quad [2.3]$$

where V is the volume of water stored within the control volume and t represents the time dimension; ***dV/dt*** represents the time rate of change of mass inside of the control volume.

Moreover, the two water flow components, I and O, can be further decomposed into their components, as expressed in Equation 2.4.

$$\frac{dV}{dt} = p - (r_s + r_g + et) = 0 \quad [2.4]$$

[26] The equations (2.1) to (2.6) are derived from Ibaraki (2010).

where p denotes the average annual rate of precipitation (L^3T^{-1}), the only component of volumetric inflow; r_s, r_g and et denote the average annual surface flow water rate, the average annual groundwater discharge (or groundwater run-off) rate, and the average annual evapotranspiration rate (L^3T^{-1}), respectively. They are the three natural components of volumetric outflow.

Equation 2.4 illustrates that in a natural system, the water inflow component (precipitation) is equal to water outflow components (surface water, groundwater discharge and evapotranspiration); and water stored (water in rivers, lakes, aquifers and the soil) in a natural system (within the control volume) does not change significantly. Figure 2.4 represents the water inflow and water outflow components of a natural system (e.g. watershed).

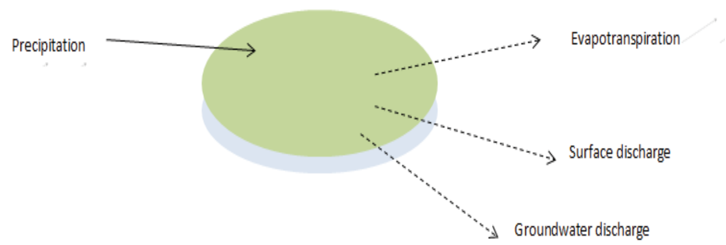

Figure 2.4 Water balance at a watershed (a natural system)

More importantly, Equations 2.3 and 2.4 include water flows, a storage term (V) and time scale (t), which are key elements for discussion in relation to water sustainability in the next section and in particular the impact humans have when withdrawing V from the system.

2.3.2.2 Human impact on local water systems

Freshwater from the environment (including groundwater and surface water) is withdrawn by human beings to meet their water needs for agriculture (irrigation), industrial and household purposes (Barth et al. 2010). Human impact on freshwater availability and sustainability needs to be included in the water balance equation (Ibaraki 2010). Accordingly, Equation 2.4 can be modified to reflect water balance at a watershed – that is the intervention from human activities:

$$p + i_r + i_a = r_s + r_g + et + r_w \qquad [2.5]$$

where i_r and i_a denote recycled sewage water and agriculture return to the system (L^3T^{-1}), respectively, and r_w denotes the rate of water withdrawal from surface water and groundwater (L^3T^{-1}).

Figure 2.5 visualises the water inflow (*I*) and water outflow (*O*) components of a watershed with human intervention.

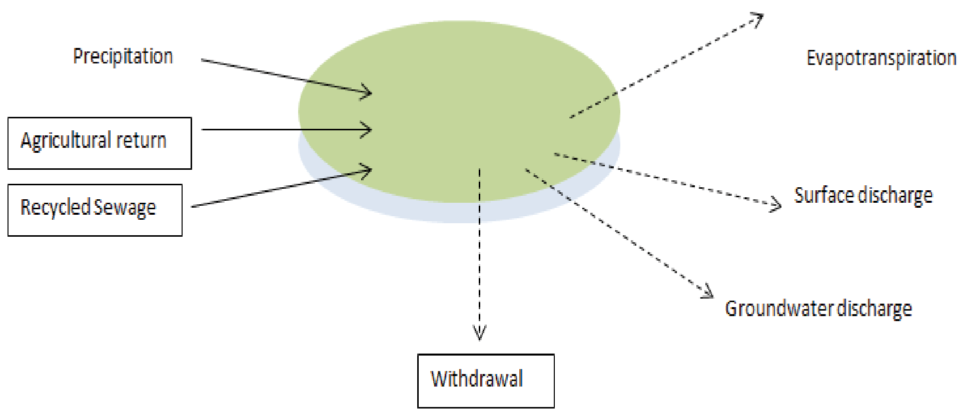

Figure 2.5 Water balance at a watershed (with human intervention)

Human-induced flow components (i_r, i_a and r_w) play an important role in the change in the volume of water stored within a local water system, which is implied as zero in the natural system (see Equation 2.6[27]).

$$\frac{dV}{dt} = (p + i_r + i_a) - (r_s + r_g + et + r_w) \qquad [2.6]$$

In some parts of the world, freshwater (e.g. surface water and groundwater) is withdrawn significantly by humans for irrigation. Over time, this leads to a considerable negative change

[27] Assuming parameters on the right hand side of Equation 2.6 are measured at the same time scale as *t*.

of water stock in these local catchments ($dV/dt << 0$), resulting in water shortage and competition for water among users.

In addition, water can be withdrawn from one system but be discharged into another. Consequently, significant artificial water recharge leads to unexpected positive change of water storage within the local water systems ($dV/dt >> 0$), resulting in groundwater salinization (as groundwater levels rise) and flooding problems in these areas.

2.3.2.3 Issues with sustainability of water

As discussed above, at the global level, water is considered sustainable in the context of the hydrological cycle as a whole. For example, unlike other commodities such as oil and coal that are defined as non-renewable resources[28], water exists in the endless recirculatory hydrological process. In addition, water that is used for irrigation, industrial and household purposes will return to the hydrological cycle and eventually will be available for reuse (Ibaraki 2010). However, when considering human impact on local water systems in respect of time, space and usability[29] of water, and in particular freshwater, there are a number of issues related to its sustainability.

First, human intervention causes imbalance in the water system. For example, water used for crop irrigation may lead to greater evapotranspiration and runoff (therefore affecting t) than in the natural system. As a result, annual global flux water cycle and global water distribution changes over time with a decrease in the freshwater reservoir volume (e.g. water stocks in river and lakes over time may be depleted) (Ibaraki 2010).

Second, the stocks (V) of freshwater resources upon which humanity can withdraw are limited. From the discussion in the previous section, only available freshwater resources (mainly surface water and groundwater), can be used by humans to meet their water demands (for example, for irrigation, industrial and household purposes). It is projected that water abstraction in 2050 will be from 50,000 to 80,000 km^3 per year due to growing world

[28] In the context that the rate of use is much greater than the rate of generation.
[29] Usability in a sense of both quantity (available and ready to be used) and quality (can be used for particular purposes).

population. Moreover, water abstracted[30] is not necessarily water actually being used to meet human needs. While a small proportion of water is consumed for irrigation, industrial and household purposes, overdrawing of water occurs due to inefficient use of water and/or poor water management (Barth et al. 2010).

Third, water abstraction leads to intense water competition among regions and among water users within a region. Distribution of available freshwater varies to a more or less significant degree in both spatial and temporal dimensions. Water can be withdrawn in one place but discharged in another place, ranging from several to some thousand kilometres in distance. Yet, when water is abstracted from a groundwater system (i.e. from a well), water at the discharge/pumping area will be recharged from surface water bodies (i.e. aquifer storage). For example, the timescale for water being recharged in the source water body can vary tremendously from less than a day to more than a million years, depending on the velocity of water which is driven by the hydrological properties of the aquifer and the distance between the discharge and recharge points (Ibaraki 2010).

Fourth, there is a time issue in respect to dV/dt where V is the volume of a necessary resource or waste remediation process. So far, we have, as a society, been thinking as though V was infinite, but it was not and now V has been more or less seriously reduced. The dV/dt is probably accelerating in a negative way. Therefore, the first element of time is when dV decreases towards zero. The second element of time is that we need to reverse dV/dt, that is, reduce its negative growth and eventually, not only get dV/dt to equal zero, but go beyond it to dV/dt greater than zero as water stocks are rebuilt. This will occur either through human catastrophe or the development of new technology, and probably social conventions.

Finally, water abstraction leads to water quality issues. A proportion of withdrawn water that is consumed for human activities gradually returns to the environment but generally with lower quality (Ibaraki 2010). This not only degrades systems but also decreases future freshwater availability as a considerable amount of water discharged is not ready to be reused or is costly to treat and recycle (given the current technology).

[30] Water withdrawals are defined as *"the amount of water taken out of rivers, streams or groundwater aquifers to satisfy human needs for water"* (Rijsberman, 2006, p8).

Ibaraki's (2010) work, in conjunction with several water sustainability studies mentioned above, provides a number of key concepts for water sustainability. First, it is argued that water is a resource only if it is available: (i) at the place where it is required, (ii) at the time when it is needed, (iii) at the quality required for its particular use, (iv) in sufficient quantity, and (v) at a low enough cost.[31] Therefore, the discussion of water sustainability is not only about available water at the global scale but mainly about whether it can be ready and suitable for use at a local level. In addition, unlike other natural resources, water sustainability is more about maintaining the balance in the flow of water through the cycle than it is about water stocks as it is, ultimately, naturally recirculated.

2.3.3 Water sustainability principles

Based on the Brundtland definition of sustainable development (The Brundtland Commission 1987), the concept of the hydrological cycle and water mass balance, and the discussion of some of the key theoretical issues with water sustainability in the previous sections, this section aims to propose a number of water sustainability principles to provide a foundation for discussion of water sustainability for crop production in the next sections.

The heart of water sustainability principles is the consideration of the use of available freshwater resources by the current generation to meet their own needs, which will cause negative impacts on the global hydrological system and availability of freshwater resources for future generations (The Economics of Ecosystems and Biodiversity 2013).

2.3.3.1 Principle 1

Discussion of water sustainability needs to be placed in the context of human intervention in the natural environment through abstraction (e.g. water withdrawals from the natural environment) as well as discharges impacting on natural systems (e.g. impacting on the quality of water in the natural environment or adding to the system). This causes imbalance in the natural hydrological system and shifts the equilibrium point of the water cycle to another state (in which available freshwater at a particular place reduces over time).

[31] For example, though ocean water is the major water resource and abundant, it is currently costly to convert salted water into freshwater using desalination techniques.

2.3.3.2 Principle 2

Available freshwater resources (groundwater and surface water) are the water resources that can be consumed by human beings to meet their own needs. In order to conserve water stock in the long-term, minimizing water abstractions from these natural resources is necessary. Therefore, efficient management of groundwater and surface water abstraction needs to be considered as a step towards water sustainability.

2.3.3.3 Principle 3

In the previous section, it is argued that water can be considered as a usable and useful resource only if it is available (i) where it is required, (ii) when it is needed, (iii) with a quality for its particular uses, (iv) in sufficient amounts to meet the particular needs, and (v) at a reasonable cost[32] (Ibaraki 2010; Kanae 2010). Therefore, the discussion of water sustainability is not really about available water at the global scale but mainly about whether it is available and suitable for use at a local level.

2.3.3.4 Principle 4

Water stored within a local water system is the resource from which water is withdrawn. However, change in volume of water storage over time, dV/dt, does depend on water flows of the system. Therefore, discussion of water sustainability needs to take into consideration of both water stock and flows of water.

2.3.3.5 Principle 5

Water plays a critical role in production processes of agriculture and several important industries (e.g. food and manufacturing) (Barth et al. 2010; Rijsberman 2006). This means inadequate water supply will impact business production outcomes, and hence, its profitability (Cammarano et al. 2012; Jackson et al. 2011; Long et al. 2010). However, it is evident that we face the risk of a shortage of freshwater resources (Jackson, Khan & Hafeez 2010; Raskin et al. 1997; Rijsberman 2006). This leads to increasing competition among water users, increased water costs, and more stringent environmental regulation, which makes it more difficult for businesses with high water needs to maintain their economic growth in the long-term (Cammarano et al. 2012; Jackson et al. 2011; Khan et al. 2006). Therefore, the

[32] For example, though ocean water is the major water resource and abundant, it is currently costly to convert salted water into freshwater using desalination techniques.

link between business profitability and water use needs to be taken into consideration to capture both economic sustainability (e.g. as a going concern) and the sustainable use of water (the environmental sustainability of the enterprise with respect solely to its water use) of the business.

2.4 Conclusion

This chapter provides a theoretical discussion of water sustainability at the global scale which lays out the foundation for conceptualising water sustainability at the crop business level discussed in Chapter 3. This includes development of a set of water sustainability principles, based on hydrology and contemporary sustainable thinking, to provide a clearer and better understanding of what defines water sustainability generally. In summary, the heart of the set of water sustainability principles is the consideration of human intervention in the natural environment (e.g. water abstraction from the natural environment) as well as human impact on natural systems. In addition, it is argued that water sustainability is not really about available water at the global scale but mainly about whether it is available and suitable for use at a local level. Therefore, discussion of water sustainability needs to take into consideration of both water stock and flows of water, and efficient management of groundwater and surface water abstractions needs to be considered to minimise disturbance on the natural environment as a step towards sustaining water systems. Furthermore, for crop businesses, in order to maintain going concern, they need to consider both economic and environmental sustainability. In this respect, the link between business profitability and water use needs to be taken into consideration to capture both economic sustainability and water sustainability of the business. These water sustainability principles will be applied to a specific local focus which is cotton businesses in Australia.

Furthermore, this chapter theoretically addresses key parameters that define an overall definition of what constitutes water sustainability, which provides overall targets for Chapter 3. One of the key parameters that defines water sustainability which has not yet been considered in extant water sustainability literature is that if an unsustainable human activity results in V decreasing to a point where other legitimate uses (i.e. ecosystem stability, domestic use) become insufficient then the unsustainable activity should be modified so that its contribution to decreased dV/dt is reduced. This definition also allows for unsustainable drinking water abstraction to be modified by return of wastewater. At the crop business level, such general definition of water sustainability can be applied to address the extent to which crop production withdraws water from the environment and how runoff from irrigation can be managed and recycled to reduce the water impost of crop cultivation on the environment.

Chapter 3. Theory of Crop Water Flows

3.1 Introduction

The previous chapter discussed issues related to water sustainability at the global and regional levels. The environmental impact on water in a natural ecosystem was described in terms of its contribution to the negative dV/dt characteristic of such systems. Sustainability requires that dV/dt approaches zero, and in the case of severely disrupted systems, it should become positive.

Water use in crop production will now be assessed in this context, with the goal of identifying the reasons for the tension generally assumed to lie between environmental and economic sustainability. Broadly they can be sketched as follows. Economic sustainability requires profitability and, in a water-limited cropping environment, that will mean abstraction of water for irrigation. However, this leads to a negative dV/dt, and, as we have just discussed, environmental sustainability requires a positive dV/dt.

While the issue of improving water sustainability in agriculture, a setting that has the largest human imposts on *V*, has drawn increasing attention (Moore, Robertson & Routley 2011; Pereira, Cordery & Iacovides 2012; Tennakoon & Milroy 2003), most research has focused on crop water use efficiency.[33] However, when a holistic view is taken, from the point of water abstraction through to making a profit, a more nuanced perspective is necessary.

Section 3.2 lays the foundation of such a view, describing, from a theoretical basis, water flows through a cropping system.[34] In aggregate, this description encompasses what I term the *crop water process model* which provides a theoretical link between water flow components and crop yield at an operational level. The model also allows identification of a number of key sustainability performance measures in Section 3.3 which will form part of the EPMS designed in Chapter 4. Finally, the conclusion contains a summary of the above and lays out how this provides the theoretical basis for the design of a decomposition ratio model in Chapter 4.

[33] Crop water use efficiency is defined as the ratio of crop yield to crop water use (Tennakoon & Milroy 2003).
[34] A cropping system is defined as the volume of land, soil and atmosphere where a crop is grown.

3.2 Crop water process model

Water is considered at the heart of crop agriculture; the primary process of crop production is photosynthesis through which transpiration (the evaporation of water from plants) and atmospheric carbon dioxide are exchanged and the latter is used in the synthesis of organic carbon compounds (i.e. sugar) to feed the plants using energy obtained from sunlight (Pereira, Green & Villa Nova 2006). Some of the carbon is used to provide metabolic energy to the plant with the remainder used for growing structures (stems, leaves, roots and so on) and reproductive structures (fruit, seeds) which are generally the products valued by mankind.

Insufficient water supply during crop growth significantly affects crop yield and quality (Bange & Constable 2006; Cammarano et al. 2012; Jackson et al. 2011; Long et al. 2010). There is some scientific evidence that shows crop agriculture is facing a challenge of rainfall variability (in terms of both rainfall amount and frequency), which partly arises from changes in the climate (Jackson et al. 2011; The Economics of Ecosystems and Biodiversity 2013) and partly from growing competition from the environment and urban growth (Gleick 1998; Ibaraki 2010). Rainfall variability affects crop yield and quality of rainfed crops[35], and increases reliance on environmental abstraction of water[36] for irrigated crops (Grassini et al. 2011; Jackson et al. 2011; Jackson, Khan & Hafeez 2010; Mateos et al. ; Mehta et al. 2013; Oweis, Farahani & Hachum 2011; Pereira, Green & Villa Nova 2006; Smith, Raine & Minkevich 2005; Tennakoon & Milroy 2003; Yeates, Constable & McCumstie 2010). For example, it is estimated that around 85% of Australian cotton crops are irrigated (Cammarano et al. 2012). Similarly, in California, agriculture is heavily dependent on irrigation water which is withdrawn from surface and groundwater and accounts for 80% of total freshwater withdrawals in the state (Mehta et al. 2013). Therefore, irrigation water is considered as one of the key water inputs for a crop and may need to be added in a cropping system.

This thesis considers two sustainability aspects of crop businesses – water and economic sustainability, and how to incorporate them into a single assessment of crop businesses' sustainability performance. To do this, first it is necessary to gain an understanding of how water flows across a cropping system and how water relates to crop production output.

[35] Rainfed (or dryland) crops are crops that rely only on rainfall not irrigation for water.
[36] Environmental abstraction of water refers to irrigation water, which is water withdrawn from natural water systems, such as groundwater or rivers (Ibaraki 2010).

3.2.1 Water balance for a root zone

This section provides a background of water balance for a root zone under natural conditions. Figure 3.1 is a schematic diagram of the water balance for a root zone. The root zone is a crucial focus as this is the soil volume, explored by roots, which holds the water resource on which the plant draws, by root uptake. The plant depends explicitly on this and, with rare exceptions, requires that the soil water resource is reasonably frequently replenished.

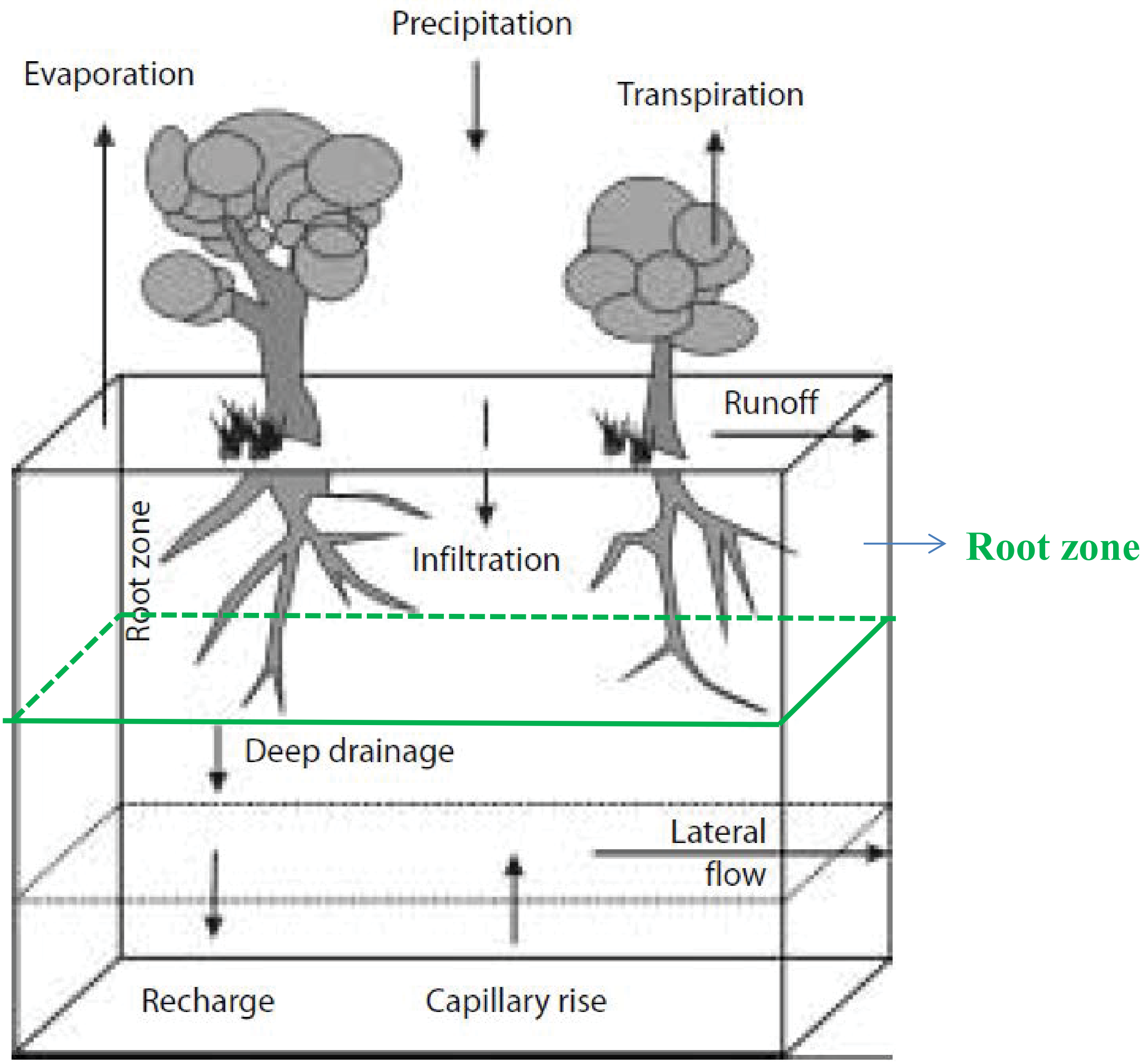

Figure 3.1 Schematic diagram of the water balance for a root zone
Source: Zhang et al. 2002

Precipitation or rainfall is the key water inflow component to the root zone[37]; whereas soil evaporation, transpiration[38], deep drainage and run-off are the four key water outflow components (see Figure 3.1). The difference between water inflow to and water outflow from the root zone is change in soil water. Soil water storage is defined as the volume of water that is held in the soil within the plant's root zone (Zhang, Walker & Dawes 2002). Accordingly, water balance for a root zone can be expressed as follows:

$$\text{Change in soil water} = \text{Rainfall} - (\text{Transpiration} + \text{Soil evaporation} + \text{Deep drainage} + \text{Runoff}) \quad [3.1]$$

Of the four water outflow components, transpiration refers to the amount of water lost from plants through stomata, whereas soil evaporation refers to water evaporated from wet soil surfaces. Water lost by transpiration is exchanged for carbon assimilation, the primary process of plant growth (Passioura 2006; Pereira, Green & Villa Nova 2006). In addition, deep drainage refers to water that drains beyond the plant root zone. Deep drainage occurs when water inputs exceed the soil water storage capacity of a plant. In contrast, run-off refers to excess water from rain that flows over the land – also called as surface runoff. This water loss occurs when water is applied to the soil surface faster than it can infiltrate the soil (Zhang, Walker & Dawes 2002).

Not all water held in the soil is equally available to support plant growth. Excess water is held only temporarily and some water, at the drier end of the range, cannot be extracted by actively growing plants. This issue is elaborated in Section 3.2.2.4.

3.2.2 Crop water process model

In this section, a water process model for an irrigated crop is constructed, based on water balance for a root zone described above, to lay out three main water components of a cropping system; crop water supply (the flow of water supply to the cropping systems), transpiration (the flow of water contributing to productive output), and crop water loss (the flow of water representing non-productive water).

[37] For irrigated crop, irrigation is an additional water input to supplement precipitation when the latter is insufficient to adequately meet crop needs.
[38] The amount of water lost from plants through stomata.

3.2.2.1 The cropped field

An irrigation[39] farm generally has two scales at which water can be considered. The field scale encompasses the operations and flows in a defined sub-area of the farm, growing a particular crop. There may be many fields, not all operating in synchrony. The farm, in contrast, has a unitary aspect, with generally one central water storage and one, or a few, water sources replenishing the storage. Irrigation water for each field is drawn from the storage. There are exceptions to this, but it is a generally useful construct to identify key water processes. I begin at the field scale. Figure 3.2 demonstrates a water process model for a cropped field.

[39] Irrigation is referred as the supply of additional water to a crop so that any inadequacies in supply of water from rain are alleviated.

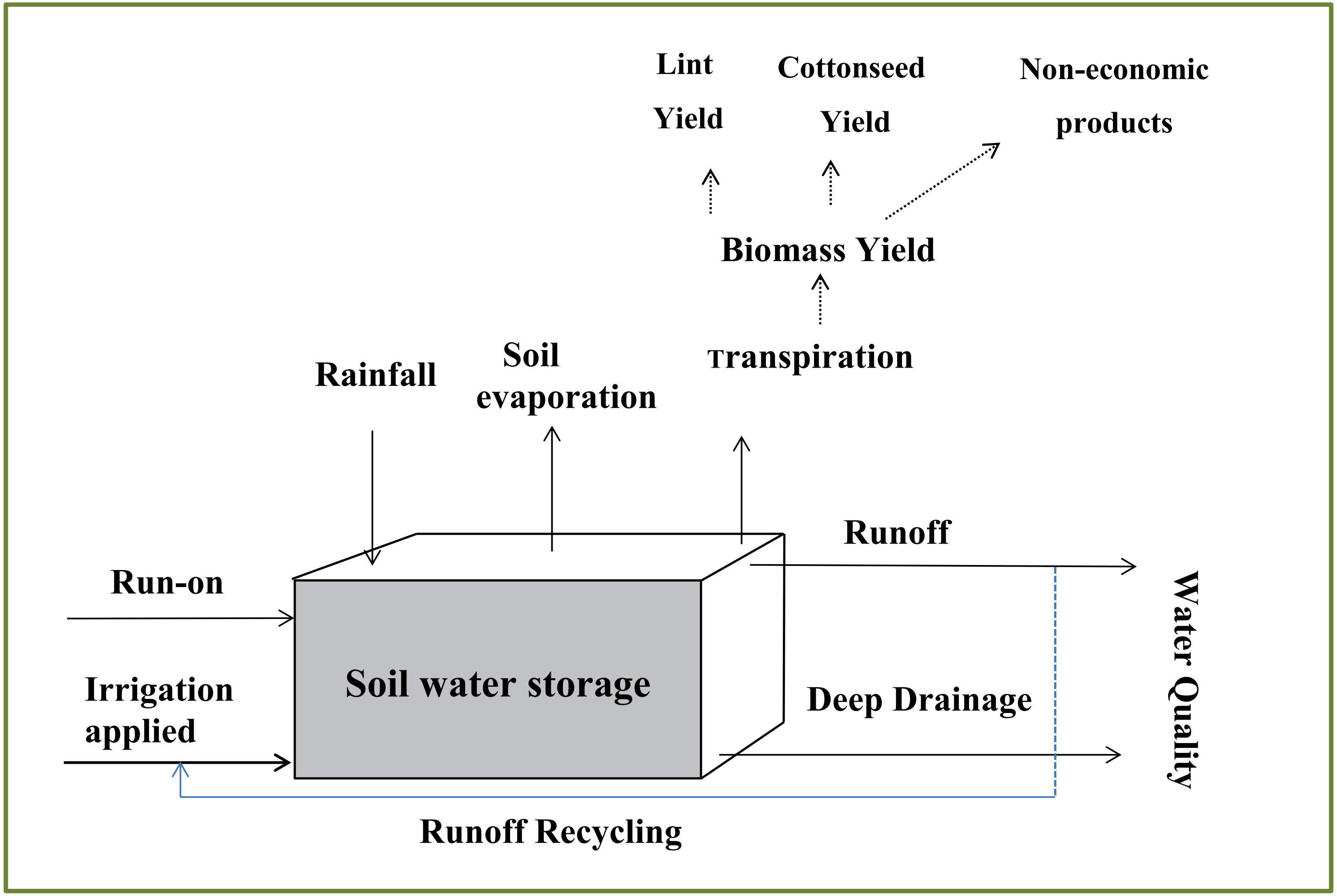

Figure 3.2 Crop water process model

Based on the crop water process model, discussions of each type of water resource, including how it is sourced, will be laid out to provide insights into its environmental sustainability which will be discussed in Section 3.3. Furthermore, the link between water for irrigation applied to a cropped field and water storage at the farm scale will be discussed in Section 3.2.3.

3.2.2.2 Crop water supply

Water supply to the crop includes all types of water resources flowing into the cropping system. As described in Eq. (3.2)[40], crop water supply for irrigated crops typically comprises rainfall, irrigation applied to the cropping system, and run-on from adjacent areas. The formula for crop water supply of a cropped field, *i*, in a particular crop season, *t*, is therefore:

$$\text{Crop water supply}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) = \text{Rainfall}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{Irrigation applied}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{Run} - \text{on}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.2]$$

In this thesis, crop water flow components are measured in mega litres[41] per hectare (ML/ha).

Rainfall

Rainfall comprises two components; rainfall directly on the field and rainfall on catchments, from which runoff and seepage contribute to the inflow of water systems, such as reservoirs, dams and rivers. In this thesis, the term "rainfall" is defined as comprising the rainfall component that falls directly on the cropped field while the rainfall component on catchments is defined within the irrigation component of water supply to a cropping system.

Rainfall frequency and amounts are a characteristic of a given location, with long-term climatic trends and familiar short-term variation around those trends (Langousis & Kaleris 2012). Historical data of the climate factors of a particular geographical area (climate station)

[40] The equations (3.2) to (3.11) are derived from the crop water process model constructed in Section 3.2.2 (Figure 3.2).
[41] 1 mega litre is 1,000, 000 litres. Therefore 1 mm of applied (or lost) water equals 100 ML/ha.

can be obtained from climatic databases, for example SILO climate data[42], for Australian locations.

The major problem of rainfall availability is that the long-term availability of water in any location may be affected by changes in climate (Jackson et al. 2011). Therefore, relying on rainfall as the main water source for crop production may lead to low production yield and low quality in unfavourable climatic seasons (Hochman et al. 2013; Jackson et al. 2011). In dryland cropping, irrigation is not available and the crop must be managed so that its transpirational demands do not outstrip water supply from rainfall at the site (Hochman et al. 2013; van Ittersum et al. 2012).

Rainfall falling on the crops[43] is considered as a free water resource[44](Cammarano et al. 2012). This means crop businesses will not incur direct water costs for crop production if solely rainfed. However, crop businesses have to manage water risk and consider the trade-off between water cost savings (when irrigation is available) and crop profitability (Cammarano et al. 2012; Jackson et al. 2011).

Irrigation

Irrigation is the supply to the field of supplementary water sufficient to alleviate any water deficits resulting from inadequate rainfall. In this respect, irrigation is carried out to potentially eliminate the risk of not completely satisfying transpirational demands (Cammarano et al. 2012; Gaydon, Meinke & Rodriguez 2012; Grassini et al. 2011).The intent is to distribute water evenly to the soil so that the entire root zone can be uniformly rewet. Successful irrigation therefore comprises two key aspects; distribution and scheduling.

a. Distribution

A mechanism is used to transport water from one entry point to all points of the field. In the case of pressurised systems such as sprinklers, their design should achieve the necessary uniformity. Surface flow systems such as flood or furrow irrigation use the soil surface itself as the transport system with water flowing down a slight gradient engineered into the surface.

[42] SILO is an enhanced climate database hosted by The Science Delivery Division of the Department of Science, Information Technology, Innovation and the Arts (DSITA), providing Australian climate data from 1889 to the present (Department of Science- Information-Technology Innovation and the Arts 2014).
[43] There are legislative restrictions on retention of runoff from non-cropped areas.
[44] In terms of direct water cost.

In all systems, water distribution is followed by infiltration, the movement of liquid water into the soil, generally in a downward direction. Sources of inefficiency, particularly for furrow irrigation, will be discussed later in Chapter 6.

b. Scheduling

For most irrigation systems, water is applied in a batch-wise way, refilling the storage capacity of the root zone in a short period. The plants draw water from soil water reservoirs over the next period, which may be in the order of days or weeks. The key management decisions are when to replenish the crop soil reservoirs and how much water to apply. Inadequate rewetting and excessive rewetting both can harm crop growth and the efficiency with which water is used. Relevant details will also be discussed in Chapter 6.

Run-on

Run-on refers to the amount of water run-on to a farming system from up-slope land. The amount of run-on depends on soil type, slope and condition, up-slope of the crop site (Zhang, Walker & Dawes 2002). Typically, water run-on is a small component[45] and is ignored in this thesis.

3.2.2.3 Crop water loss

Water loss from the system occurs as either water vapour lost in evaporation (soil evaporation and transpiration) or as liquid water loss. These two components are classified as evaporation and water output. The separation is made because while a liquid water flow can be a mechanism for transporting soil, salts, pesticides and nutrients out of the cropping system into the environment, water vapour cannot, of itself, be polluting. The crop water process model demonstrates a link between liquid water flows (e.g. deep drainage and run-off) and quality of water output from the cropping system (see equation 3.3).

The formula for crop water loss can be expressed as follow:

$$\text{Crop water loss}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Water output}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Evaporation}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \qquad [3.3]$$

[45] We ignore replenishment of the soil water reserves by flooding across river floodplains.

Evaporation

Two categories of evaporative water loss from the cropped field system are defined as evaporation from soil surfaces (soil evaporation) and from plants as (transpiration).[46] As discussed earlier, during carbon assimilation, transpired water is exchanged for carbon dioxide which is converted into plant biomass comprising grain, fibre or other harvestable product (Passioura 2006). While transpiration is considered as a productive water component, soil evaporation is considered as a non-productive component. In other words, evaporation can be partitioned into productive (transpiration) and non-productive (soil evaporation) components.

Traditionally, soil evaporation and transpiration are combined as **evapotranspiration**, which is calculated with the Penman–Monteith equation (Pereira, Green & Villa Nova 2006**.** In this thesis, soil evaporation and transpiration are presented separately in order to distinguish between productive water (transpiration) to produce an economic product (e.g. cotton lint) and non-productive water (water lost from the soil due to evaporation).

$$\text{Evaporation}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Transpiration}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Soil evaporation}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.4]$$

As discussed above, wet soil surfaces, for example, after rain and following surface or sprinkler irrigation, initially evaporate water at a rate similar to an open water surface (Khan & Hanjra 2008; Salvador et al. 2011). However, once surface drying occurs, the evaporation rate decays at the square root of time (Sommer et al. 2012). Therefore, frequent rewetting of the surface potentially exposes the field to significant evaporative losses. Such non-productive water loss needs to be taken into consideration in the discussion of water sustainability performance of a crop business.

Water Output

In the crop water process model (see equation 3.5), two categories of liquid water discharged from the system are presented; deep drainage and run-off.

[46] At the field level, we do not consider evaporation from free water surfaces (e.g. distribution channels, on-farm storage). In addition, because free water surfaces exist in the field for relatively short periods in the crop cycle, a simplifying assumption was made that free water surface evaporation is equal to zero at the field scale for this thesis.

$$\text{Water output}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Deep drainage}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Runoff}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$$

[3.5]

a. Deep drainage

Deep drainage from the field refers to water loss that occurs when either rainfall or irrigation water inputs to the root zone exceed the water deficit in the soil[47] (Moore, Robertson & Routley 2011; Smith, Raine & Minkevich 2005). As a result, excess water drains from the soil store to deep soil strata where the roots cannot reach it (Zhang, Walker & Dawes 2002). Loss through deep drainage may be substantial for surface irrigated crops, which potentially leads to significant environmental harm and an annual loss of 2.5 ML/ha of water that could be beneficially used for growing additional crop (Smith, Raine & Minkevich 2005).

b. Runoff

When water is applied to the soil surface at a rate greater than the infiltration rate, the excess water moves across the field surface as gravity-driven flow and runs off the field, hence its name. Runoff can have negative impact, both because it can cause soil and nutrient lost by erosion and also because it represents a non-productive loss of water from the crop. Surface flow systems depend on this same process for water distribution and hence are particularly susceptible to runoff losses.

At the field scale, runoff is recycled. This is discussed later in Section 3.2.3

3.2.2.3 Change in soil water

Soil water (*SW*) is defined as the amount of water held in the soil at a particular point in time. Figure 3.3 shows a soil water diagram with various soil water-related parameters, including:

(i) **Saturation (*SAT*)**: amount of soil water at saturation, that is, all soil pores are filled with water.

(ii) **Drained upper limit (*DUL*)**: amount of soil water at drained upper limit or field capacity. DUL is also known as field capacity. Larger pores have drained under gravity and smaller pores retain water.

[47] Soil water deficit will be discussed in detail in the next section.

(iii) **Lower Limit at 15 bar (*LL15*)**: amount of soil water corresponding to a soil water potential at 15 bar. LL15 roughly represents the minimum water content to which plants can dry the soil.

(iv) **Plant available water (*PAW*)**: the difference between drained upper limit and lower limit at 15 bar.

(v) **Extractable soil water (*ESW*)**: the difference between soil water and lower limit at 15 bar.

(vi) **Soil water deficit (*SWD*)**: the difference between drained upper limit and soil water.

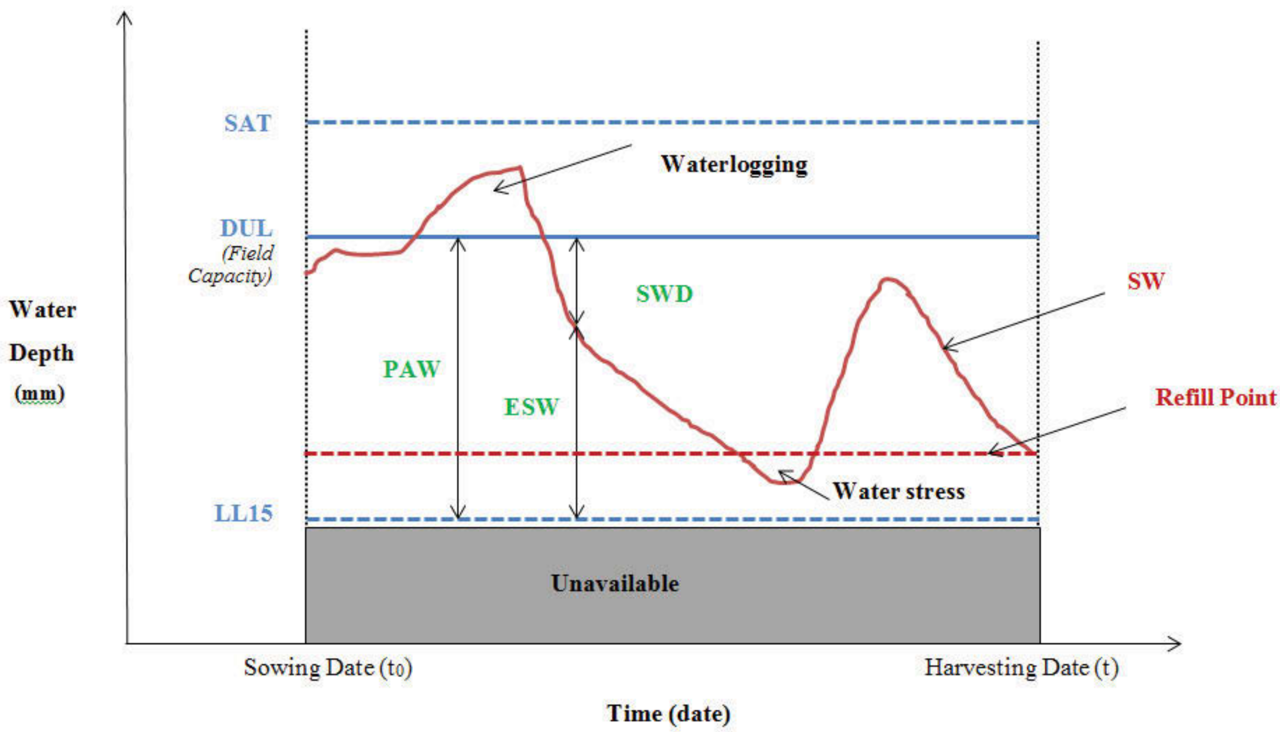

Figure 3.3 Soil water diagram

Figure 3.3 lays out some of the key soil water-related parameters to provide a foundation for setting up irrigation schedules to support plant growth free of water stress.

As defined above, plant available water (*PAW*) represents potential plant available water - the volume of water held in the soil depth, explored by the crop roots, between the maximum water content after free drainage (field capacity) and the minimum water content at which plants cannot continue to support growth (permanent wilting point). Furthermore, a fraction of *PAW*, extractable soil water (*ESW*)[48] represents the soil water storage or actual plant available water which can be withdrawn by the crop roots to support plant growth. The sum of *ESW* and soil water deficit (*SWD*) is *PAW*.

Irrigation and rainfall replenish soil water to field capacity (e.g. replenish *ESW*), while the growing crop continuously depletes this store (e.g. reduces *ESW*). Good management ensures the store is neither overfilled to the point where soil is waterlogged nor depleted to the point where plant growth is affected (water stress). Both cases will reduce the ability of the plant to achieve its potential yield. The ratio of *ESW* to *PAW*, which is called fraction of *PAW*, is typically used as a trigger for irrigation, i.e. to determine when irrigation should take place to support plant growth.

Soil water storage under water deficit conditions

The soil provides a practical interfacial zone between water supply and root water uptake. If one could supply water continuously at low rates to match instantaneous root water uptake, directly to the roots, then soil water content would have little influence on crop cultivation. However, in the case of dryland cultivation, rainfall is intermittent and most forms of irrigation tend to supply water at rates much faster than plant uptake. Therefore, soil water storage provides the buffer between water supply and plant uptake.

Drivers of PAW

The key parameters controlling potential *PAW* are: soil type, as texture has a great influence on the values for field capacity and permanent wilting point; and management, to the extent that compaction is avoided as it both limits water storage and root exploration. Soil health is shown as having an influence, both positive in terms of the beneficial effects of soil microflora on soil structure, and negative in terms of the effects of soil-borne pathogens that may compromise plant water uptake capacity (Bone et al. 2010) .

Change in soil water

The volume of soil water within the root zone may change over the life of the crop, depending on where one draws the time boundaries delimiting the crop (Zhang, Walker & Dawes 2002). This change may represent either an additional source of water for the crop or

[48] Which is also called **Readily available water** (RAW).

a net drain on water supply, depending on the direction of the net change over the season. In this thesis, the change in soil water is defined as follows:

$$\text{Change in soil water}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Soil water}_{\text{it,at harvest date}}\left(\frac{\text{ML}}{\text{ha}}\right) - \text{Soil water}_{\text{it,at sowng date}}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.6]$$

3.2.2.4 Crop water balance

Based on the water mass balance principle, changes in soil water are equal to the difference between total crop water supply and total crop water loss. Accordingly, the water balance of a cropping system can be expressed as:

$$\text{Change in soil water}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) - \text{Crop water loss}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.7]$$

Equation 3.7 can be rearranged as follows:

$$\text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Crop water loss}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Change in soil water}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.8]$$

In this thesis, based on the crop water process model (see Fig. 3.2) and the discussion above, transpiration, the productive water loss component, is separated from non-productive crop water loss components. Furthermore, change in soil water is considered as a loss because, generally, the soil is wetter at the end of the season. Therefore, crop water supply equals sum of transpiration and crop water loss, which comprises soil evaporation, deep drainage, run-off and change in soil water. Equation 3.9 below provides a foundation for further discussion of crop water use efficiency in the next section.

$$\text{Crop water supply}_{it}\left(\frac{ML}{ha}\right) = \text{Transpiration}_{it}\left(\frac{ML}{ha}\right) + \text{Crop water loss}_{it}\left(\frac{ML}{ha}\right) \quad [3.9]$$

Whereas crop water supply and crop water loss are defined in Equations 3.10 and 3.11.

$$\text{Crop water supply}_{it}\left(\frac{ML}{ha}\right) = \text{Rainfall}_{it}\left(\frac{ML}{ha}\right) + \text{Irrigation applied}_{it}\left(\frac{ML}{ha}\right) \quad [3.10]$$

$$\begin{aligned}\text{Crop water loss}_{it}\left(\frac{ML}{ha}\right) \\ &= \text{Soil evaporation}_{it}\left(\frac{ML}{ha}\right) \\ &+ \text{Deep drainage}_{it}\left(\frac{ML}{ha}\right) + \text{Runoff}_{it}\left(\frac{ML}{ha}\right) \\ &+ \text{Change in soil water}_{it}\left(\frac{ML}{ha}\right)\end{aligned} \quad [3.11]$$

3.2.3 Water at the farm scale

The key characteristic of water flows at the farm scale, particularly on irrigated cotton farms, is a central storage which provides a single locus of water flow. Water for irrigation is drawn from this and it is replenished by recycled water and water abstracted from the environment.

3.2.3.1 Recycled runoff

Heavy rainfall events and surface irrigation systems may generate runoff (Jun et al. 2011; Zhang, Walker & Dawes 2002), as illustrated in Fig. 3.2. The regulatory treatment of runoff aims to encourage crop growers to mitigate runoff to the environment for two reasons (Jun et al. 2011). First, runoff can be treated as a resource (after recycling). Minimizing runoff to the environment means both minimising water loss from a farming system and minimising expenditure (abstraction costs). Second, recycling of run-off helps to prevent runoff carrying pollutants off-farm.

Total water runoff is a sum of runoff from irrigation and runoff from rainfall:

$$\text{Total water runoff}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) = \text{Runoff from rainfall}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{Runoff from irrigation}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.12]$$

In Australia, legislation requires that water runoff from a cropping system is recycled proportionally back to the cropping system[49]. Ratios of recycled runoff vary between 75%–85% depending on water management practices applied by crop businesses.

With a given ratio of recycled runoff, the amount of water runoff that is recycled back to water storage systems of the crop business can be calculated as follows:

$$\text{Recycled runoff}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) = \text{Total water runoff}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) \times \text{Ratio of recycled runoff}_{it} (\%) \quad [3.13]$$

The difference between total water runoff and the amount of recycled runoff determines the amount of water loss from runoff:

$$\text{Loss from water runoff}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) = \text{Total water runoff}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) - \text{Recycled runoff}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.14]$$

3.2.3.2 Abstracted water

Water abstracted from the environment includes surface water (e.g. water pumped from a river) or groundwater (e.g. water pumped from a bore) (Ibaraki 2010).

Since the beginning of the twenty-first century, where increasing demand for irrigation water worldwide has led to potential negative impacts on the natural environment, management of water supplies has drawn growing attention from local and state governments (Gaydon,

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[49] http://www.recycledwater.com.au/

Meinke & Rodriguez 2012; Khan & Hanjra 2008; Mehta et al. 2013; Moreno-Pérez & Roldán-Cañas 2012; Rijsberman 2006). In California (US), increasing water competition among agriculture, industry and urban areas has led to water over-allocation in most watersheds in the state (Mehta et al. 2013). As a result, a number of water institutions have been developed to adapt to new water scarcity conditions and manage water competition among water users, particularly at the river basin level (or catchment level), in an attempt to conserve ecosystems and biodiversity and to sustain water resources while maintaining sustainable agriculture (Cai et al. 2011; Khan et al. 2006; Mehta et al. 2013; Naramngam & Tong 2013; Reidsma et al. 2012; Rifkin 2005; Rijsberman 2006).

In Australia, for example, in order to obtain irrigation water, farmers are required to have a licence to abstract surface water or groundwater (Department of Environment and Primary Industries 2014). In areas where water sharing plans are implemented, licensed surface water users can apply for a surface water licence from their local rivers (Australasian Legal Information Institute 2014). In contrast, in areas where water sharing plans have not commenced, farmers need to apply for licences to construct a bore to take water from groundwater sources (Department of Natural Resources and Mines 2014) .

Water availability

Availability of freshwater from surface and groundwater sources is driven by environmental factors such as climate and geography (Jackson et al. 2011; Zhang, Walker & Dawes 2002). For example, in drought years, fresh water availability is very low (Jackson et al. 2011; Oweis, Farahani & Hachum 2011). Furthermore, the amount of water allocation for irrigation (if water is available) is not only dependent on physical water availability in those water sources, but also water competition and the water allocation policy of local governments or states (Department of the Environment 2014). For example, decisions on how water resources of the Murray River System are shared are based on competition among human needs, especially during periods of extremely low water availability in the Murray River (Department of the Environment 2014). The NSW system allows water entitlement holders to carry over unused water from one season to the next (with a given percentage of upper limit) so that they can manage water scarcity risk better (Australasian Legal Information Institute 2014).

Given that recycled runoff contributes to the total amount of water available to supply the cropping system (crop water supply), the amount of water abstracted from the environment to supplement rainfall to ensure sufficient water to completely satisfy transpirational demand is reduced by the amount of recycled runoff[50]:

$$\text{Irrigation abstracted}_{\,it}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Irrigation applied}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) - \text{Recycled runoff}_{\,it}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.15]$$

When replacing the irrigation applied component in the Equation 3.10 by irrigation abstracted and recycled runoff components from the Equation 3.15, total crop water supply can be expressed as the sum of three water components:

$$\text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Rainfall}_{\,it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Recycled runoff}_{\,it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Irrigation abstracted}_{\,it}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.16]$$

As the amount of water abstracted from the environment for irrigation has a significant impact on dV/dt, the key parameter that defines water sustainability, reducing the amount of water abstracted by improving water management practices with regard to recycling of runoff (i.e. improving ratios of recycled runoff) is a step towards water sustainability.

Types of environmental water

Water can be accessed through entitlement under a water licence or purchased another licence holder who sells their unused allocation in a water trading market (Department of Environment and Primary Industries 2014; Department of Natural Resources and Mines 2014). In this thesis, such water is classified in two groups: licensed water[51], which is defined

[50] Assuming that there is no water loss from the water storage systems.
[51] In order to gain access to and use licensed irrigation water, the crop business is required to have a water licence issued by statutory water rights administered by State and Territory governments: http://www.nationalwatermarket.gov.au/about/rights.html.

as water allocation where delivery entitlements are owned by irrigators[52] (i.e. crop businesses), and traded water, which is defined as water bought from other businesses via water trading markets (for example, Murray Irrigation's Exchange) (Department of the Environment 2014), a market mechanism that enables the buying and selling water access licenses or annual allocation water.[53]

Accordingly, total water abstracted from the environment is a sum of licensed and traded water:

$$\text{Irrigation abstracted}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Licensed irrigation}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Traded irrigation}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \qquad [3.17]$$

Climate and geographic factors (seasonal rainfall amount, farm location), farm characteristics (i.e. soil type, slope of land, farm size), and operational management decisions (specifically irrigation-related management decisions, such as irrigation methods, ratio of water recycled, irrigated crop area, when water sustainability is considered), will determine the total amount of irrigation water that needs to be abstracted, as well as the proportion of licensed and traded water that need to be accessed for crop production in a given year.

Environmental water cost

Since the beginning of the twenty-first century, there has been increasing competition for water abstracted from the natural environment. This has led to demand, particularly from industry (including agriculture), exceeding water availability, leading to increased water costs, more stringent environmental regulation, making it more difficult for crop businesses to be sure of their economic sustainability and growth in the long-term (Blum 2009; Jackson, Khan & Hafeez 2010; Mehta et al. 2013; Naramngam & Tong 2013; Passioura 2006; Rijsberman 2006; van Ittersum et al. 2012). Therefore, the problem of water availability for sustaining and developing a business does not only lie in calculating the optimal amount of

[52] For example, for areas in NSW, water licences are generally issued by the NSW Government: http://www.water.nsw.gov.au/water-licensing/about-licences.

[53] See an example of general water dealings including the trading of water access licenses under the *Water Management Act 2000 (NSW)* in : http://www.water.nsw.gov.au/water-licensing/dealings-and-trade

water for irrigation to ensure optimal growth, but also in sourcing that water, either through existing allocations (licensed) or water available on the water market (traded), and the cost associated with each type of water.

The price paid for water (i.e. $/ML) varies between licensed water and traded water, across years and locations.[54] In Chapter 4 the water cost will be discussed in detail, taking into consideration the ratio of licensed and traded water.

3.2.3.3 Simplifying assumptions

A complete treatment of farm scale water flows would include both several asynchronously irrigated fields and natural factors influencing the stored volume of water, such as precipitation falling on the surface of the dam, evaporation from the water surface, and deep drainage through the floor of the storage. In this thesis, the simplified farm is assumed to have, effectively, only one field.

As the intent is to compare the effects of different management practices on the field in relation to water sustainability, the influence of precipitation, water surface evaporation and deep drainage on the stored volume is assumed to be constant across cases and is therefore not included.

3.3 Theoretical link between crop water supply components and crop production components

In this section, I provide a theoretical discussion on the link between crop water supply components and crop production components. Earlier, transpiration was defined as the water lost from the crop during photosynthesis. In a real sense, the plant is obliged to exchange water for carbon, which ultimately is partially used to generate economic products. This section examines the parameters that have been used, or should be used, to describe this crucial exchange.

[54] See an example of *State Water Pricing Application: 2014-15 – 2016-17* issued by the Australian Government in https://www.accc.gov.au/regulated-infrastructure/water/state-waters-regulated-charges-2014-17-review/final-decision

3.3.1 Issues of inconsistent definitions and validity of crop water performance measures in the literature

This section provides a brief review on how the concept of crop water efficiency is defined in the crop literature. Based on this, issues of inconsistent definitions and validity of water efficiency measures are discussed.

3.3.1.1 Inconsistent terminology and definitions of water efficiency measures

The literature surrounding efficiency of water used by plants is bedevilled by inconsistent terminology. For instance, water use efficiency (WUE) has been used, as noted by (Sinclair, Tanner & Bennett 1984, p. 36) for scales "*ranging from gas exchange by individual leaves over a few minutes to grain yield response to irrigation treatments through an entire season*". Usually, the context makes clear what scale is being considered and hence what variables are important, but ambiguity remains. It is also noted that the same parameter might be used for quite different purposes. One common meaning of transpiration ratio is that equivalent to small-scale WUE, i.e. the amount of dry matter produced by a crop per unit of mass of water used (Forbes & Watson 1992). However, transpiration ratio has also been used to describe the ratio of transpiration to evapotranspiration (Kato, Kimura & Kamichika 2004).

Moreover, while another body of the crop literature has used crop water productivity (CWP) terminology to express the relationship between the amount of crop produced and volume of water used (Igbadun et al. 2006; Pereira, Cordery & Iacovides 2012), the WUE terminology has also been used to express the concept of CWP (Blum 2009; French & Schultz 1984). For example, Blum (2009) defines WUE as a ratio of biomass to water-use and transpiration efficiency (TE) as WUE at the leaf level, which is "*the amount of water transpired per given unit of CO_2 fixation*" (p.120). In addition, several definitions and terms are used to express the concept of CWP and WUE. For example, water use (technical) efficiency is defined as the ratio of biomass to water consumed, while water use (economic) efficiency and water use (hydraulic) efficiency are defined as the value of crop product(s) per unit of water volume consumed and the volume of water actually used to the volume of water supply to irrigated crops, respectively (Igbadun et al. 2006).

Another term that has also been used to express the relationship between crop production and the volume of water input is the water use index (WUI). More particularly, three different terms are used to express this relationship, including agronomic water use index (AWUI), defined as the ratio of crop yield to the volume of water input; crop water use index (CWUI), defined as the ratio of crop yield to the volume of water used by the crop (evapotranspiration) in production; and economic water use index (EWUI), defined as gross revenue per water input (Igbadun et al. 2006).

In brief, the water use efficiency concept has been used in crop science research to describe how efficient crop water use is converted into crop output, or how water adds value to a crop business (Blum 2009; Cossani, Slafer & Savin 2012; Hochman, Holzworth & Hunt 2009; Liu-Kang & Hsiao 2004; Moore, Robertson & Routley 2011; Passioura 2006; Pereira, Cordery & Iacovides 2012; Tennakoon & Milroy 2003; van Halsema & Vincent 2012). However, there are three main issues in the literature surrounding crop water efficiency measurement. First, different terminologies are used to express the concept of "water use efficiency" or the relationship between crop yield and crop water use, including WUE, CWP and CWUI. Second, different water terms are used to define the denominator (e.g. water component) of water efficiency measures; for example, water used by the crop in production (evapotranspiration), water transpired (transpiration), water use, water input, water consumed, irrigation water, and water supply. In addition, the numerator of water efficiency measures (e.g. crop output) can be either crop yield or revenue of the crop. This means the water use concept is expressed with different meanings (and in relation to various scales), making the concept of water use efficiency ambiguous and inconsistent. Third (and in contrast to the first issue), the same WUE measure is used to express two different concepts of water efficiency; the first is the extent to which crop yield is produced per unit of water use, while the second is the percentage of a water component (e.g. transpiration) to another aggregate water component (e.g. evapotranspiration).

3.3.1.2 The validity issue of irrigation water efficiency measures

Improving water-efficient irrigation has become an important issue in irrigation research and practice (Pereira, Cordery & Iacovides 2012). New indicators have been developed with an attempt to capture water-efficient irrigation performance. For example, Pereira et al. (2012) propose two different indicators to express water use efficiency (or water productivity) of irrigated crops, WP and WP_{Irrig}, both of which are defined as the ratio of the actual crop yield achieved (Y_a) and the water used. However, the denominator of WP refers to the total water use (*TWU*), including rainfall and irrigation, while the denominator of WP_{Irrig} only refers to the irrigation water use (*IWU*) (see Equations 3.18 and 3.19).

$$WP_{it}\left(\frac{kg}{ML}\right) = Y_{a,it}\left(\frac{kg}{ha}\right) \div TWU_{it}\left(\frac{ML}{ha}\right) \quad [3.18]$$

$$WP_{Irrig,it}\left(\frac{kg}{ML}\right) = Y_{a,it}\left(\frac{kg}{ha}\right) \div IWU_{it}\left(\frac{ML}{ha}\right) \quad [3.19]$$

Pereira et al. (2012) argue that the same amount of crop yield (e.g. Y_a) are driven not only by the amount of irrigation water applied to the crop, but also by the amount of rainfall water provided to the crop. However, I argue that there is a validity issue associated with the proposed WP_{Irrig} indicator in this study.

As discussed in Section 3.2.2.2, rainfall and irrigation are the two main water sources that are used for irrigated crops. Irrigation is applied to supplement rainfall when rainfall is not sufficient to meet transpirational demands of the crop (Cammarano et al. 2012; Gaydon, Meinke & Rodriguez 2012; Grassini et al. 2011). The relation between economic yield of a crop and these two water sources is illustrated in Figure 3.4.

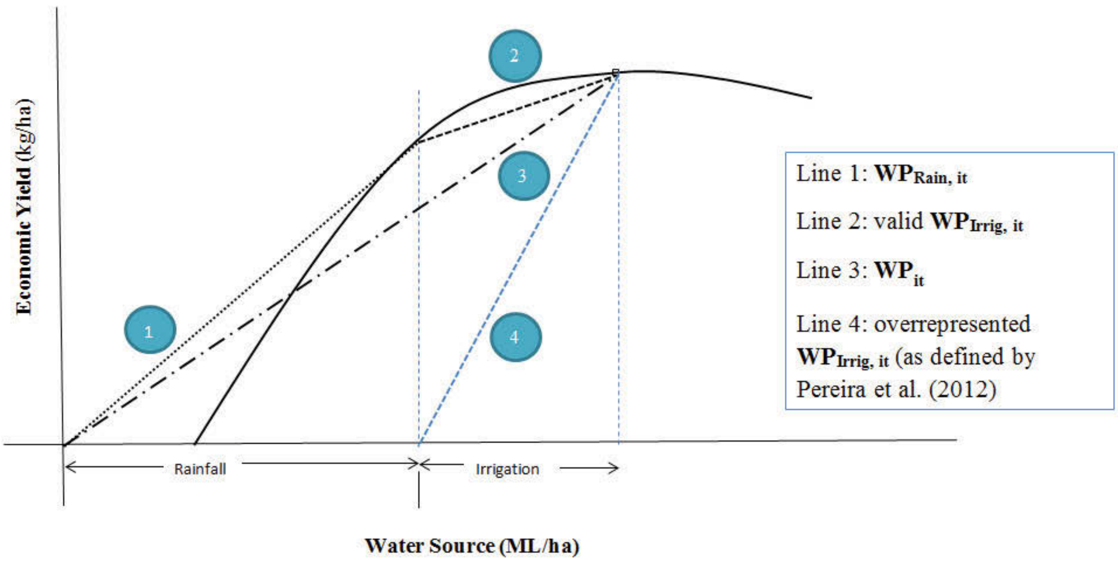

Figure 3.4 Relation between crop economic yield and water source

As rainfall can support some crop growth (see line 1 in Fig. 3.3), irrigation activities contribute an incremental amount of economic yield that can be generated by the application of irrigation (see line 2 in Fig. 3.3), which captures the accurate irrigation water use efficiency. Therefore, while the irrigation *WUE* measure (e.g. WP_{Irrig} indicator in Pereira et al.'s 2012 study) is proposed as a measure of how efficient irrigation water is used to generate economic yield, an irrigation water use efficiency measure that is expressed as the ratio between total economic yield obtained by the crop business and irrigation amount suffers a validity issue since the economic value of irrigation use is over-represented. This is because the measure does not exclude the proportion of economic yield generated by rainfall (see line 4 in Fig. 3.3). This raises an issue with the validity of irrigation water use efficiency measures, which relates to the extent to which the measure can capture the efficient use of irrigation with respect to crop production output.

If irrigation depends on water abstracted from the environment, and sustainability directs that this should be reduced towards zero, perhaps through better use of rain, then WPI_{rrig}, as defined, will tend to infinity as improvements occur, while WPI_{rrig} (actual) will tend to zero. Targets at infinity are practically useless for managers.

Furthermore, in their study of economic evaluation of cotton lint yield in different cotton areas in Australia, Cammarano et al. (2012) provide the comparisons of lint yield (kg/ha) response to irrigation amount (mm) among three different cotton locations in which rainfall amount (and other environmental factors) are different. This leads to invalid comparison and hence invalid evaluation of economic outcomes of cotton product with respect to irrigation application across regions, since the contribution of rainfall to the economic outcomes of the crop is not separated from that of irrigation.

3.3.2 Crop water use measurement

In this section, theoretical discussion as to how to overcome the ambiguity and inconsistency in water use efficiency definitions in the extant literature is developed, as well as how to overcome the validity issue of water use efficiency measurement.

First, in order to avoid confusion on water use efficiency definitions, the convention proposed by Purcell & Currey (2003) has been adopted. In this the ratio of two similar qualities is designated as an efficiency measure, and the ratio of dissimilar quantities as an index.

Second, the generally accepted use of irrigation is to ensure crop productivity is not limited by water deficits that might otherwise occur during the crop life cycle. In this respect, both rainfall and irrigation contribute to the total economic outcomes of the crop. This means when total economic yield/value is considered, total crop water supplied to the crop (e.g. sum of rainfall and irrigation applied) should be incorporated in one assessment. By doing this, the validity issue of irrigation water use efficiency is overcome. Furthermore, when irrigation is applied to supplement rainfall when this resource is not sufficient to meet the transpirational demands of the crop, the abstraction of water from the environment for irrigation constitutes an impost on the environment, questioning the sustainability of irrigated production.

The first sentence of the paragraph above provides a central position from which the sustainability of irrigated cotton production can be objectively and quantitatively evaluated, by considering processes both up and downstream from this position. Before doing this, however, the central position needs to be somewhat more development. In the following subsections, theoretical links among water coming into the crop system, water actually used by the crop to generate biomass and cash (generated from economic yield) coming out from the crop system, lay out the foundation for discussion of the sustainability of irrigated cotton production.

To begin, I assume that, as sufficient water will be supplied to avoid water-related limitations to crop growth, other limitations that can be reduced by management, for example, by providing sufficient fertilisers and adequate pest and disease control, will also be avoided. The crop should therefore grow as well as the prevailing weather conditions allow.

3.3.2.1 Transpiration index

Crop research reports that the evaporative loss of water from within plant leaves, transpiration, is a necessary corollary of the primary process of photosynthetic carbon dioxide assimilation and subsequent biomass accumulation (Blum 2009; Passioura 2006). The ratio of transpiration to biomass is termed the transpiration index. Over a cropping season, we will use transpiration index (TI) as a ratio between cumulative transpiration and cumulative biomass. The relation between transpiration and biomass accumulation can be demonstrated in Equation 3.20.

$$\text{Transpiration index}_{it}\left(\frac{kg}{ML}\right) = \text{Biomass yield}_{it}\left(\frac{kg}{ha}\right) \div \text{Transpiration}_{it}\left(\frac{ML}{ha}\right) \quad [3.20]$$

The transpiration index is affected by ambient CO_2 concentration, which we will ignore as our focus is on any given single crop for which this will be constant; humidity and leaf temperature will be, across a season, characteristic of the site and climate (Sinclair, Tanner & Bennett 1984). It will not be affected by crop nutrition and water supply, nor by insect and disease burden (Liu-Kang & Hsiao 2004). Therefore, in this thesis, the transpiration index is treated as a constant.

We can therefore visualise the transpiration index for a crop in a given year and location as a linear relation between transpiration and biomass to a point defined by (T_{max}, $Y_{B,max}$) which represents the maximum biomass for that crop and the transpiration needed to achieve it (see Equation 3.21. This point also represents for that year, the best use of the environment, the major uncontrolled variable in farming, by the cotton crop for the least water use.

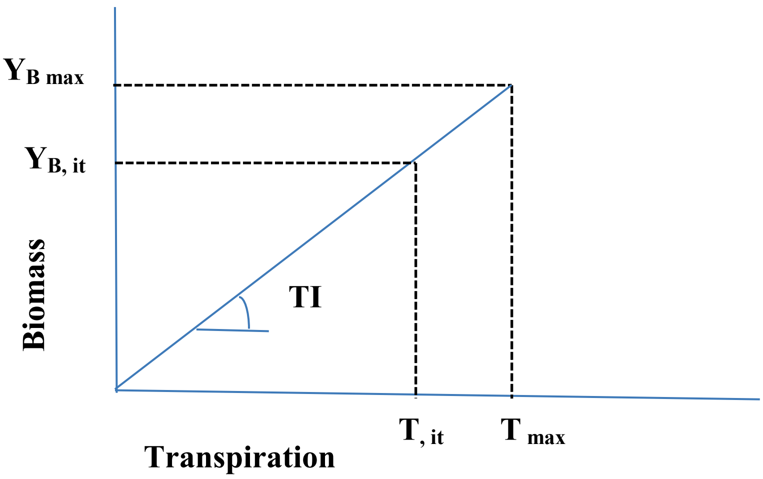

Figure 3.5 Theoretical relation between transpiration and biomass

$$\text{Transpiration index}_{it}\left(\frac{\text{kg}}{\text{ML}}\right) = \text{Maximum Biomass yield}_{it}\left(\frac{\text{kg}}{\text{ha}}\right) \div \text{Maximum Transpiration}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.21]$$

A key assumption is that sufficient water can be provided such that weather is the only limitation to growth. T_{max} represents the minimal amount of water that the crop will need to achieve maximum growth (sourced from rainfall and/or irrigation). The transpiration index can be decomposed into its two variables, water on the upstream side of our logical chain and biomass yield on the downstream side, which will be discussed in Sections 3.3.2.2 and 3.3.2.3, respectively.

3.3.2.2 Crop water supply components

Two components of crop water supply are considered in this subsection: the proportion of the crop water supply that is used for transpiration and the adequacy of this to support the desired growth of the cotton crop. To describe this, we introduce two terms – water input efficiency and water resource efficiency.

Water input efficiency

Water input efficiency is defined as the ratio between transpiration and crop water supply (Purcell & Currey 2003). This measure describes how effectively water at the field boundary is distributed to all crop roots, used only for uptake by the plants and transpiration, and is expressed as follow:

$$\text{Water input efficiency}_{it}\ (\%) = \text{Transpiration}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \div \text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.22]$$

Water input efficiency has a theoretical maximum of 100% (or 1.0) when crop water supply equals transpiration. Based on Section 3.2, and more particularly Equation 3.9, it is argued that there may be four reasons for water input efficiency to be less than 1.0. First, some of the rainfall may runoff and be partially lost before it can be recycled. Second, heavy or protracted rain may wet the profile so that drainage below the root zone occurs. Third, after rain and surface irrigation, the soil surface is wet leading to surface evaporation. Finally, poor irrigation management, or choice of irrigation system, may lead to runoff and deep drainage losses.

While values of water input efficiency less than 1.0 might indicate inefficiencies, we need to isolate those that may not be susceptible to improved management. For instance, deep drainage losses from rainfall may be reduced by irrigation management that maintains soil wet enough for crop growth, but sufficiently below the drained upper limit to allow storage of water infiltrating during rain. However, depending on the soil and climate, deep drainage may not be completely eliminated. Depending on the mechanisms involved in the irrigation system, it may not be possible to prevent some deep drainage or runoff, no matter how proficiently the system is managed. The only recourse then is to change the system.

Water input efficiency can be further decomposed, particularly if calculations show it to be lower than expected, to determine where unexpected drainage, runoff and evaporative losses are diverting water from root uptake and hence transpiration. This is a well-known analysis in agriculture and will not be developed further here.

Water resource efficiency

A farm, by definition, has exclusive use of the climate incident on it. We may imagine that this exclusively places some responsibility on the farm manager to make the most efficient use possible of these environmental resources. The result (T_{max}, $Y_{B,max}$) represents the best growth possible in the environment with just adequate water, and hence best use of the environmental resources (see Figure 3.5). Poorer growth will have a result (T, Y_B), smaller than (T_{max}, $Y_{B,max}$), representing a less efficient use of the environment.

The efficiency with which environmental resources are used, with water supply as the controlling factor, we term as water resource efficiency, which is quantified as:

$$\text{Water resource efficiency}_{\text{it}}(\%) = \text{Biomass yield}_{\text{it}}\left(\frac{\text{kg}}{\text{ha}}\right) \div \text{Maximum Biomass yield}_{\text{it}}\left(\frac{\text{kg}}{\text{ha}}\right) \qquad [3.23]$$

and, because the transpiration index is a constant for that crop and season,

$$\text{Water resource efficiency}_{\text{it}}(\%) = \text{Transpiration}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \div \text{Maximum transpiration}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.24]$$

Water resource efficiency has a theoretical maximum of 100% (or 1.0). The ratio between transpiration and maximum transpiration describes how adequately the water taken up by the crop allows it to grow to its environmentally-limited potential, for which transpiration is equal to maximum transpiration and hence the ratio is equal to 1.0.

There may be circumstances when a farm manager intentionally aims for water resource efficiency less than 1.0. In rainfed cropping, for instance, the total crop water supply may be less than maximum transpiration for the site. A crop managed for maximum transpiration and hence maximum biomass yield will experience severe water deficits before maturity, and biomass yield may tend towards zero. Different management, for example, sowing the crop at a lower plant density, will intentionally reduce transpiration so that it more closely matches the water supply and hence biomass yield becomes higher than zero.

For irrigated cotton, the general assumption is that water, while having a finite cost, can be managed so that the operator's target is for (T_{max}, $Y_{B,max}$). Given this, a necessary crop water supply volume can be calculated.

3.3.2.3 Harvest index

Turning to yield, the downstream side of our logical chain, the frequent circumstance in agriculture is that only part of the total biomass provides an economic product to be harvested. For cotton, only the lint and seed provide economic returns. Of the two economic products produced by cotton crops, lint has a higher economic value and hence improving lint yield is a subject of interest to crop scientists. The relationship between lint yield and biomass is described by the harvest index (Blum 2009; Passioura 1996):

$$\text{Harvest index}_{\text{it}} = \text{Lint yield}_{\text{it}}\left(\frac{\text{kg}}{\text{ha}}\right) \div \text{Biomass yield}_{\text{it}}\left(\frac{\text{kg}}{\text{ha}}\right) \quad [3.25]$$

In Equation 3.25, the harvest index represents the fraction of primary economic yield of total biomass. It can be expressed as units of kg economic product per kg biomass or as a percentage. To be consistent with our convention described earlier, this should be designated as efficiency as both lint yield and biomass have the same units. However, the term harvest index is so well entrenched in agricultural literature and is so lacking in ambiguity that our use of it is non-controversial.

By definition, the harvest index describes the efficiency with which the plant converts assimilated carbon into economic product. This conversion will be affected by crop management decisions a,s well as choice of genotype and direct environmental effects on reproductive development (Blum 2009; Stewart et al. 2010). An estimate of the harvest index can be gained from breeding trials and simulations (Stewart et al. 2010). As it encompasses the effects of a broad range of management decisions, it is a measure of plant physiological efficiency that should be of significance to managers. In this thesis, it is assumed that harvest index is a constant for a cotton crop in any year.

It is necessary to note that water resource efficiency and water input efficiency must be considered independently in evaluating whether crop water supply is equal to maximum transpiration, and more importantly whether a crop business is sustainable in respect to economic and water sustainability.

3.3.3 Crop water use index

In considering the overall management of the cotton crop, a manager will have an interest in the summary position of how much lint is generated for the water supplied. This summary is captured as the crop water use index:

$$\text{Crop water use index}_{\text{it}}\left(\frac{\text{kg}}{\text{ML}}\right) = \text{Lint yield}_{\text{it}}\left(\frac{\text{kg}}{\text{ha}}\right) \div \text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \qquad [3.26]$$

Given the preceding sections, this can be decomposed to:

$$\mathbf{Crop\ water\ use\ index_{it}}\left(\frac{\mathbf{kg}}{\mathbf{ML}}\right)$$
$$= \text{Biomass yield}_{\text{it}} \left(\frac{\text{kg}}{\text{ha}}\right) \text{ x Havest index}_{\text{it}} \div \text{ Crop water supply}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right)$$
$$= \text{Transpiration}_{\text{it}} \left(\frac{\text{kg}}{\text{ML}}\right) \text{x Transpiration index}_{\text{it}} \text{ x Havest index}_{\text{it}} \qquad [3.27]$$
$$\div \text{ Crop water supply}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right)$$
$$= \mathbf{Water\ input\ efficiency_{it}}(\%) \mathbf{\ x\ Transpiration\ index\ _{it}\ x\ Havest\ index_{it}}$$

Crop water use index can be related to a range of management decision domains as shown in Figure 3.6.

The decision tree allows farmers to go back and examine their performance indicators and make relevant operational decisions to improve their sustainability index. For example, when a farmer looks at the crop water use index, if the index in respect to water input efficiency turns out to be poor, irrigation management needs to be examined. On the other hand, if the harvest index is poor (i.e. very low compared to the theoretical value), it suggests that things such as pest control, disease control need to be better managed. Alternatively, if the transpiration index is poor, this means the farmer needs to improve nitrogen management practices.

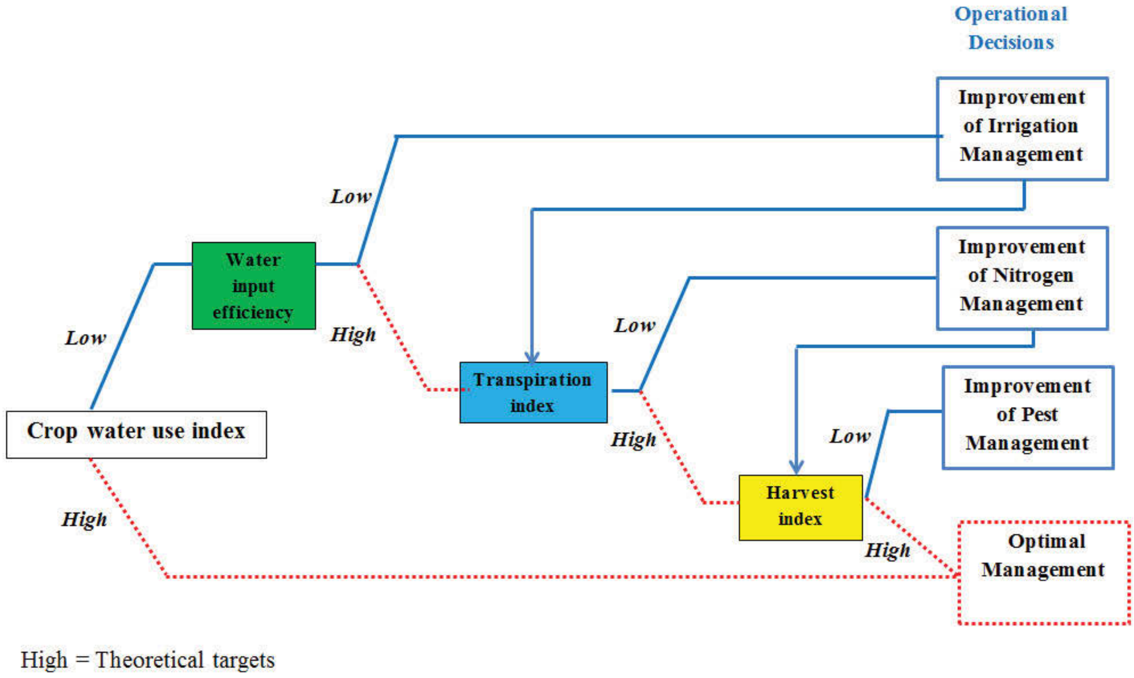

Figure 3.6 Operational decision tree

Figure 3.6 illustrates that by incorporating the transpiration index, harvest index and water input efficiency into one equation, the crop water use index provides a broad guide to managers wishing to improve crop system performance. First, low water input efficiency would suggest excessive water losses between supply point and crop root uptake, with remedies likely to be achieved in choice and engineering of the irrigation system used, in scheduling irrigation, and giving attention to water recycling systems. Second, a low transpiration index may be due to poor crop growth resulting in inadequate light interception (poor establishment, poor nutrition, unexpected restrictions in water supply to the roots, or waterlogging). Additionally, fungal root pathogens, to which cotton is susceptible, may reduce the ability of the crop to take up water. Third, the harvest index is subject to a variety of agronomic influences which can lead to its reduction. For example, insect or disease attack on foliage or developing bolls may reduce lint yield relative to biomass. Other aggregated indices of water-related crop performance might be able to indicate the presence of management problems without the ability to specifically identify possible remedies.

While the crop water use index summarises how effectively the crop exchanges water for its yield, of itself it provides inadequate information about how well that water use captures the environmental potential of the site and year. This is described, as earlier, in terms of water resource efficiency. This is closely related to another term use in the agricultural literature, yield gap, which is defined as the difference between maximum lint yield (potential yield) and actual lint yield (van Ittersum et al. 2012).

$$\text{Yield gap}_{\mathbf{it}}\left(\frac{\text{kg}}{\text{ha}}\right) = \text{Maximum lint yield}_{\mathbf{it}}\left(\frac{\text{kg}}{\text{ha}}\right) - \text{Actual lint yield}_{\text{it}}\left(\frac{\text{kg}}{\text{ha}}\right) \quad [3.28]$$

Given both the transpiration index and the harvest index as constants for that crop:

$$\begin{aligned}
&\mathbf{Yield\ gap_i}\ \left(\frac{\mathbf{kg}}{\mathbf{ha}}\right) \\
&= [\text{ Maximum biomass yield}_{\mathbf{it}}\left(\frac{\text{kg}}{\text{ha}}\right) \\
&- \text{Actual biomass yield}_{\text{it}}\left(\frac{\text{kg}}{\text{ha}}\right)] \text{ x Havest index}_{\text{it}} \\
&= [\text{Maximum transpiration}_{\mathbf{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \\
&- \text{Actual transpiration}_{\text{it}}\left(\frac{\text{kg}}{\text{ha}}\right)] \text{ x Transpiration index}_{\text{it}} \text{ x Havest index}_{\text{it}} \\
&= \mathbf{Maximum\ transpiration_{it}}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right) \mathbf{\ x\ [1} \\
&- \mathbf{Water\ resource\ efficiency_{it}}(\%)] \mathbf{\ x\ Transpiration\ index_{it}\ x\ Havest\ index_{it}}
\end{aligned} \quad [3.29]$$

3.4 Theory of crop water flows

From earlier sections, I can summarise a number of key parameters of the constructed crop water process model that define water sustainability, and some of the key water sustainability measures at a field level.

a. **Water abstracted from the environment:** defined as dV/dt, which relates to water sustainability from farm.

$$\text{Irrigation abstracted}_{\text{ it}}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Irrigation}_{\text{ it}}\left(\frac{\text{ML}}{\text{ha}}\right) - \text{Recycled runoff}_{\text{ it}}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [3.30]$$

b. **Crop water supply:** defined as water input efficiency of a cropping system.

$$\text{Crop water supply}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right)$$

$$= \text{Rainfall}_{\text{ it}} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{ Irrigation}_{\text{ it}} \left(\frac{\text{ML}}{\text{ha}}\right) \qquad (\quad)$$

$$= \text{ Rainfall}_{\text{ it}} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{Recycled runoff}_{\text{ it}} \left(\frac{\text{ML}}{\text{ha}}\right)$$

$$+ \text{Irrigation abstracted}_{\text{ it}} \left(\frac{\text{ML}}{\text{ha}}\right) \qquad [3.31]$$

$$= \text{ Transpiration}_{\text{ it}} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{ Soil evaporation}_{\text{ it}} \left(\frac{\text{ML}}{\text{ha}}\right)$$

$$+ \text{ Deep drainage}_{\text{ it}} \left(\frac{\text{ML}}{\text{ha}}\right) \text{ Runoff}_{\text{ it}} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{Change in soil water}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right)$$

$$\text{Water input efficiency}_{\text{it}} (\%) = \text{ Transpiration}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) \div \text{Crop water supply}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) \qquad [3.32]$$

c. **Theoretical link between crop water supply components and crop production components:** defined as water resource efficiency and crop water use index.

$$\text{Biomass yield}_{\text{it}} \left(\frac{\text{kg}}{\text{ha}}\right) = \text{ Transpiration}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) \text{x Transpiration index}_{\text{it}} \left(\frac{\text{kg}}{\text{ML}}\right) \qquad [3.33]$$

$$\text{Lint yield}_{\text{it}} \left(\frac{\text{kg}}{\text{ha}}\right) = \text{ Biomass yield}_{\text{it}} \left(\frac{\text{kg}}{\text{ha}}\right) \text{x Harvest index}_{\text{it}}$$

$$= \text{ Transpiration}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) \text{x Transpiration index}_{\text{it}} \left(\frac{\text{kg}}{\text{ML}}\right) \text{ x Harvest index}_{\text{it}} \qquad [3.34]$$

$$\text{Water resource efficiency}_{\text{it}}\ (\%) = \text{Transpiration}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right)$$
$$\div \text{Maximum transpiration}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) \text{Crop water use index}_{\text{it}} \left(\frac{\text{kg}}{\text{ML}}\right) \qquad [3.35]$$

$$\text{Crop water use index}_{\text{it}} \left(\frac{\text{kg}}{\text{ML}}\right)$$
$$= \text{Lint yield}_{\text{it}} \left(\frac{\text{kg}}{\text{ha}}\right) \div \text{Crop water supply}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right)$$
$$= \text{Water input efficiency}_{\text{it}} \left(\frac{\text{ML}}{\text{ha}}\right) \text{x Transpiration index}_{\text{it}} \left(\frac{\text{kg}}{\text{ML}}\right) \text{ x Harvest in} \qquad [3.36]$$

Taken together with Figure 3.6, this provides a complete summary of the key aspects of water supply, use and loss in a cotton crop and the resulting yield.

The beginning point is driven by environmental sustainability, which is improved as dV/dt for the farm tends towards zero. The end point is the production of cotton lint which has an economic value and hence is a key input to economic sustainability. However, the farm business, to be economically sustainable, must make a profit. The additional considerations necessary for that decision are laid out in the next chapter.

The summary provides some useful management targets, shown below and described earlier.

dV/dt ⟶ 0

Water input efficiency ⟶ 1.0

Water resource efficiency ⟶ 1.0

Target values for the transpiration index and harvest index are those best reported on simulated results.

A manager, planning future operations, might use the crop water process model (Figure 3.2). In the case of a predetermined allowance for dV/dt (known as the allocation of water), decisions can be made about the extent of the crop that can be adequately supported by the likely available water. Alternatively, if a desired yield and profit is required, then the necessary dV/dt can be calculated. The extent of traded purchases of water might need to be calculated to ensure this yield.

As Figure 3.6 illustrates, different management decisions will affect different components in the crop water process model. A theoretically ideal rainfed or micro-irrigated crop may have water input efficiency equal to 1.0, i.e. achieves water sustainability, but limitations on crop water supply may lead to less than maximum transpiration, and hence produce less than maximum biomass, meaning that the crop business has not capitalised on its environment. It is also possible to conceive of an irrigation system to which a theoretically adequate crop water supply is made available. However, if water input efficiency is lower than expected, transpiration is still less than maximum transpiration. In both cases, the crop is considered be sub-optimal with regards to economic sustainability in the first instance, or both economic sustainability and environmental sustainability in the second instance.

3.5 Conclusion

This Chapter provides theoretical discussion of water sustainability in the context of cotton production and development of some of the key measures of crop water and economic sustainability performance. More specifically, three main constructs are developed. First, a crop water process model is constructed based on the theoretical discussion of water sustainability in Chapter 2 and crop science theory. Second, the theoretical discussion of water sustainability of irrigated cotton production is developed. This provides a fundamental foundation for understanding the sustainability issues behind crop water use and crop production, and the theoretical link between components of crop water supply and crop water production. Third, the inherent limitations of extant research on crop water sustainability measurement are discussed, leading to the necessity of development of a set of water sustainability performance measures to better capture the concept of crop water sustainability for crop production . These measures will form part of the water and economic sustainability performance model developed in Chapter 4.

The crop water process model and crop water use index explain how crop water flows across a cropping system, how an end-to-end connection between resource utilisation and farm profitability and sustainability is established, and define a linear relationship between water resources coming in (to crop production) and cash coming out (from crop production).

One of the key contributions of the research is an attempt to define water input efficiency, water resource efficiency, and a crop water use index. Furthermore, the discussion of theoretical value of these three measures, including clearly pointing to maximising profit and minimizing footprint, imply that the developed crop water use index does not only cover the efficiency but also covers the scale of sustainability. Moreover, the work shows that we now have a theoretically defined sustainability index that can enable farmers to identify areas for improving sustainability performance and make optimal operational decisions. For example, the operational decision tree enables farmers to identify areas for improvements and make appropriate/optimal operational decisions to achieve better economic and environmental sustainability performance.

Chapter 4. Water and Economic Sustainability Performance Measurement (WESM) Model

4.1 Introduction

In the previous chapter, a number of key water sustainability measures at a field level are developed. These measures closely link to sustainability-related activities and management practices occurring at the crop production level, the level at which water sustainability issues occur and need to be managed. The measures establish a connection between water coming into a cropping system and crop production coming out the cropping system. However, a more holistic approach is necessary to develop a measure(s) that enables capture of both the economic and water sustainability performance of a crop business. Such a measure(s) can be used to support crop managers in making sustainability-related decisions at the organisational level.

As laid out in Chapter 1, one of the challenges in designing and using an EPMS is that the overall organisational decisions with regards to economic and environmental sustainability are made at the strategic level; this may, in organisational terms, be distant from where the key management decisions are made at an operational level. Ideally, the EPMS should span across all levels of the organisation, providing guidance at an operational level as well as informing and being informed by the strategic level.

In Section 4.2, the profit to water cost ratio is developed as a reasonable summary measure of water and economic sustainability performance of a crop business – this incorporates information about both economic sustainability and environmental sustainability. However, the measure itself suffers from a lack of transparency as to how sustainability activities and decisions at the operational level of the crop business impact the business' overall sustainability performance.

Section 4.3 reviews a decomposition ratio analysis approach and provides the rationale behind the application of this approach in this chapter to establish a theoretical connection between the summary level and operational level of a crop business. Taking this approach, in Section 4.4, I decompose the profit to water cost ratio over seven levels and articulate the logical and theoretical links between the summary water and economic sustainability performance measure at the business level and its drivers at the operational level. The building block of the profit to water cost ratio is called the Water and Economic Sustainability Performance Measurement (WESM) model. This approach enables me to provide explanation of how and why the developed WESM model - a new form of EPMS – can be used to support crop managers in managing, evaluating and improving crop water and economic sustainability performance.

Furthermore, the link between the crop water process model developed in Chapter 3 and the designed WESM model is described in Section 4.5. This lays out how the WESM model is integrated with the crop water process model and will be used in later chapters of this thesis to provide empirical evidence on how the designed EPMS (WESM) can be used to assist managers with better sustainability-related decision making and control. The designed WESM will provide the basis for empirical work (crop simulation modelling) in the later chapters of the thesis.

4.2 Profit to water cost ratio as the summary water and economic sustainability measure

4.2.1 Measurement of water and economic sustainability performance for crop businesses

In Chapter 2, I argue that to provide a valid assessment to encourage a business to move towards sustainability, business profitability and environmental resource use need to be considered in one equation to capture both economic and environmental sustainability of the business. More specifically, in the agricultural context, water shortage and increasing water cost are predicted to become key constraints for agriculture, making managing risks associated with water shortage and high water cost crucial for crop businesses to be sustainable (Hamdy, Ragab & Scarascia-Mugnozza 2003; Jackson et al. 2011; Khan et al. 2006). This means managing risks associated with water shortage and high water cost is of crucial importance for crop businesses to move towards sustainability.

As outlined in Chapter 3, crop water supply to a farming system generally comes from two main sources; rainfall and irrigation. From the environmental sustainability perspective, rain falling directly on cropping systems is not considered to be disturbing the natural systems.[55]

[55] However, crop businesses do need to consider the uncontrollable factors associated with rainfall supply.

In contrast, irrigation water is considered to be *water abstracted from the environment* and needs to be withdrawn from rivers or groundwater sources for irrigation. Sustainability Principle 2 in Section 2.3.3 emphasises that managing and minimising groundwater and surface water abstraction needs to be considered as a step towards water sustainability.

From an economic perspective, excluding water capture and storage costs, rainfall is a "free" water resource, which is free of cost while irrigation water abstracted from the environment and distributed mechanically is costly. Given the assumption that rainfall is a free water resource, total water cost represents irrigation cost. Hence, low water cost indicates less irrigation water in both volume and dollar terms. In this respect, crop management practices resulting in low water cost signal that the crop business moves a step towards both economic sustainability and environmental sustainability. However, another aspect needs to be considered, which is the economic return associated with those crop management practices. A business cannot be considered as a sustainable business if it improves environmental sustainability but incurs an economic loss.

The discussion above leads to the necessity of developing a summary measure that can capture both the concept of crop water sustainability for crop production (i.e. water cost) and its relation to economic sustainability (i.e. profitability) of the crop business.

Extant crop water literature proposes a number of crop water performance measures in an attempt to establish a link between economic return and water resourcing, including the economic water use index for irrigation and the economic water use index for crop water supply (Cammarano et al. 2012; Igbadun et al. 2006; Pereira, Cordery & Iacovides 2012). However, these measures are either invalid as they do not capture the proportion of rainfall that also contributes to crop production or are insufficient since the amount of economic return (rather than total sales revenue) and total water cost (rather than volume of crop water supply) are not presented explicitly in these measures.

Furthermore, while the developed crop water use index in Chapter 3 can incorporate lint yield and crop water supply in one equation, and hence can be used as a valid water and economic sustainability measure to support crop managers in evaluating and managing their sustainable manage practices at the operational level, it still does not demonstrate the link between economic and water sustainability performance of a crop business explicitly.

4.2.2 Profit to water cost ratio as a summary measure for crop water and economic sustainability

Based on the discussion in Section 4.2.1, a summary measure of water and economic sustainability performance must be a comprehensive measure. This should include an economic sustainability dimension, such as operating profit, and an environmental dimension, such as water cost.

Therefore, the profit to water cost ratio cost ratio, which is defined as the amount of operating profit generated by each dollar spent on water resource (see Equation 4.1 below) is an appropriate summary sustainability measure for three main reasons.

$$Profit\ to\ water\ cost\ ratio_{it}\left(\frac{\$\ operating\ profit}{\$\ water\ cost}\right) = Operating\ profit_{it}\left(\frac{\$}{ha}\right) \div Total\ water\ cost_{it}\left(\frac{\$}{ha}\right) \qquad [4.1]$$

First, as expressed in Equation 4.1, operating profit is a measure of economic return of a crop business and irrigation water cost is an indicator of the water impost of cotton cultivation on the environment. Accordingly, the profit to water cost ratio is proposed to emphasise the link between economic sustainability (captured by profit, a summary of the economic status of the business as a going concern) and environmental sustainability (captured by water cost, reflecting both the value and volume of water abstracted from the environment) of a crop business.

It is a ratio indicating the overall sustainability performance of a crop business and can be used as part of the performance measurement system to support crop managers in evaluating, managing and improving their economic and environmental sustainability performance. A business that is increasingly economically and environmental sustainable would be increasing profit and decreasing water consumption. Therefore, when a crop business can maintain its economic sustainability performance while improving its environmental sustainability performance, the business increases its business sustainability.

Second, building upon economic theory, when there is a resource constraint, a business is better off maximising economic return per unit of constraint (Barney 1991; Hart 1995). In the context of agriculture where water is evidenced as a resource constraint (Rijsberman 2006), profit to water cost ratio is a useful measure to optimise water resource use. Therefore, when water is the constraint, improvement of economic return per unit of water resource, taking climate factors into consideration, is a step towards sustainability.

Third, there are two implications of water cost within irrigation. As profit to water cost ratio uses water cost rather than water volume, it better reflects when a business intentionally uses higher security and therefore higher cost water which, by definition, has a potentially greater environmental impact when abstracted. In this respect, profit to water cost ratio demonstrates that from an economic and environmental perspective, a crop business needs to take into consideration not only the amount of water resource used (i.e. the volume of crop water supply) but also the cost of the environmental resource (i.e. cost of irrigation water).

One could argue that the ratio of operating profit to irrigation amount can be proposed as a summary sustainability measure for crop businesses. However, this ratio does not convey a similar story to the profit to water cost ratio. In fact, it provides invalid information as the ratio does not capture the proportion of operating profit generated by rainfall (as discussed in Chapter 3). On the other hand, one could argue that the ratio of operating profit to total crop water supply can be proposed as a summary sustainability measure for crop businesses since it captures both rainfall and irrigation water sources. However, as the ratio does not distinguish between ‘free’ water sources and those that cost money to withdraw from the environment, it does not capture the concept of water sustainability explicitly. In this respect, it is argued that the proposed profit to water cost ratio is a more comprehensive summary sustainability measure.

4.2.3 Limitations of profit to water cost ratio as a single measure for evaluating and managing crop water and economic sustainability

The profit to water cost ratio (I argue) is a good summary sustainability measure that can be used as an informative high-level measure at the business level for supporting crop managers in assessing the overall water and economic sustainability performance of the crop business. However, there are two limitations to this measure when used as a single measure for evaluating, improving and forecasting economic and water sustainability performance of crop businesses.

First, while such an aggregate measure can provide an overall figure about economic return per dollar of water cost spent for crop production, and the extent to which crop cultivation imposes on the environment, it provides limited theoretical explanation about what actually drives the business' water and economic sustainability performance. As a ratio, the profit to water cost ratio changes because of changes in one or both terms involved. However, by only looking at the profit to water cost ratio and its change, the crop manager does not know explicitly whether the change is driven by the change in economic return on crop water supply or the change in water cost and how they change. Information about the underlying drivers of the profit to water cost ratio is useful for managers to gain better understanding of how to improve the profit to water cost ratio and, hence, how to manage the overall sustainability performance of the crop business. Therefore, it is necessary to decompose the profit to water cost ratio into its components and translate changes of these components to inform important intermediary outcomes or implications for management decisions.

Second, as outlined in Chapter 1, sustainability issues need to be managed at the operational level of a business as it is the level at which business activities actually occur and sustainability issues arise. In this respect, a connection between the developed summary measure and measures that closely link to the operational level is necessary.

Therefore, without knowing the cause and effect of the overall sustainability performance, particularly the driving factors that directly relate to businesses' activities at the operational level, it seems to be impossible for managers to identify areas for improving crop businesses' sustainability performance to move towards sustainability. In other words, in order to support managers in evaluating, managing and improving their businesses' sustainability performance, it is of crucial importance to identify and establish the theoretical links between factors at the operational level that affect the overall sustainability performance of the business.

One way to articulate the logical relations between the high level measures (i.e. the summary measure) and the low level measures (i.e. drivers of the summary measure and/or measures that are closely linked to activities at the operational level) is to use a decomposition ratio analysis approach.

4.3 Design of Water and Economic Sustainability Measurement Model - A decomposition ratio analysis approach

4.3.1 Overview of the decomposition ratio analysis approach

Financial ratio analysis (e.g. decomposition ratio analysis) is an accounting technique for financial statement analysis, based on a structural approach to allow the ratio scheme to be presented in a clear, simple, structured and hierarchical way (Nissim & Penman 2001; Soliman 2008). One of the distinct features of the ratio analysis approach is that a single financial ratio presented as a high level performance measure for analysis (for example, return on common equity, a summary profitability ratio in the financial analysis) can be decomposed into more detailed and specific descriptors of a firm's performance. Ratios in lower levels of the ratio scheme are identified as finer information about those higher up. Therefore, the approach not only helps to determine relevant ratios but also provides a structured and organized way for the analysis of the summary ratio (Nissim & Penman 2001; Soliman 2008).

Decomposition ratio analysis also allows for a transparent and accurate analysis of a firm's operations (Nissim & Penman 2001; Soliman 2008). For example, in the analysis of profitability, the ratio analysis approach allows separation of the different components of operating profitability and the profitability identified with the financing activities. It also allows decomposition of return on net operating assets into two components; profit margin and asset turnover, which are accounting signals that measure different aspects of a firm's operation (Penman 2003; Soliman 2008). Moreover, as the ratio scheme can be decomposed into more detailed and specific drivers of a firm's performance, changes in overall performance can be traced in a more detailed manner (Nissim & Penman 2001; Soliman 2008).

Financial ratio analysis is applied for financial statement analysis in financial accounting (Nissim & Penman 2001; Soliman 2008) for comparison and valuation purposes. For example, Nissim and Penman (2001) apply the structural approach of ratio analysis technique to financial statement analysis for equity valuation. Soliman (2008) also reveals that the DuPont analysis technique is used by market participants for forecasting future earnings as its components contain an incremental and viable form of information about the operating characteristics of a firm and provide exploratory power about changes in future profitability. In addition, Penman (2003) suggests that by clearly articulating the various links between operational level activities and firm value, the relative materiality of different actions and/or strategies can be evaluated by market participants and researchers who are interested in evaluating various accounting and other decisions.

4.3.2 Applying the decomposition analysis approach to EPMS design

While the decomposition ratio analysis approach outlined in the previous section provides a number of advantages in relation to establishment of a clear and structured way to link a set of measures, this approach has not been considered thoughtfully with several issues of PMS design, including the validity issue and the useability issue of EPMS. For example, while Figge and Hahn (2013) attempt to apply the DuPont analysis technique as an integrated tool to support decision-making for more efficient use of environmental resources, there are a number of issues with their study. First, Figge and Hahn (2013) only analyse the first level breakdown of the eco-efficiency measure, which means more detailed and specific drivers of a firm's eco-efficiency performance are not determined. Second, in their empirical work, they provide an analysis of the carbon-efficiency of international car manufacturers. This is not consistent with their theoretical work in respect to the creation of 'Sustainable Value' – as natural resources efficiency and CO_2 efficiency convey two different aspects of environmental sustainability. While the former relates to the degree of natural resources used for organisational production processes; the later relates to the degree of pollution to the natural environment due to the discharge of wastes (gaseous, liquid or solid wastes) from the organisational production processes. This illustrates the important role of determining the actual drivers of the summary/aggregate measure (in this case the eco-efficiency measure) to successfully capture environmental sustainability performance of an organisation.

Furthermore, the usability of a performance measurement system refers to the balance between the meaningfulness and the usefulness of the PMS. These two important characteristics of PMS seem to pull in opposite directions (Floridi et al. 2011; Veleva 1994). On the one hand, a meaningful set of measures need to provide valid and adequate information about specific performance aspects of an organisation that they are intended to represent (Bhargava, Dubelaar & Ramaswami 1994; Ittner & Larcker 2003). This means, in most case, the set of measures need to be relatively complex to be able to fully reflect what it is supposed to capture (Floridi et al. 2011; Veleva 1994). On the other hand, the same set of measures needs to be simple and clear enough to provide useful information to enable system users to understand and use the information to make better management decisions and control (Veleva 1994). In the context of EPMS, in addition to increasing the use of multiple financial and non-financial performance measures (Ittner & Larcker 2001; Kaplan & Norton 1996; Malmi & Brown 2008), the inclusion of environmental performance measures increases the complexity of the system (Floridi et al. 2011; Veleva 1994). The question of how to design different measures to capture different performance aspects of an organisation, which are expressed in different dimensions, and present them in a way to provide both overall and detailed assessment still remains a challenge (Boiral & Sala ; de Oliveira, Serra & Salgado ; Ittner & Larcker 2001; Jabbour 2010; Miles, Munilla & McClurg 1999).

One way to deal with the usability of PMS is to apply the decomposition ratio analysis approach to enable a range of ratios to be tied together in a hierarchal, logical and structured way in which the high level measures contain information about the lower level measures. By doing this, a building block of a set of linked measures is established for better information provision to support better decision making and control.

4.4 The analysis of crop water and economic sustainability

4.4.1 Analysis of the profit to water cost ratio

In this thesis, the ratio analysis approach is applied for analysis of crop water and economic sustainability for three main reasons. First, it allows more thorough analysis of water and economic sustainability performance of a crop business through decomposition of the proposed summary water and economic sustainability measure – the profit to water cost ratio – into its levels in order to gain insights into the causes and effects of the change in the overall sustainability performance.

Second, it enables establishment of the theoretical links between the summary sustainability measure and information down the hierarchy towards the operational level where water related environmental issues actually occur. By doing this, the key drivers of the overall water and economic sustainability performance of crop businesses are identified and (un)sustainability crop management practices are identified for improvement of profit to water cost ratio – a step towards water sustainability.

Third, the ratio analysis approach allows us to distinguish between different aspects/decisions of the crop business's operation; for example, decisions related to water use, irrigation systems or crop production. This supports managers in evaluating and/or comparing the outcomes of various management practices at the operational level for better sustainability decision making and control.

The analysis of the drivers of the profit to water cost ratio in the following section is called *water and economic sustainability analysis*. While I apply the decomposition ratio analysis approach that is traditionally applied to analysis of profitability, several modifications are proposed to enable capture of various crop water and economic sustainability aspects of a business.

In the following sections, the profit to water cost ratio is broken down into its drivers over seven levels of analysis. These seven levels are depicted in the WESM model diagram (see Figure 4.1). Each level contains information about the lower level. Theoretical justifications of the decomposition are provided with the analysis of these seven levels, including explanations of how high level measures from Level 1 to Level 5 are defined and decomposed into its drivers, as well as how low level measures in Level 6 and Level 7 are calculated and linked to input data of WESM (i.e. key parameters of the crop water process model, accounting data, irrigation data, crop data which can be generated via either available information sources in the real-world or simulation modelling).

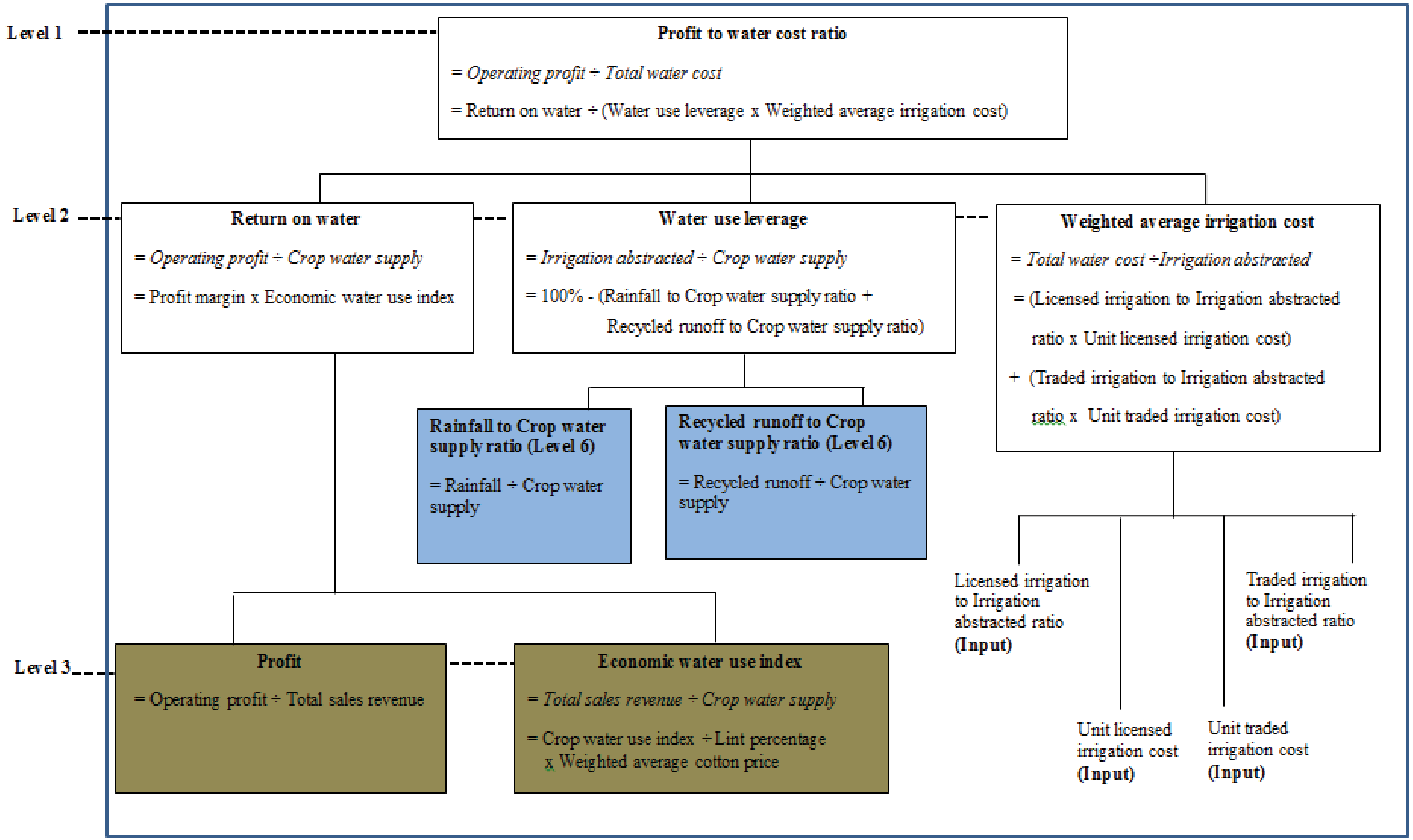

Figure 4.1 Levels 1 to 3 of the WESM model

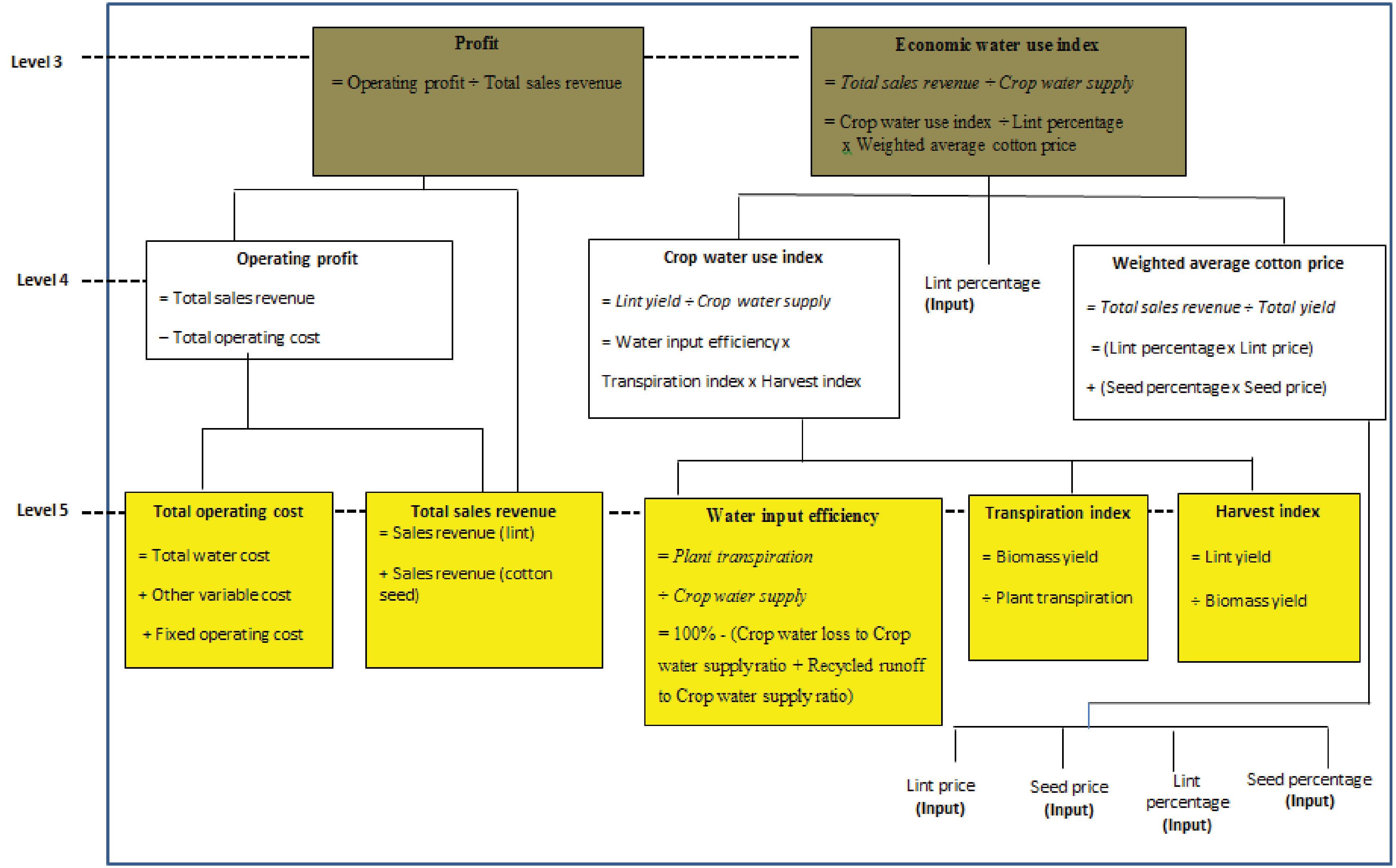

Figure 4.1 Levels 3 to 5 of the WESM model

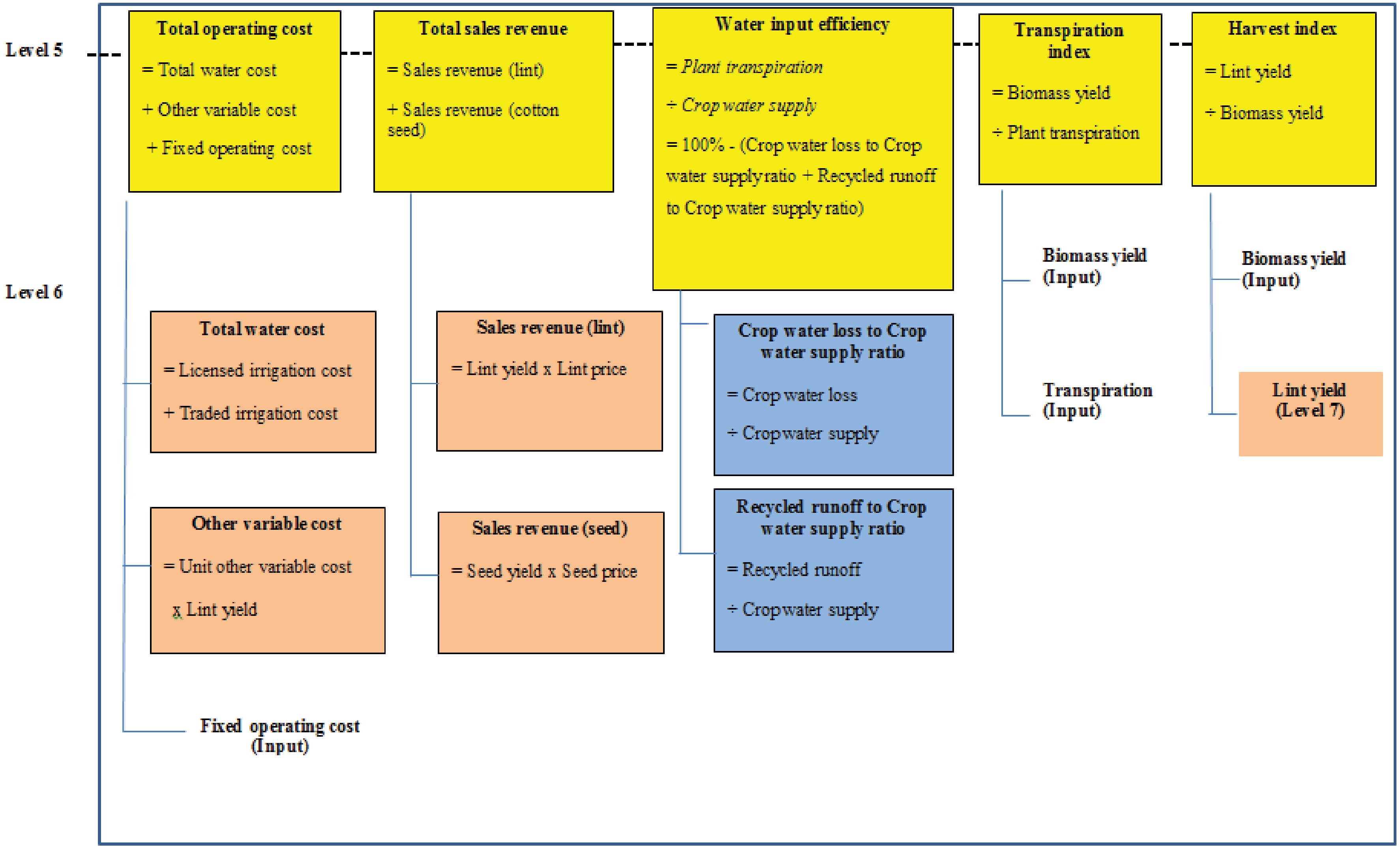

Figure 4.1 Levels 5 to 6 of the WESM model

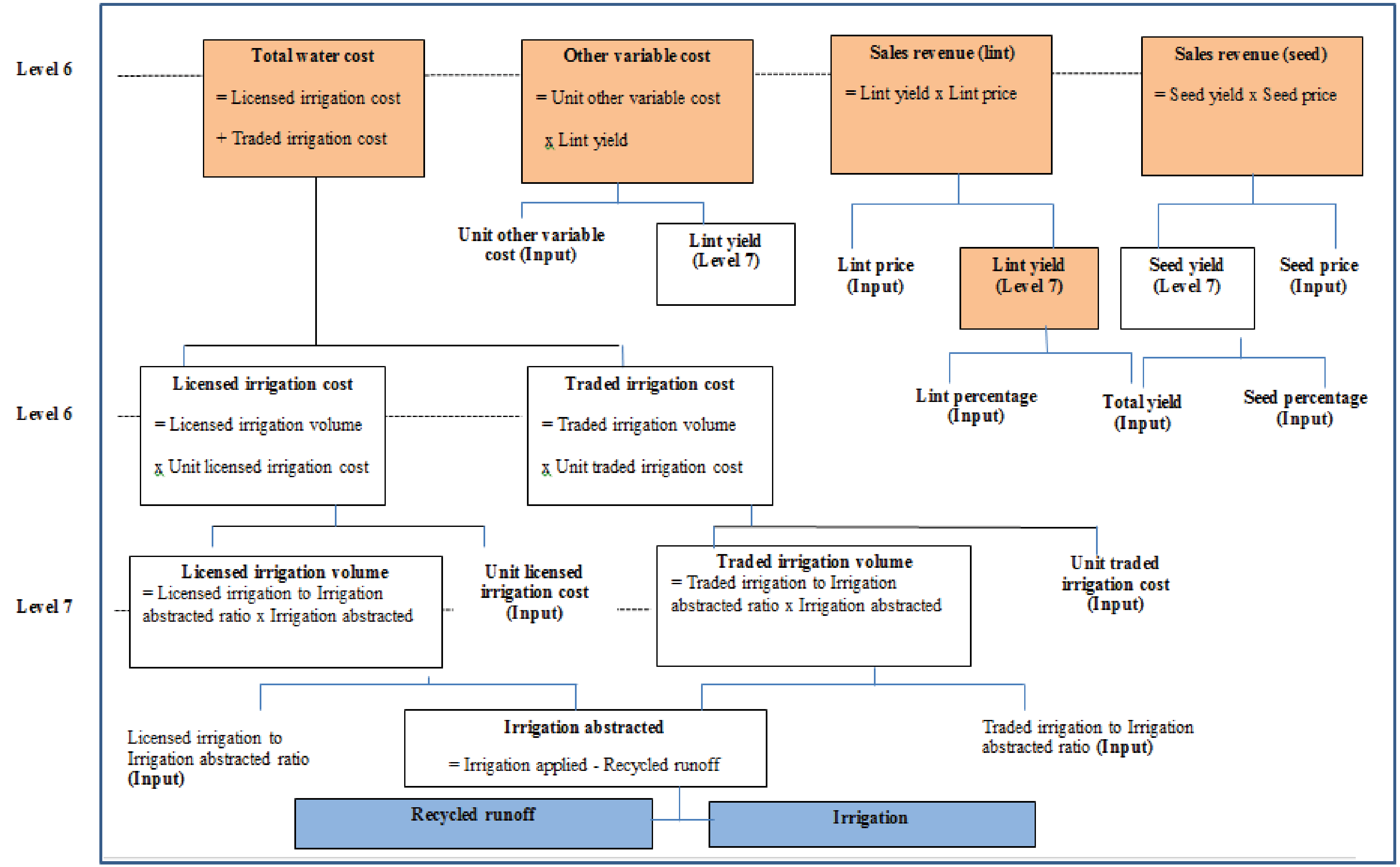

Figure 4.1 Levels 6 to 7 of the WESM model (economic low-level measures)

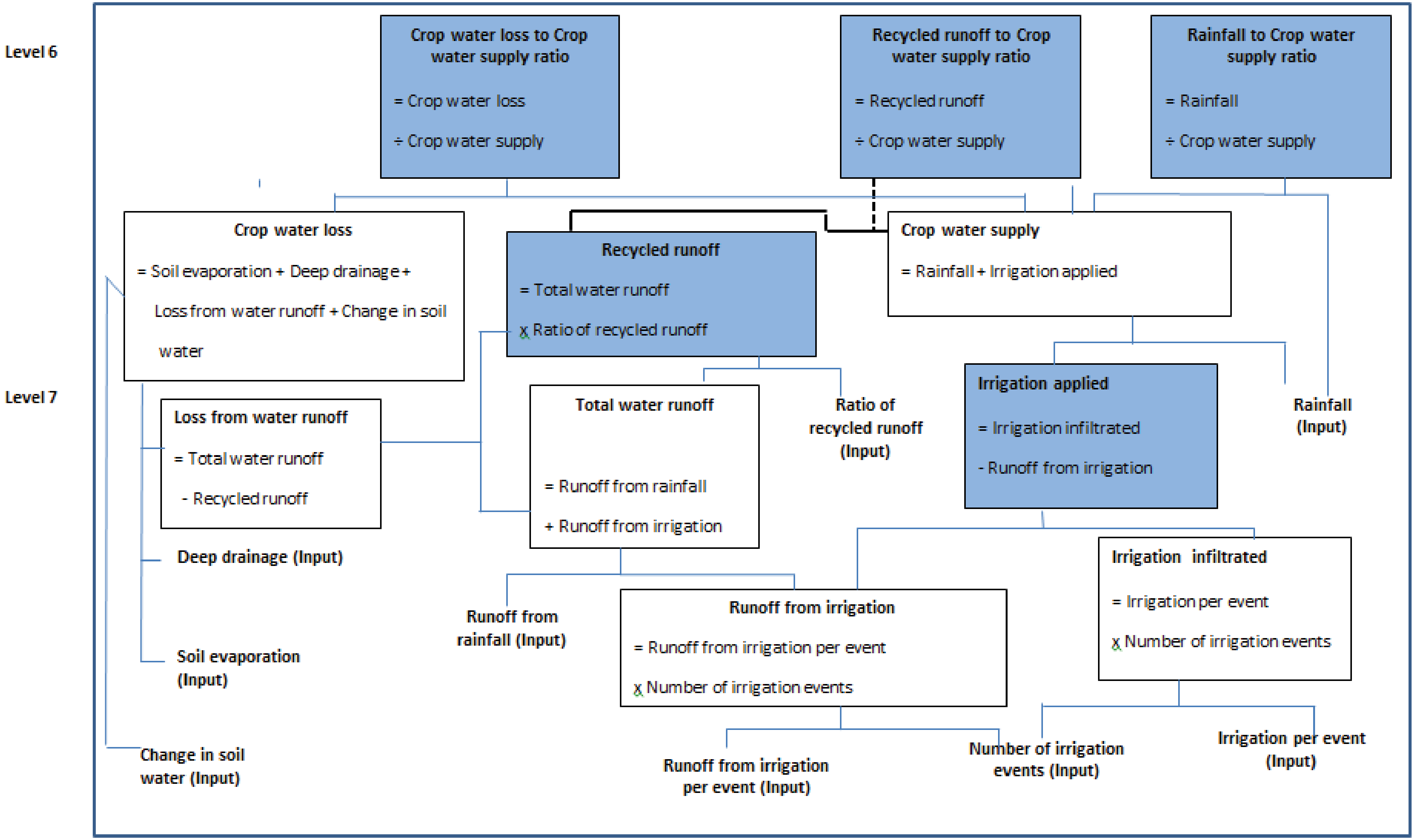

Figure 4.1 Levels 6 to 7 of the WESM model (environmental low-level measures)

4.4.2 First-level analysis: Decomposition of profit to water cost ratio

In the first level breakdown, to gain more insights into whether the change in the profit to water cost ratio is driven by its numerator (operating profit) or its denominator (total water cost), the summary measure is decomposed into its three components named as return on water, water use leverage, and weighted average irrigation cost. The logical relation between profit to water cost ratio and its three drivers is expressed as follows:

$$\text{Profit to water cost ratio}_{\text{it}}\left(\frac{\text{\$ operating profit}}{\text{\$ water cost}}\right) = \text{Return on water}_{\text{it}}\left(\frac{\$}{\text{ML}}\right) \div \left[\text{Water use leverage}_{\text{it}}\ (\%) \times \text{Weighted average irrigation cost}_{\text{it}}\left(\frac{\$}{\text{ML}}\right)\right] \quad [4.2]$$

Where: return on water, water use leverage, and weighted average irrigation cost are defined in Equation 4.3, Equation 4.4 and Equation 4.5, respectively.

$$Return\ on\ water_{it}\left(\frac{\$}{ML}\right) = Opening\ profit_{it}\left(\frac{\$}{ha}\right) \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right) \quad [4.3]$$

$$Water\ use\ leverage_{it}\ (\%) = \left[Irrigation\ abstracted_{it}\left(\frac{ML}{ha}\right) \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right)\right] \times 100\% \quad [4.4]$$

$$Weighted\ average\ irrigation\ cost_{\ it}\left(\frac{\$}{ML}\right)$$
$$= \ Total\ water\ cost_{it}\left(\frac{\$}{ha}\right)$$
$$\div \ \ Irrigation\ abstracted_{\ it}\left(\frac{ML}{ha}\right) \qquad [4.5]$$

Table 4.1 summarises the formulas related to the first-level of analysis.

Comparing Equation 4.1, which presents the formula for calculating the profit to water cost ratio, to Equation 4.2, which shows its break-down into three drivers, taking into consideration of Equations 4.3, 4.4 and 4.5, it is proved that they are equal.

$$Profit\ to\ water\ cost\ ratio_{it}\left(\frac{\$\ operating\ profit}{\$\ water\ cost}\right)$$
$$= Operating\ profit_{it}\left(\frac{\$}{ha}\right) \div Total\ water\ cost_{it}\left(\frac{\$}{ha}\right)$$
$$= \ \text{Return on water}_{\text{it}}\left(\frac{\$}{\text{ML}}\right)$$
$$\div \left[\text{Water use leverage}_{\text{it}}\ (\%)\right.$$
$$\left.\times\ \text{Weighted average irrigation cost}_{\ \text{it}}\left(\frac{\$}{\text{ML}}\right)\right] \qquad [4.6]$$
$$= \left[\text{Opening profit}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) \div\ \text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)\right]$$
$$\div \left[\left[\ \text{Irrigation abstracted}_{\ \text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)\right.\right.$$
$$\left.\div\ \text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)\right]$$
$$\left.\times \left[\ \text{Total water cost}_{\ \text{it}}\left(\frac{\$}{\text{ha}}\right)\ \div\ \text{Irrigation abstracted}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)\right]\right]$$
$$= Operating\ profit_{it}\left(\frac{\$}{ha}\right) \div Total\ water\ cost_{it}\left(\frac{\$}{ha}\right)$$

Table 4.1 WESM analysis: The first-level analysis

Variable	Level	Formula
$\textbf{Profit to water cost ratio}_{\textbf{it}}\left(\frac{\text{\$ operating profit}}{\text{\$ water cost}}\right)$	**Level 1**	$= \text{Opening profit}_{it}\left(\frac{\$}{ha}\right) \div \text{Total water cost}_{it}\left(\frac{\$}{ha}\right)$ $= \textbf{Return on water}_{\textbf{it}}\left(\frac{\$}{\textbf{ML}}\right) \div \left[\textbf{Water use leverage}_{\textbf{it}}\ (\%) \times \textbf{Weighted average irrigation cost}_{\textbf{it}}\left(\frac{\$}{\textbf{ML}}\right)\right]$
$\text{Return on water}_{it}\left(\frac{\$}{ML}\right)$	Level 2	$= \text{Opening profit}_{it}\left(\frac{\$}{ha}\right) \div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)$
$\text{Water use leverage}_{it}\ (\%)$	Level 2	$= \left[\text{Irrigation abstracted}_{it}\left(\frac{ML}{ha}\right) \div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)\right] \times 100\%$
$\text{Weighted average irrigation cost}_{it}\left(\frac{\$}{ML}\right)$	Level 2	$= \text{Total water cost}_{it}\left(\frac{\$}{ha}\right) \div \text{Irrigation abstracted}_{it}\left(\frac{ML}{ha}\right)$

The first level breakdown of the profit to water cost ratio enables us to distinguish between two sustainability aspects: economic sustainability (captured by return on water and weighted average irrigation cost) and environmental sustainability (captured by water use leverage)[56]. More specifically, it provides us a better understanding of how change in economic return on crop water supply, and/or change in proportion of crop water sources (i.e. rainfall versus irrigation abstracted), and/or or change in proportion of irrigation allocation (i.e. licensed irrigation versus traded irrigation) [57], affect the change of the overall water and economic sustainability performance of a crop business.

Furthermore, the decomposition of the profit to water cost ratio into its three components demonstrates that by relying solely on the summary measure for evaluating sustainability performance of a crop business, a crop manger may end up with suboptimal/inaccurate decisions. The following example is used to support this argument.

To control for climate factors, two farms in the same location are considered in this example. Farm A gains an economic return (in terms of operating profit) of $100 per ML of Crop water supply by sourcing 60% of crop water from irrigation water. Given the cost of irrigation water being $60/ML (NSW Department of Primary Industries 2015), using Equation 4.2, profit to water cost ratio of Farm A equals to $2.77 of operating profit per $ of water cost (= $100/ML÷ (60% x $60/ML)).

In contrast, Farm B gains an economic return (in terms of operating profit) of $85 per ML of Crop water supply by only sourcing 50% of crop water supply from irrigation water. Given the same irrigation cost of $60/ML, profit to water cost ratio of Farm B equals to $2.66 of operating profit per $ of water cost (= $80/ML÷ (50% x $60/ML)). The difference in profit to water cost ratio between Farm A and Farm B is $0.11 of operating profit per $ of water cost (= $2.77 – $2.66). Assuming that both Farm A and Farm B spent $573 (NSW Department of Primary Industries 2015), or irrigation cost per ha and the size of two farms are 400 irrigated

[56] The return on water measure is a type of eco-efficiency measures while the water use leverage measure is a measure to capture crop businesses' impacts on the natural water systems. Therefore, in the WESM model, the eco-efficiency measure forms part of the model but the measure itself is not sufficient to capture crop water sustainability.

[57] As discussed in Chapter 3, irrigation water can be obtained from two sources: licensed irrigation – irrigation water allocation with delivery entitlements owned by the crop business, and traded irrigation – irrigation water bought from other licensed irrigators via water trading market.

ha, Farm A gains an additional $25,212 (=$0.11 x 573 x 400) of operating profit for a crop season. From an economic perspective, it can be concluded that Farm A is more sustainable than Farm B. However, from an environmental perspective, Farm A relies on water withdrawn from the environment more than Farm B, which is argued to be a less sustainable practice. Consequently, when a crop business improves its profit to water cost ratio by sourcing a higher proportion of irrigation in total Crop water supply, it is a less sustainable business.

This example illustrates that achievement of higher profit to water cost ratio does not always mean that the crop business is moving towards sustainability. While a profit to water cost ratio is argued as a valuable summary indicator, a crop manager who uses the ratio must be prepared to decompose it into its drivers to gain more insight into the cause and effect of its change. Furthermore, for more valid evaluation of sustainability of the crop business, the manager needs to consider the trade-off between economic sustainability and water sustainability if the two sustainability aspects move in two different directions.

4.4.2.1 The effect of return on water

In the first-level breakdown, return on water is isolated as an important driver of the profit to water cost ratio. Return on water is defined as a measure of economic return on the water resource.

In this thesis, operating profit represents crop businesses' economic return. Businesses' activities comprise of operating activities and financial activities (Nissim & Penman 2001; Penman 2003). Financial activities are irrelevant in water sustainability analysis which focuses on operating decisions, such as water source decisions and water management decisions in relation to crop production. In addition, volume of Crop water supply, comprising rainfall water and irrigation water, represents water resources that are supplied to a crop business for crop production. Accordingly, return on water is expressed as the ratio of operating profit generated by total amount (volume)[58] of Crop water supply (see Equation 4.3).

[58] Amount of water refers to volume (ML) of water. Whereas, unit cost of water refers to cost of water ($/ML)

Mathematically, as illustrated in Equation 4.2, assuming the other drivers hold constant, improving return on water will result in increased profit to water cost ratio, and hence increased overall water and economic sustainability performance of the crop business. In addition, from an economic point of view, since water is considered as an environmental resource constraint (as discussed previously), the return on water measure reflects the degree to which operating profit is generated by one unit of this resource constraint. This measure provides useful information for economic sustainability-related decision making by a crop business, as maximising profitability generated per unit of resource constraint is a way for the business to be sustainable. In this respect, improvement of return on water is argued as a step towards to sustainability.

However, other factors also need to be considered in the analysis of water and economic sustainability of the crop business. Since the denominator of the return on water ratio captures total Crop water supply, the ratio reveals the amount of operating profit generated by all sources of water supplied to the crop business. This means it does not provide information on how water is sourced (e.g. rainfall versus irrigation) to capture a distinction between a *water coming naturally elemen*t (rainfall) and a *water abstracted from the environment element* (irrigation), as well as a distinction between two components of irrigation water (licensed irrigation water and traded irrigation water). In addition, the measure does not reveal the cost structure of irrigation water (e.g. licensed irrigation water cost versus traded irrigation water cost). These two pieces of information are captured by the other two drivers of the profit to water cost ratio.

Furthermore, while the return on water describes the relation between profitability and environmental resource (e.g. water resource in this thesis) that a business uses for its production, it does not inform explicitly the extent to which economic return can be created from each dollar of sales, or the ability of water resource used in crop production to generate sales (e.g. sales from lint product and sales from cotton seed product). The former relates to operating activities of a crop business whilst the later relates to water management practices at the operational level of the crop business. In the second-level of analysis that is discussed in a following section (Section 4.4.3), the return on water is decomposed into its drivers to gain insights into how operating activities and operational management practices affect the return on water of the crop business.

4.4.2.2 The effect of weighted average irrigation cost

The second component of the profit to water cost ratio is weighted average irrigation cost. This is a measure that informs the water rate (i.e. $ of water cost per 1 ML of water) that a crop business has to pay on average for all its water sources to supply to its cropping system for crop production. Weighted average water cost is expressed as the ratio of total water cost incurred by a crop business to the total amount of Crop water supply to the crop business (see Equation 4.7).

$$Weighted\ average\ irigation\ cost_{\ it}\left(\frac{\$}{ML}\right) = Total\ water\ cost_{it}\left(\frac{\$}{ha}\right) \div\ Crop\ water\ supply_{\ it}\left(\frac{ML}{ha}\right) \qquad [4.7]$$

As discussed in Section 4.2.1, it is assumed in this thesis that rainfall is a free water resource, with no costs associated with capturing, recycling or storing rainfall to supply the crop business. Taking this assumption, per unit water cost measure becomes weighted average irrigation cost, demonstrating average water cost for the crop business for every unit (i.e. ML) of irrigation water withdrawn. This measure is expressed in Equation 4.5. Accordingly, the second component of the profit to water cost ratio considered in this thesis is a special form of the weighted average water cost measure, which is weighted average irrigation cost.[59]

Mathematically, as illustrated in Equation 4.2, given the other drivers are held constant, reducing weighted average irrigation cost will result in an increase in the profit to water cost ratio. In addition, from an economic point of view, as total water cost forms a (negative) part of operating profit created by a crop business, reducing the weighted average irrigation cost will lead to increased operating profit – this helps to reinforce the value of profit to water cost ratio. In this respect, reducing the weighted average irrigation cost is a step towards crop water and economic sustainability.

[59] As a special form of the weighted average water cost measure when rainfall cost is assumed zero, Equation 4.7, compared with Equation 4.5, shows that the rainfall components in both a dollar term and quantity term (i.e. ML of water) are excluded from the numerator and denominator of the measure, respectively.

As outlined in Chapter 3, irrigation water can be obtained by crop businesses from two main sources – licensed irrigation water and traded irrigation water. While the weighted average irrigation cost measure provides useful information about the unit irrigation water cost (i.e. $/ML) that a crop business has to pay on average for its two irrigation water sources, it is still unclear what actually drives weighted average irrigation cost. In the next section (Section 4.4.3), the weighted average irrigation cost is further decomposed into the two individual irrigation components to allow us to gain more insight into how irrigation water is sourced and specifically how the relative weights (in volume) of each component of irrigation water and their associated unit costs (i.e. $/ML) affect the weighted average water cost, as well as the total water cost of the crop. This provides the foundation for further analysis on the magnitude effects of licensed and traded water volume and cost on weighted average irrigation cost, and the trade-off between traded irrigation and licensed irrigated sourcing decisions, when evaluating the overall water and economic sustainability performance of a crop business.

Furthermore, since the weighted average irrigation cost measure (in assumption) only captures the volume and cost of the irrigation water component, while excluding the rainfall component of Crop water supply, it is necessary to include another driver of profit to water cost ratio that measures the degree to which Crop water supply to a cropping system is sourced by irrigation and rainfall components.

4.4.2.3 The effect of water use leverage

The third driver of the profit to water cost ratio is water use leverage. This ratio is defined as the degree to which Crop water supply to a cropping system is sourced by water abstracted from the environment (i.e. irrigation abstracted). The higher the water use leverage, the more dependent a crop business is on abstracted irrigation sources to produce a crop.

Water use leverage is expressed as the ratio of irrigation abstracted over Crop water supply (see Equation 4.4). Water use leverage builds on an analogy with the financial leverage described in the financial accounting literature (Nissim & Penman 2001; Penman 2003; Soliman 2008). While the financial leverage indicates the use of borrowed capital to lever up the return on equity of the business, the water use leverage reveals the use of abstracted water to improve crop yield, and thus economic return, for the crop business.

Mathematically, Equation 4.2 shows that, where other drivers are held constant, reducing water use leverage will lead to increased profit to water cost ratio, and hence increased overall water and economic sustainability performance of the crop business. This is because water cost (the denominator of the profit to water cost ratio) is directly related to amount of abstracted irrigation (the numerator of the water use leverage). In addition, from an environmental sustainability point of view, the more irrigation water withdrawn from the environment, either via surface water (e.g. water withdrawn from a river) or groundwater (e.g. water pumped from a bore), the bigger the impact of the crop business on water systems is. In this respect, reducing water abstraction for irrigation, and hence reducing the water use leverage, is a step towards crop water sustainability.

However, from an economic point of view, irrigation is carried out to potentially eliminate the risk of the crop suffering water deficits when rainfall receipts are insufficient to completely satisfy transpirational demands. This means irrigation contributes proportionally to the economic return of the crop business.

The discussion above highlights that the water use leverage measure reflects the risk of rainfall resource shortage and the risk of economic return. As the effect of irrigation use on economic sustainability and environmental sustainability of a crop business may go in opposite directions, it is of crucial importance to consider trade-offs between these two sustainability aspects and the potential risks associated with them when evaluating the overall sustainability performance of the crop business.

Furthermore, one way to reduce the proportion of abstracted irrigation in total Crop water supply is to improve water utilisation efficiency by improving water management practices at the operational level. For a crop business that uses furrow irrigation systems, better management of water runoff from rainfall and furrow irrigation systems results in more water runoff being recycled to the water system of the farm which can be recirculated for crop production. In the second-level of analysis that is discussed in the next section (Section 4.4.3), the water use leverage is decomposed into its drivers to provide a better understanding of how water management practices at the operational level can help to improve the water use leverage so that the overall sustainability performance of the crop business can be improved.

4.4.3 Second-level analysis: Decomposition of return on water, water use leverage and weighted average irrigation cost

The first-level of analysis uncovers the three drivers of the profit to water cost ratio, but each of these drivers refers to different aspects of sustainability and relates to different crop management practices/decisions. In the second-level analysis, the three drivers of the profit to water cost ratio are further decomposed into their drivers. The analysis is summarised in Table 4.2.

4.4.3.1 Drivers of return on water

Return on water can be decomposed into its two components: profit margin and economic water use index as expressed in Equation 4.8.

$$Return\ on\ water_{it}\left(\frac{\$}{ML}\right) = Profit\ margin_{it}(\%) \times Economic\ water\ use\ index_{it}\left(\frac{\$}{ML}\right) \quad [4.8]$$

Where profit margin and economic water use index are defined in Equation 4.9 and Equation 4.10 respectively.

$$Profit\ margin_{it}(\%) = \left[Opearing\ profit_{it}\left(\frac{\$}{ha}\right) \div Total\ sales\ revenue_{it}\left(\frac{\$}{ha}\right)\right] \times 100\% \quad [4.9]$$

$$Economic\ water\ use\ index_{it}\left(\frac{\$}{ML}\right) = Total\ sales\ revenue_{it}\left(\frac{\$}{ha}\right) \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right) \quad [4.10]$$

Table 4.2 WESM analysis: The second-level analysis

Variable	Level	Formula
Panel A: Analysis of return on water		
$\mathbf{Return\ on\ water_{it}}\left(\frac{\$}{ML}\right)$	**Level 2**	$= \text{Operating profit}_{it}\left(\frac{\$}{ha}\right) \div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)$ $= \mathbf{Profit\ margin_{it}}(\%) \times \mathbf{Economic\ water\ use\ index_{it}}\left(\frac{\$}{\mathbf{ML}}\right)$
$\text{Profit margin}_{it}(\%)$	Level 3	$= \left[\text{Operating profit}_{it}\left(\frac{\$}{ha}\right) \div \text{Total sales revenue}_{it}\left(\frac{\$}{ha}\right)\right] \times 100\%$
$\text{Economic water use index}_{it}\left(\frac{\$}{ML}\right)$	Level 3	$= \text{Total sales revenue}_{it}\left(\frac{\$}{ha}\right) \div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)$
Panel B: Analysis of water use leverage		
Water use leverage (%)	**Level 2**	$= \left[\text{Irrigation abstracted}_{it}\left(\frac{ML}{ha}\right) \div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)\right] \times 100\%$ $= \mathbf{100\%} - [\mathbf{Rainfall\ to\ crop\ water\ supply\ ratio}\ (\%) + \mathbf{Recycled\ runoff\ to\ crop\ water\ supply\ ratio}\ (\%)]$
Rainfall to crop water supply ratio (%)	Level 6	$= \text{Rainfall}_{it}\left(\frac{ML}{ha}\right) \div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)$

Recycled runoff to crop water supply ratio (%)	Level 6	$= \text{Recycled runoff}_{it} \left(\frac{ML}{ha}\right) \div \text{Crop water supply}_{it} \left(\frac{ML}{ha}\right)$
Panel C: Analysis of weighted average irrigation cost		
Weighted average irrigation $\text{cost}_{it} \left(\frac{\$}{ML}\right)$	**Level 2**	$= \text{Total water cost}_{it} \left(\frac{\$}{ha}\right) \div \text{Irrigation abstracted}_{it} \left(\frac{ML}{ha}\right)$ $= \left[\textbf{Licensed irrigation to Irrigation abstracted ratio}_{it}\ (\%) \times \textbf{Unit licensed irrigation cost}_{it} \left(\frac{\$}{\textbf{ML}}\right)\right]$ $+ \left[\textbf{Traded irrigation to Irrigation abstracted ratio}_{it}\ (\%) \times \textbf{Unit traded irrigation cost}_{it} \left(\frac{\$}{\textbf{ML}}\right)\right]$
Licensed irrigation to Irrigation abstracted ratio_{it} (%)	Input	$= \left[\text{Licensed irrigation}_{it} \left(\frac{ML}{ha}\right) \div \text{Irrigation abstracted}_{it} \left(\frac{ML}{ha}\right)\right] \times 100\%$
Traded irrigation to Irrigation abstracted ratio_{it} (%)	Input	$= \left[\text{Traded irrigation}_{it} \left(\frac{ML}{ha}\right) \div \text{Irrigation abstracted}_{it} \left(\frac{ML}{ha}\right)\right] \times 100\%$
Unit licensed irrigation $\text{cost}_{it} \left(\frac{\$}{ML}\right)$	Input	Accounting Data
Unit traded irrigation $\text{cost}_{it} \left(\frac{\$}{ML}\right)$	Input	Accounting Data

Comparing Equation 4.3, which shows the formula for calculating the return on water measure, to Equation 4.8, which demonstrates the break-down of return on water into its two drivers, taking into account of Equations 4.9 and 4.10, it is proved that they are equal.

$$\begin{aligned}
&Return\ on\ water_{it}\left(\frac{\$}{ML}\right) \\
&= Operating\ profit_{it}\left(\frac{\$}{ha}\right) \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right) \\
&= Profit\ margin_{it}(\%) \times Economic\ water\ use\ index_{it}\left(\frac{\$}{ML}\right) \\
&= \left[Operating\ profit_{it}\left(\frac{\$}{ha}\right) \div Total\ sales\ revenue_{it}\left(\frac{\$}{ha}\right)\right] \\
&\times \left[Total\ sales\ revenue_{it}\left(\frac{\$}{ha}\right) \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right)\right] \\
&= Operating\ profit_{it}\left(\frac{\$}{ha}\right) \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right)
\end{aligned} \qquad [4.11]$$

The decomposition of return on water into profit margin and economic water use index enables us to distinguish between operating activities, which drive profitability of the crop business, and resource use - related decisions, which drive the economic water use index of the crop business.

The effect of profit margin

As demonstrated in Equation 4.9, the profit margin is the ratio of operating profit to total sales revenue. Profit margin is well-defined and widely used in the financial accounting literature to measure the net profit as a percentage of sales revenue (Nissim & Penman 2001; Soliman 2008).

While the profit margin reveals the profitability of each dollar of sales, this measure per se only refers to the economic aspect of a business and not its environmental sustainability which in this case relates to how efficient water resource is used in the crop production process in generating sales revenue for the crop business. The later aspect is captured by the second driver of the return on water.

Furthermore, from Equation 4.8, it is seen that where the economic water use index is unchanged, an increase in profit margin will lead to an increase in return on water. In this respect, it is necessary to identify the driving factors of profit margin and understand how changes in the profit margin's drivers affect the return on water and ultimately the profit to water cost ratio. In the next section, the numerator (operating profit) and denominator (sales revenue) of the profit margin ratio will be decomposed into their components to allow the establishment of the information hierarchy from the business level down to the lower level of a crop business.

The effect of economic water use index

As described in Equation 4.10, economic water use index is defined as the value of crop products (total sales revenue) produced per unit of water volume (i.e. ML) supplied to the cropping system. Similar to the asset turnover ratio, presenting the sales revenue generated for each dollar of net operating assets, described in the financial ratio analysis literature to measure asset utilization and efficiency[60] (Figge & Hahn 2013; Soliman 2008), the economic water use index is referred to as a measure of efficient use of an environmental resource (e.g. water resource in this thesis).

One of the key contributions of this research is that the economic water use index allows an end-to-end connection between water resource utilisation and crop profitability. As the numerator of the economic water use index captures total sales revenue (including sales revenue of all crop products) and its denominator includes all water sources input to the cropping system, the index explicitly demonstrates a relationship between water resource coming in (to the crop production) and cash coming out (from the crop production). As such, the economic water use index is a useful measure for quantifying the use of water resource by a crop business to create its value.

Equation 4.8 also indicates that improvement in the economic water use index will improve the return on water measure. In order to gain insights into the impact water management decisions have, including irrigation decisions and water storage and recycling decisions, on

[60] For example, the efficient use of property, plant and equipment, efficient inventory processes, and working capital efficiency (Penman 2003).

the economic water use index, this measure will be further broken down into its drivers in the next section (Section 4.4.4).

Analysis of the drivers of return on water

In the second-level breakdown of the WESM model I establish the relationship between the profitability of each dollar of sales (profit margin) and the use of water to the generation of sales (economic water use index). The decomposition of the return on water measure reveals that the economic return of a crop business in respect to water resource comes from two sources: profit margin and economic water use index. This means that for a crop business, as a higher proportion of each dollar of sales ends up in operating profit and/or the more sales are generated from water resource supplied to the crop business, the higher the economic return on water resource.

A crop business can produce a given level of return on water (for example, $120/ML or $120 of operating profit generated for every 1 ML of water supplied) in two ways. First, the business can have a relatively high profit margin (for example, 30% or $0.3 of operating profit is generated for every $1 of sales revenue) but low economic water use index (for example, $400/ML or $400 of sales revenue is generated for every 1 ML of water supplied). Second, the business can have a relatively high economic water use index (for example, $600/ML or $600 of sales revenue is generated for every 1 ML of water supplied) but low profit margin (for example, 20% or $0.2 of operating profit is generated for every $1 of sales revenue).

While the first driver of return on water is predominantly a profitability measure, the second component is an efficiency measure. On the one hand, profitability measurement is related to operating cost, including water cost.[61] On the other hand, the economic water use index is driven by water management decisions/practices which inform how efficiently a crop business uses water resources to generate crop product(s). External factors (e.g. climate factors, regional characteristics, water policy), which impact availability of water resource (both rainfall and irrigation) and water cost, are considered contributing factors to the two components of the return on water.

[61] As the focus of this thesis is water and economic sustainability, in the lower levels of analysis, water cost will be isolated to allow examination of the impact of cost of water resources on businesses' profitability.

4.4.3.2 Drivers of weighted average irrigation cost

In the second-level of analysis, weighted average irrigation cost is decomposed into unit costs of individual irrigation components and the relative weights (in volume) of each type of irrigation water of the total irrigation water withdrawn by a crop business.

Weighted average irrigation cost is calculated in very much the same way as weighted average cost of capital in financial accounting research. For example, given that debt and equity are two main financing (capital) sources of a firm, carrying two different types of cost of capital, namely cost of debt and cost of equity respectively, the weighted average cost of capital is calculated (see Equation 4.8) taking into account the relative weights of each component of the capital structure of the firm.

$$\begin{aligned} &Weighted\ average\ cost\ of\ capital\ (\%) \\ &\quad = [Equity\ (\$) \div Total\ capital\ (\$)] \times Cost\ of\ Equity\ (\%) \\ &\quad + [Debt\ (\$) \div Total\ capital\ (\$)] \times Cost\ of\ Debt\ (\%) \end{aligned} \tag{4.12}$$

In the context of irrigation sources in agriculture, as discussed in Chapter 3, crop businesses can obtain irrigation water from two main sources – licensed irrigation water and traded irrigation water. Part of the decision to allow water trading was a hope that this would lead to water being used by the most efficient or profitable farmers, who could afford the trades thus returning maximum dollar benefit to society for use of a public good.

Furthermore, as water prices (i.e. $/ML) vary between licensed water and traded water, across years and locations[62], average irrigation costs are calculated based on the relative weights (in volume) of each component of total irrigation water withdrawn as follows:

[62] See an example of State Water Pricing Application: 2014-15 – 2016-17 issued by the Australia Government in https://www.accc.gov.au/regulated-infrastructure/water/state-waters-regulated-charges-2014-17-review/final-decision

$$Weighted\ average\ irrigation\ cost_{it}\ \left(\frac{\$}{ML}\right)$$
$$= \Bigg[Licensed\ irrigation\ to\ Irrigation\ abstracted\ ratio_{it}\ (\%)$$
$$\times\ Unit\ licensed\ irrigation\ cost_{it}\ \left(\frac{\$}{ML}\right)\Bigg] \qquad [4.13]$$
$$+ \Bigg[Traded\ irrigation\ to\ Irrigation\ abstracted\ ratio_{it}\ (\%)$$
$$\times\ Unit\ traded\ irrigation\ cost_{it}\ \left(\frac{\$}{ML}\right)\Bigg]$$

In Equation 4.13, unit licensed irrigation cost ($/ML) and unit traded irrigation cost ($/ML) represent water prices ($/ML) of licensed water and traded water respectively. In addition, licensed irrigation to Irrigation abstracted ratio (%), and traded irrigation to Irrigation abstracted ratio (%), which capture the relative weights (in volume) of each type of irrigation water of the total irrigation water withdrawn by a crop business respectively, are expressed below:

$$Licensed\ irrigation\ to\ Irrigation\ abstracted\ ratio_{it}\ (\%)$$
$$= \Bigg[Licensed\ irrigation_{it}\ \left(\frac{ML}{ha}\right) \qquad [4.14]$$
$$\div\ Irrigation\ abstracted\ _{it}\left(\frac{ML}{ha}\right)\Bigg]\ \times 100\%$$

$$Traded\ irrigation\ to\ Irrigation\ abstracted\ ratio_{it}\ (\%)$$
$$= \Bigg[Traded\ irrigation_{it}\ \left(\frac{ML}{ha}\right) \qquad [4.15]$$
$$\div\ Irrigation\ abstracted\ _{it}\left(\frac{M}{ha}\right)\Bigg]\ \times 100\%$$

As indicated in the WESM model diagram (see Figure 4.1) and Table 4.2, these four components of the weighted average irrigation cost are input into the WESM model to enable quantification of this second-level measure.

4.4.3.3 Drivers of water use leverage

As expressed in Equation 4.4, water use leverage is the ratio of irrigation water abstracted to total crop water supply. In the second-level of analysis, the water use leverage measure is decomposed into various water sources supplied to the cropping system of a crop business. This allows us to establish the link between the measure of water sustainability at the high level and components at the operational level of the crop business which are driven by water management decisions.

The crop water process model constructed in Chapter 3 shows that two main sources of crop water supply to a cropping system are rainfall and irrigation, and irrigation is needed to supplement rainfall where there is insufficient rainfall supplied to the cropping system (see Equation 3.10). From a management perspective, the rainfall component is considered as an uncontrollable factor while the irrigation component is determined and controlled by water management by irrigation decisions, including irrigation method, irrigation scheduling decisions, and runoff recycling practice.

Furthermore, as discussed in Section 3.2.3, recycled runoff can be treated as a source of water supply, and hence reduces the water impost of cotton cultivation on the environment (see Equation 3.15). Therefore, crop water supply comprises three components, rainfall, recycled runoff, and irrigation water abstracted (see Equation 3.16).

When water recycling is taken into account, the water use leverage measure expressed in Equation 4.4 can be rearranged as follow:

$$\begin{aligned} Water\ use\ leverage_{it}\ (\%) \\ &= 100\% \\ &- [\text{Rainfall to crop water supply ratio } (\%) \\ &+ \text{Recycled runoff to crop water supply ratio } (\%)] \end{aligned} \quad [4.16]$$

Equation 4.16 demonstrates more recycled runoff means less water needs to be abstracted from the environment. As such, the water use leverage measure of the crop business can be improved for better water sustainability performance.

As discussed above, the level of irrigation applied to a cropping system, and the level of recycled runoff are driven by a range of water management decisions that are made at the operational level of a crop business; this includes irrigation system decisions, irrigation scheduling decisions, and water recycling decisions. The impact of such decisions with regard to water management is captured by the drivers of the water use leverage that are laid out in Level 7 of the WESM model, including irrigation applied per event, runoff from irrigation per event, number of irrigation events, ratio of recycled runoff. By establishing the link between the water use leverage and its drivers, the impact of water management decisions at the operational level of a crop business on its water sustainability performance can be quantified and managed.

4.4.4 Third-level analysis: Decomposition of profit margin and economic water use index

The first-level breakdown of the WESM model shows that profit to water cost ratio is driven by economic return of a crop business in respect to water resource (return on water), the degree to which a crop business is dependent on irrigation sources to produce crop products (water use leverage), and how irrigation is sourced (weighted average irrigation cost). In the second-level breakdown, the drivers of weighted average irrigation cost and water use leverage are identified. Since these drivers directly link to water management decisions at the crop production level, including how crop water supply is sourced and how irrigation is sourced, the relationship between operational decisions with regard to water management and these two drivers of profit to water ratio is established to enable quantification and management of the impact of such operational decisions on the overall sustainability performance of a crop business.

In addition, also in the second-level analysis of WESM model, it is revealed that return on water is driven by the profitability of a crop business (profit margin) and how efficient water resource is used to generate sales revenue for the crop business (economic water use index). While measures, such as profit to water cost ratio, water use leverage, weighted average irrigation cost, return on water, profit margin, economic water use index, are argued in this thesis as higher level sustainability measures because they do not directly link to activities of the crop production (or capture the science behind crop production output at the operational level), such high level measures provide limited explanation about the drivers of water and economic sustainability performance. Therefore, in the third-level analysis, the two drivers of return on water are further decomposed into their components that are directly related to the operational level of a crop business where sustainability issues are argued to occur.

4.4.4.1 Drivers of profit margin

Mathematically, ratios change because of changes in one or both terms involved (e.g. the numerator and denominator). In order to gain insights to what actually drives the profit margin ratio, it is required to decompose each of its terms into their components. As defined in Equation 4.9, operating profit is the numerator and total sales revenue is the denominator of the profit margin. Accordingly, these two components of the profit margin ratio are arranged in the next level down of the WESM model (i.e. Level 3) (see Figure 4.1) and also presented in Table 4.3.

Table 4.3 WESM analysis: The third-level analysis

Variable	Level	Formula
Panel A: Analysis of profit margin		
$\textbf{Profit margin}_{\textbf{it}}(\%)$	**Level 3**	$= \left[\text{Operating profit}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) \div \text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right)\right] \times 100\%$
$\text{Operating profit}_{\text{it}}\left(\frac{\$}{\text{ha}}\right)$	Level 4	$= \text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) - \text{Total operating cost}_{\text{it}}\left(\frac{\$}{\text{ha}}\right)$
$\text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right)$	Level 5	$= \text{Sales revenue}_{\text{it}}(\text{lint})\left(\frac{\$}{\text{ha}}\right) + \text{Sales revenue}_{\text{it}}\ (\text{cotton seed})\left(\frac{\$}{\text{ha}}\right)$
Panel B: Analysis of economic water use index		
$\textbf{Economic water use index}_{\textbf{it}}\left(\frac{\$}{\textbf{ML}}\right)$	**Level 3**	$= \text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) \div \text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)$ $= \textbf{Crop water use index}_{\textbf{it}}\left(\frac{\textbf{kg of lint}}{\textbf{ML}}\right) \div \textbf{Lint percentage}_{\textbf{it}}(\%)$ $\times\ \textbf{Weighted average cotton price}_{it}\left(\frac{\$}{\textbf{kg of total product}}\right)$
$\text{Crop water use index}_{\text{it}}\left(\frac{\text{kg of lint}}{\text{ML}}\right)$	Level 4	$= \text{Lint yield}_{\text{it}}\left(\frac{\text{kg of lint}}{\text{ha}}\right) \div \text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)$
$\text{Weighted average cotton price}_{it}\left(\frac{\$}{\text{kg of total yield}}\right)$	Level 4	$= \text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) \div \text{Total yield}_{\text{it}}\left(\frac{\text{kg of total product}}{\text{ha}}\right)$
$\text{Lint percentage}_{\text{it}}\ (\%)$	WESM Input	$= \left[\text{Lint yield}_{\text{it}}\left(\frac{\text{kg of lint}}{\text{ha}}\right) \div \text{Total yield}_{\text{it}}\left(\frac{\text{kg of total product}}{\text{ha}}\right)\right] \times 100\%$

From an accounting perspective, operating profit is calculated by deducting the amount of operating cost[63] from sales revenue.

$$\text{Operating profit}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) = \text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) - \text{Total operating cost}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) \quad [4.17]$$

Equations 4.9 and 4.17 reveal that total sales revenue and total operating cost are the two drivers of operating profit and profit margin measures.

Operating cost consists of various costs associated with activities undertaken for crop production, including cultivation cost, planting cost, irrigation cost, fertiliser cost, and so on (see Appendix A1). One way to improve the profitability of a crop business is to cut costs incurred by the business. More specifically, in respect to water resources, improvement of water management would result in less irrigation water required for crop production and hence reduced irrigation costs. In the fifth-level of analysis (see Appendix A2: Table A1, Panel E), total operating costs will be decomposed into their components in order to isolate irrigation costs from other operating cost. This enables crop managers to quantify the impact of water management decisions on the profitability of the crop business.

Furthermore, as demonstrated in Equation 4.9 and Equation 4.17, where the total operating cost is held constant, the more the total sales revenue generated by a crop business, the higher the profitability of the crop business. From a crop production perspective, total sales revenue generated by a crop business comprises of sales revenue generated from the primary product (i.e. lint product in cotton production) and sales revenue generated from the by-product (i.e. cotton seed product in cotton production). For each of the sales revenue components, its value is driven by two factors: a crop factor (production output/yield), and an economic factor (i.e. selling price). In the fifth-level of analysis (see Appendix A2: Table A1, Panel E),), total sales revenue will be further decomposed into its components for examining its driving factors and identifying areas for improvement.

[63] As mentioned above, this thesis only focuses on operating activities, not financing activities, when examining water and economic sustainability since it is argued that sustainability issues arise as a result of unsustainable activities undertaken in the process of producing crop products. Accordingly, only operating cost – cost incurred to undertake operating activities at the operational level of a crop business – is considered in the analysis.

4.4.4.2 Drivers of economic water use index

In the third-level of analysis, the economic water use index is decomposed into its three drivers: crop water use index, weighted average cotton price, and lint percentage, as described below:

$$Economic\ water\ use\ index_{it}\left(\frac{\$}{ML}\right)$$
$$= Crop\ water\ use\ index_{it}\left(\frac{kg\ of\ lint}{ML}\right) \div Lint\ percentage_{it}(\%) \qquad [4.18]$$
$$\times\ Weighted\ average\ cotton\ price_{it}\left(\frac{\$}{kg\ of\ total\ product}\right)$$

Where crop water use index is defined in Chapter 3 (Section 3.3.3, Equation 3.26), while lint percentage and weighted average cotton price are defined below:

$$Lint\ percentage_{it}\ (\%) =$$
$$= \left[Lint\ yield_{it}\left(\frac{kg\ of\ lint}{ha}\right) \qquad [4.19]\right.$$
$$\left.\div\ Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right)\right] \times 100\%$$

$$Weighted\ average\ cotton\ price_{it}\left(\frac{\$}{kg\ of\ total\ yield}\right) =$$
$$= Total\ sales\ revenue_{it}\left(\frac{\$}{ha}\right) \qquad [4.20]$$
$$\div\ Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right)$$

In Equation 4.19 and Equation 4.20, total yield refers to sum of the output of all crop products. In the context of cotton production, total yield comprises lint yield and cotton seed yield.

$$Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right) = Lint\ yield_{it}\left(\frac{kg\ of\ lint}{ha}\right) + Seed\ yield_{it}\left(\frac{kg\ of\ seed}{ha}\right) \quad [4.21]$$

Since the crop water use index measure only defines the relationship between the output of the primary product of a cotton crop (e.g. lint yield) and the amount of water supplied for crop production, lint percentage is incorporated into crop water use index in order to capture the total economic yield of the crop.

$$\begin{aligned} &Crop\ water\ use\ index_{it}\left(\frac{kg\ of\ lint}{ML}\right) \div Lint\ percentage_{it}(\%) \\ &= \left[Lint\ yield_{it}\left(\frac{kg\ of\ lint}{ha}\right) \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right)\right] \\ &\div \left[Lint\ yield_{it}\left(\frac{kg\ of\ lint}{ha}\right) \div Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right)\right] \times 100\% \\ &= Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right) \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right) \end{aligned} \quad [4.22]$$

In addition, by incorporating the weighted average cotton price into the Equation 4.22, the relationship between total sales revenue generated by a crop business and the water resource provided to the crop business for crop production processes is established.

$$\begin{aligned}
&Crop\ water\ use\ index_{it}\left(\frac{kg\ of\ lint}{ML}\right) \div Lint\ percentage_{it}(\%) \\
&\quad \times Weighted\ average\ cotton\ price_{it}\left(\frac{\$}{kg\ of\ total\ product}\right) \\
&\quad = \left[Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right)\right. \\
&\quad \left.\div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right)\right] \\
&\quad \times \left[Total\ sales\ revenue_{it}\left(\frac{\$}{ha}\right)\right. \\
&\quad \left.\div Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right)\right] \\
&\quad = Total\ sales\ revenue_{it}\left(\frac{\$}{ha}\right) \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right)
\end{aligned} \qquad [4.23]$$

Comparing Equation 4.10, which defines the economic water use index measure, to Equation 4.23, where the economic water use index measure is decomposed into its three components, it is proved that they are equal.

The decomposition of the economic water use index measure into its three drivers is useful to crop managers in terms of looking at potential increases in economic return of the crop business on water resource through improvements in those three drivers.

The effect of crop water use index

The crop water use index is defined as the amount of primary crop product produced per unit of water volume supplied to the cropping system. In the third-level breakdown, the crop water use index is isolated as an important driver of the economic water use index measure, focusing on the primary (high-value) product of cotton production. If crop economic factors (e.g. lint price and cotton seed price) and lint percentage in cotton products remain constant, improving the crop water use index is the key factor to drive increases in the economic water use index.

As discussed in detail in Section 3.3.3, the crop water use index provides a means of evaluating the ability of a crop business to generate primary crop product from each unit of water volume supplied to the cropping system. In addition, it can be a useful measure for crop managers to look at potential increases in crop yield, and hence economic return, per unit of the resource constraint (water resource). However, by merely looking at the value of the crop water use index, it is not known what (management) factors actually drive this measure. Therefore, in the fourth-level of analysis, the crop water use index will be further decomposed into its components to allow us to identify (management) areas for improvements of crop businesses' performance.

The effect of lint percentage

The lint percentage component, the second driver of the economic water use index, is a measurement of the weight ratio of lint to total lint and cotton seed. This measure is mainly determined by the type of cotton cultivars selected in a particular field (Verhalen, Greenhagen & Thacker 2003). For varieties that are currently supplied and used for cotton production in Australia, lint percentage varies between 39% and 44%.[64]

As expressed in Equation 4.23, incorporation of lint percentage into crop water use index enables us to establish the link between total yield of a crop, which contributes to the overall economic outcome of the crop business, and the Crop water supply to the cropping system. As illustrated in the WESM model diagram, the lint percentage variable is an input variable, forming a part of the economic water use index.

The effect of weighted average cotton price

The third component of the economic water use index is weighted average cotton price. This measure represents the average selling price of cotton products (i.e. $/kg) that a crop business offers its customers. Since a cotton business produces two economic products (lint product and cotton seed product), the constructed weighted average cotton price provides a simple way to incorporate both products into one dimension for capturing the total income a crop business generates from cotton production.

[64] http://www.csd.net.au/varietyguide.

In very much the same way as the weighted average irrigation cost is calculated, weighted average cotton price of a crop business is calculated by dividing total sales revenue generated for a period by total yield produced in that period (see Equation 4.20).

Weighted average cotton price captures the economic dimension of the economic water use index. If crop management factors (e.g. captured by the crop water use index) and lint percentage in cotton products remain constant, higher weighted average cotton price will result in a higher economic water use index. Since weighted average cotton price consists of two crop production components, lint and cotton seed, each of which carries a different economic value, it is essential to further decompose this measure into its components to gain more insights into what drives the total economic value of a crop business. Accordingly, in the next section, weighted average cotton price will be further broken down into its components.

4.4.5 Fourth-level analysis: Decomposition of crop water use index and weighted average cotton price

The breakdown of the economic water use index measure enables crop managers to distinguish between the managerial effect, which is captured by the crop water use index, and economic effect, which is captured by weighted average cotton price on this measure. In the fourth-level analysis, the crop water use index and the weighted average cotton price are further decomposed into their drivers in order to enable us to gain insights into what affects change in these two measures. The analysis is summarised in Appendix A2 – Table A1 – Panel D.

4.4.5.1 Decomposition of crop water use index

The decomposition of the crop water use index into its three drivers (water input efficiency, transpiration index and harvest index) was conducted in Chapter 3 (see Equation 3.27). As discussed in Section 3.3.3, the three drivers of the crop water use index is useful to crop managers for identifying management areas for continuous improvement in order to move towards sustainability.

Improving water input efficiency is a step towards crop water sustainability

In respect to the water aspect of crop production, the theoretical link between lint yield and transpiration described in Equation 4.37 demonstrates that plant transpiration is the only water outflow component that contributes to crop production, and hence, adds value to a crop business. However, the crop water process model illustrated in Chapter 3 (see Figure 3.2) reveals that a portion of Crop water supply to the cropping system does not contribute to crop production and is considered as crop water loss (non-productive water component).

Crop water loss negatively affects economic and water sustainability performance of a crop business in a number of ways. First, as irrigation is one of the two main water sources supplied to a cropping system, as indicated in the crop water process model (see Figure 3.2), water lost from the cropping system (e.g. deep drainage, water run-off and soil evaporation) means more irrigation water is required for crop production (given the same amount of rainfall). Increasing irrigation abstraction from surface or groundwater within a water system potentially causes imbalance in the water system (Ibaraki 2010). This is one of the key issues related to water sustainability addressed in Chapter 2.

Second, since irrigation is costly, increasing irrigation leads to increasing cost of water incurred by the crop business (Cammarano et al. 2012). Furthermore, increasing the amount of water abstracted for irrigation leads to increasing water competition among water users – agriculture, industry, environment and urban areas (Mehta et al. 2013; Rijsberman 2006). This will impact the ability of crop businesses to sustain their economic growth in the long-run. Third, the amount of water lost could be beneficially used to grow more crops. This not only helps to improve the profitability of the crop business but also allows increased supply of cotton products to society. Finally, increasing water loss means more water being discharged to the natural environment. The quality of water output from cropping systems has become a great concern in respect to water sustainability (Chapagain et al. 2006; Ibaraki 2010). It is evident that water loss from deep drainage causes significant environmental harm (Smith, Raine & Minkevich 2005).

Therefore, a crop business to move towards economic and water sustainability requires improving the efficient use of crop water input to a cropping system to capture more of the water supply for use in transpiration. However, while the water input efficiency provides useful information on how well water resource is managed, how efficient crop water resource is used, and how changes in water input efficiency affect changes in crop water use index, it is not yet clear, among various water components defined in the crop water process model, which are the key driving factors of water input efficiency with regard to water management generally and irrigation decisions particularly. In the next section, the water input efficiency will be further decomposed into its water components.

4.4.5.2 Decomposition of the weighted average cotton price

Similar to how the weighted average irrigation cost measure is decomposed into its components (see Equation 4.13), the weighted average cotton price is broken down into two components of crop production, taking into consideration their relative weights to the total production, and their associated selling prices.

$$Weighted\ average\ cotton\ price_{it}\left(\frac{\$}{kg\ of\ total\ yield}\right) = \left[Lint\ percentage_{it}\ (\%) \times Lint\ price_{it}\left(\frac{\$}{kg}\right)\right] + \left[Seed\ percentage_{it}\ (\%) \times Seed\ price_{it}\left(\frac{\$}{kg}\right)\right] \quad [4.24]$$

Where seed percentage is the weight ratio of cotton seed to total lint and cotton seed and defined as below.

$$Seed\ percentage_{it}\ (\%) = \left[Seed\ yield_{it}\left(\frac{kg\ of\ seed}{ha}\right) \div Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right)\right] \times 100\% \quad [4.25]$$

Since total yield consists of lint yield and seed yield, the sum of lint percentage[65] and seed percentage equal to 100%.

$$Seed\ percentage_{it}\ (\%) = 100\% - Lint\ percentage_{it}\ (\%) \quad [4.26]$$

The decomposition of the weighted average cotton price above is based on the three components that affect this measure are lint percentage, lint price and cotton price. When the

[65] See Equation 4.29 for definition of lint percentage.

effect of lint percentage, which is mainly driven by types of crop variety selected for growing cotton crops, is isolated, the weighted average cotton price is driven by two economic factors: lint price and cotton seed price. As indicated in the WESM model diagram (see Figure 4.1), lint price and cotton seed price are input variables to the WESM model to enable quantification of the weighted average cotton price measure.

Furthermore, cotton lint is a significantly higher value product than cotton seed.[66]Consequently lint price is considered as the main economic factor that drives the average price of cotton products. Compared to cotton seed, a smaller change in lint price can result in greater change in the weighted average cotton price, leading to greater change in the economic value of a crop business. The selling price of cotton lint is typically driven by both external factors, such as market competition, demand for crop products at a particular time of the year, futures contracts, as well as internal factors, such as fibre quality which is driven by irrigation management and other crop management.

The decomposition of the weighted average cotton price allows us to identify the key drivers of the average selling price of cotton products. In addition, another benefit of decomposing the weighted average cotton price is that break-even analysis can be conducted to determine the break-even point in lint yield (e.g. what level of lint yield produced does the crop business start to make profit) and/or the break-even point in lint price (e.g. at which lint price does the crop business start to make profit). This analysis can be a useful tool to support crop managers in planning crop production and managing risks associated with the business' profitability.

4.4.6 Fifth-level analysis: Decomposition of total sales revenue, total operating cost and water input efficiency

4.4.6.1 Drivers of total sales revenue

In the fifth-level of analysis, the two sources of crop sales revenue will be further decomposed into their crop and economic factors.

[66] For example, from a sample budget for furrow irrigated cotton for Central and Northern NSW area (2014 – 2015) (NSW Department of Primary Industries 2015), the selling prices of lint product and cotton seed product are $2.09/kg of lint and $0.32/kg of cotton seed, respectively.

$$Total\ sales\ revenue\ _{it}\left(\frac{\$}{ha}\right)$$
$$= Sales\ revenue\ (lint)_{it}\left(\frac{\$}{ha}\right) \qquad [4.27]$$
$$+\ Sales\ revenue\ (cotton\ seed)_{it}\left(\frac{\$}{ha}\right)$$

Where sales revenue from lint product and cotton seed product are determined based on their associated production output and selling price.

$$Sales\ revenue\ (lint)_{it}\left(\frac{\$}{ha}\right)$$
$$= Lint\ yield_{it}\left(\frac{kg\ of\ lint}{ha}\right) \times Lint\ price_{it}\left(\frac{\$}{ha}\right) \qquad [4.28]$$

$$Seed\ revenue\ (cotton\ seed)_{it}\left(\frac{\$}{ha}\right)$$
$$= Seed\ yield_{it}\left(\frac{kg\ of\ seed}{ha}\right) \times Seed\ price_{it}\left(\frac{\$}{ha}\right) \qquad [4.29]$$

Given lint percentage and total yield are WESM model input variables, lint yield and seed yield can be calculated as below.

$$Lint\ yield_{it}\ \left(\frac{kg\ of\ lint}{ha}\right)$$
$$= \Big[Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right) \qquad [4.30]$$
$$\times\ Lint\ percentage_{it}\ (\%)\Big]\ \div 100\%$$

$$Seed\ yield_{it}\ \left(\frac{kg\ of\ seed}{ha}\right) = \left[Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right) \times (1 - Lint\ percentage_{it}\ (\%))\right]\ \div 100\% \qquad [4.31]$$

Therefore, the economic value (e.g. total sales revenue) of a crop business is driven by crop factors (total yield and lint percentage) and economic factors (lint price and cotton seed price).

$$Total\ sales\ revenue\ _{it}\left(\frac{\$}{ha}\right) = Lint\ price_{it}\left(\frac{\$}{ha}\right) \times \left[Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right) \times Lint\ percentage_{it}\ (\%)\ \div 100\%\right] + Seed\ price_{it}\left(\frac{\$}{ha}\right) \times \left[Total\ yield_{it}\left(\frac{kg\ of\ total\ product}{ha}\right) \times (1 - Lint\ percentage_{it}\ (\%))\ \div 100\%\right] \qquad [4.32]$$

The decomposition of total sales revenue into its components enables us to isolate economic factors and crop factors when analysing the effect of crop management practices on the economic value of a crop business. Equation 4.32 reveals that if other components are constant, total yield is the key driver of total sales revenue. Furthermore, crop research discusses that water is one of the key driving factors for achieving potential yield (Hochman et al. 2013; van Ittersum et al. 2012). Therefore, increased water availability and improved water management practices need to be considered by crop managers for potential increase in crop yield.

4.4.6.2 Drivers of total operating cost

When crop managers look for potential increases in the profitability of the crop business through operational cost savings, it is of crucial importance for them to understand what factors drive the total operating cost and how to manage them. In this section, total operating cost is first decomposed into its two cost components: variable operating cost and fixed operating cost.

$$\begin{aligned} Total\ operating\ cost_{it}\left(\frac{\$}{ha}\right) \\ = \ Variable\ operating\ cost\left(\frac{\$}{ha}\right) \\ +\ Fixed\ \ operating\ cost_{it}\left(\frac{\$}{ha}\right) \end{aligned} \qquad [4.33]$$

In the WESM analysis, the unit analysis chosen is a unit of crop area (e.g. a hectare) and the cost object considered is lint production. In this respect, fixed operating cost is considered as operating cost that do not change in relation to the level of lint production. In contrast, variable operating cost is defined as cost that changes in proportion to the level of lint production.

Furthermore, with regard to water management, it is essential for crop managers to isolate irrigation cost from other variable operating costs in order to gain a better understanding of the effect of water management, including irrigation management, on the total operating cost and hence profitability of the crop business. Accordingly, three cost items that form total operating costs are defined in Equation 4.34.

$$\begin{aligned} Total\ operating\ cost_{it}\left(\frac{\$}{ha}\right) \\ = \ Total\ water\ cost_{it}\left(\frac{\$}{ha}\right) + Other\ variable\ cost_{it}\left(\frac{\$}{ha}\right) \\ +\ Fixed\ \ operating\ cost_{it}\left(\frac{\$}{ha}\right) \end{aligned} \qquad [4.34]$$

By definition, fixed operating costs remain unchanged (within a relevant range of lint production). This component is treated as an input variable to the WESM model. In addition, apart from irrigation cost, other variable cost is assumed as a function of lint yield with unit other variable cost as its coefficient.

$$Other\ variable\ cost_{it}\left(\frac{\$}{ha}\right)$$
$$= \ Unit\ other\ variable\ cost_{it}\left(\frac{\$}{kg\ of\ lint}\right) \quad [4.35]$$
$$\times\ Lint\ yield_{it}\left(\frac{kg}{ha}\right)$$

The most important driver of total operating cost, with regard to the water management aspect, is decomposed into its two components: licensed irrigation cost and traded irrigation cost.

$$Total\ water\ cost_{it}\left(\frac{\$}{ha}\right) =$$
$$= \ Licensed\ irrigation\ cost_{it}\left(\frac{\$}{ha}\right) \quad [4.36]$$
$$+\ Traded\ irrigation\ cost_{it}\left(\frac{\$}{ha}\right)$$

Where licensed irrigation cost and traded irrigation cost are driven by their irrigation volume and unit irrigation cost.

$$Licensed\ irrigation\ cost_{it}\left(\frac{\$}{ha}\right)$$
$$= \ Licensed\ irrigation\ volume_{it}\left(\frac{ML}{ha}\right) \quad [4.37]$$
$$\times\ Unit\ licensed\ irrigation\ cost_{it}\left(\frac{\$}{ML}\right)$$

$$Traded\ irrigation\ cost_{it}\left(\frac{\$}{ha}\right) = Traded\ irrigation\ volume_{it}\left(\frac{ML}{ha}\right) \times Unit\ traded\ irrigation\ cost_{it}\left(\frac{\$}{ML}\right) \quad [4.38]$$

4.4.6.3 Drivers of water input efficiency

Water input efficiency is defined in Chapter 3 as a measure that captures the degree to which crop water supply is actually used for carbon assimilation to generate biomass. As demonstrated in Equation 3.22, transpiration is a numerator and crop water supply is a denominator of the ratio.

However, by only looking at transpiration, which is the amount of water required by plants to produce biomass, and total crop water supply, it does not provide information on how well crop managers manage and use crop water. It is the crop water loss components or non-productive water components that make the water input efficiency poor. Therefore, in the fifth-level of analysis, the water input efficiency measure is further broken down into productive and non-productive water components.

$$Water\ input\ efficiency_{it}(\%) = \left[Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right) - Crop\ water\ loss_{it}\left(\frac{ML}{ha}\right) - recycled\ runoff\right] \div Crop\ water\ supply_{it}\left(\frac{ML}{ha}\right) \quad [4.39]$$

Equation 4.39 reveals that maximising water input efficiency will ensure that the maximum possible proportion of available fresh water supplied is used for transpiration to yield biomass. Ideally, when no water loss[67] or use other than transpiration occurs, actual crop water use is equal to total crop water supply. In this case, water input efficiency achieves its theoretical maximum value of 100%.

[67] Therefore, there is also no water runoff that needs to be recycled.

In reality, water input efficiency is less than 100% due to evaporation from soil and/or evaporation from free water surfaces (such as dams and channels), deep drainage, loss from run-off, and change in soil water. Equation 3.11 describes four non-productive water components of water loss.

Water supplied that is lost from the farming system by these processes does not contribute to yield and can therefore be considered a loss from the system. Where that water is purchased and abstracted from the environment, this represents a financial cost of some significance. Therefore, for a crop business to be environmentally (in terms of water) and economically sustainable, it is essential to improve water management practices to enable water input efficiency value to move closer to its theoretical value.

While soil evaporation is partly driven by non-controlling factors (e.g. climate factors, soil characteristics of the region) and loss from water runoff can be managed through better water recycling management practices, the deep drainage component, which contributes significantly to total water lost from crop production under furrow irrigation systems, can be managed/controlled via better irrigation scheduling management.

4.4.7 Sixth and seventh level analysis

The sixth and seventh level look at the effect of economic factors and factors at the crop production level described in the crop water process model in Chapter 3 on higher level measures of the WESM model diagram. This includes:

a. The effect of lint price, cotton seed price and harvest index on weighted average cotton price
b. The effect of plant transpiration and transpiration index on biomass yield
c. The effect of individual operating cost items other than water cost on other operating costs
d. The effect of weighted average irrigation cost and irrigation amount on total water cost
e. The effect of crop water supply and crop water loss on water input efficiency
f. The effect of different types of water sources, including rainfall, irrigation (licensed) and irrigation (traded) on crop water supply.

In the WESM model diagram and Appendix 4.2 (Level 6 and Level 7 of the WESM model), it is shown that most of the measures laid out in Level 6 and 7 of the analysis link to the components (crop water flow components and crop yield) described in the crop process model and other economic factors. As discussed in Chapter 3, these components are driven by crop production activities at the operational level of a crop business and relate to on-farm management decisions.

Furthermore, Appendix A2 (Tables A2 and A3) present a list of WESM input variables – accounting data and crop water process model parameters, respectively. In addition, Appendix A2 (Tables A4 and A5) summarise WESM high-level measures (from Level 1 to Level 5) and WESM low-level measures (Level 6 and Level 7), respectively.

4.5 The link between the crop water process model and the WESM model

This section describes the link between the two models, the crop water process model and the WESM model, incorporating on-farm accounting data. This provides an end-to-end view that allows crop managers and researchers to identify and calculate key water and economic sustainability indicators, which when linked together can contribute to more sustainability-related decision making.

The starting point is the crop water process model which demonstrates the phenomenon being studied in this thesis – a cotton cropping system. As described in Chapter 3, the crop water process model presents the supply of water to the cotton crop from a range of water sources and its partitioning into productive (transpiration) and non-productive water losses. The essential feature of crop production is the transaction enacted by the plant where transpiration is exchanged for carbon assimilation, the primary process which leads to the production of biomass consisting of economic yield – lint and cottonseed – and other dry matter components (Pereira, Green & Villa Nova 2006). In addition, there is a range of operational decisions, as well as the variability of the weather experienced by the crop, that drive the outcome of the crop production (Pereira, Green & Villa Nova 2006).
Key components of the crop water process model, including water sources (rainfall and irrigation), transpiration (T), non-productive water loss (evaporation, deep drainage and

runoff), and biomass yield (lint yield and cotton seed yield)[68], are input to the ratio decomposition model (at the lowest level, i.e. level seven). This provides a logical link between aggregate water and economic sustainability indicators and crop production parameters which capture the phenomenon behind crop production and issues of sustainability of water at the operational level of the crop business. In addition, accounting data, including the selling price of lint and cotton seed, unit irrigation cost and other operating costs, are required to allow the calculation of key water sustainability performance indicators presented in this chapter. Figure 4.2 presents the link between the two models.

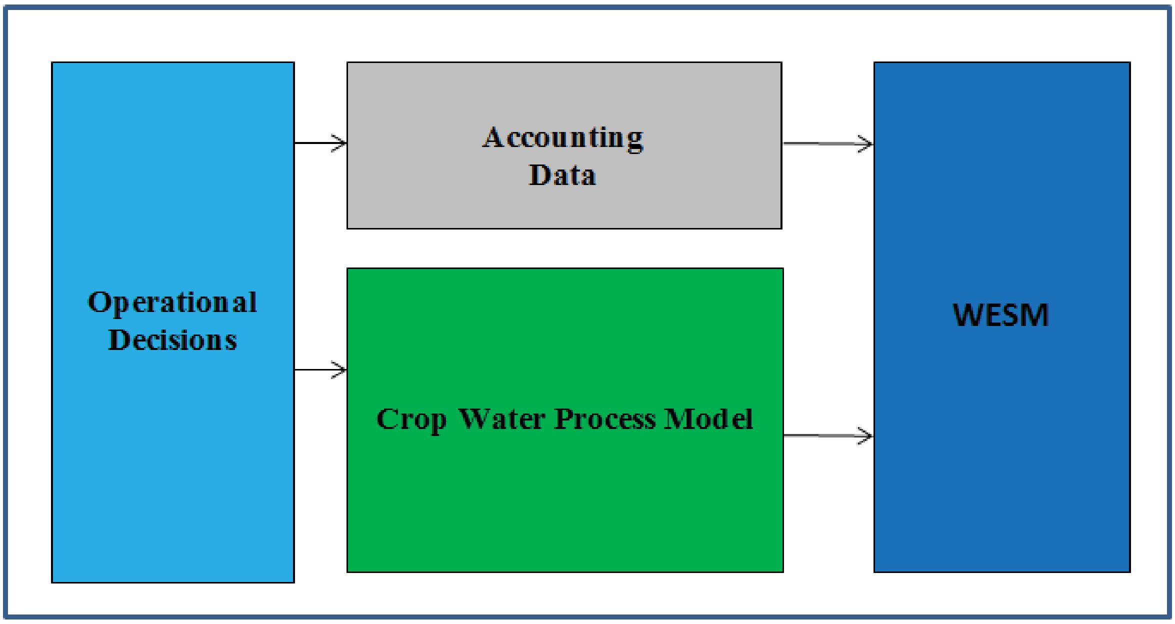

Figure 4.2 The link between the crop water process model and the WESM model

The WESM model designed in this chapter, which is integrated with the crop water process model developed in Chapter 3 and builds upon the decomposition ratio analysis approach, provides a new theoretical construction of EPMS design. By doing that I answer the first component of the research question considered in this thesis.

4.6 Conclusion

In this Chapter, I apply the decomposition ratio analysis technique to the development of the water and economic sustainability performance measurement (WESM model) - a form of

[68] While fibre quality plays an important role in determining economic value of a cotton crop business (Long et al. 2010), the simulation model I use (which I will outline in the methods chapters) DSSAT has not yet simulated fibre quality. Therefore, fibre quality is not included in the studied models.

EPMS that can be used in the context of water and economic sustainability for cotton production in crop agriculture.

The starting point is the summary water sustainability measure, profit to water cost ratio, decomposed into seven levels of analysis. The lowest level directly links to the crop water process model and is driven by on-farm crop management decisions. The development of the water sustainability performance model is motivated by two reasons.

First, extant literature suggests that the issue of sustainability is so complex and abstract that sustainability cannot be understood at the superior level (organisational or industrial level) and/or be captured (explicated) in a single definition. Therefore, there is a need of a framework or model for sustainability measurement which captures the link between sustainability- related activities at the operational level and the sustainability- related performance at the organisational level. Accordingly, the WESM model is designed to enable the theoretical link between the crop output and crop water components (low level measures) that were outlined in Chapter 3 and the aggregate measures (high level measures) to be established to provide useful information as to how decisions- related to water sustainability issues at the crop production level affect the overall economic and water sustainability performance of a crop business.

Second, there is a need to establish the link between some of the high level measures to capture both economic return on crop water supply and irrigation cost and irrigation leverage. This will help to overcome the issue of validity of irrigation measures in extant crop research and provide useful information on which to base irrigation- related decisions. This will allow the logical link between the high level and low level measures to be established, building upon existing knowledge of crop water measurement.

The WESM model, which lays out the key water and economic sustainability measures and describes the theoretical and logical link between the measures, will provide the basis for empirical work (crop simulation modelling) in the later chapters of the thesis. It will also enable demonstration of how to provide more useful information to support agricultural managers' decision making in relation to crop water and economic sustainability.

Chapter 5. Research Method – Crop Production Simulation Modelling

5.1 Introduction

This purpose of this chapter is to explain and justify the research method used to address the study's research question. Section 5.2 starts with an explanation as to why a crop production simulation method is chosen. This explanation includes a discussion of the underlying phenomenon and how alternative research methods make answering the research question posed in relation to this phenomenon difficult. Section 5.3 provides an overview of common crop production simulation models and the rationale behind the selection of the particular simulation model, the Decision Support System for Agrotechnology Transfer (DSSAT), used in this thesis. This is then expanded in Section 5.4 where an explanation of how the selected crop DSSAT is linked to the crop water process model, accounting information, and the water and economic sustainability measurement model (WESM) developed in Chapter 4. Section 5.5 summarises the chapter.

5.2 Method choice

The core research question addressed in this thesis is: *how can Environmental Performance Measurement Systems (EPMS) be designed and used in an agricultural setting to support managers in water and economic sustainability-related decision making and control?* While the first part of this question is addressed in the design of the WESM model, how this is model is used and how decisions around sustainability are made also need to be investigated using an appropriate method. The choice of method to provide answers to this question is going to be largely influenced by the nature of the phenomenon being studied.

5.2.1 The nature of the phenomenon being studied

The research setting being examined in the thesis is crop agriculture. There are a range of factors in crop production that make addressing the above research question a real challenge. Crop production is defined as a process of growing cultivated plants for food, fibre and feed (Henzell 2007) . There are three essential physiological processes involved in crop production; seed germination, seedling establishment and reproductive growth of the plant (Stewart et al. 2010). One of the key features of crop production is that crop output, such as crop yield and crop quality[69], is driven by crop genotypes[70] (*G*), environmental conditions (*E*), and a wide range of management practices (*M*), and the interactions between these (Bange & Constable 2006; Hochman, Holzworth & Hunt 2009; Jones et al. 2003; Keating et al. 2003; Milroy, Bange & Hearn 2004; van Ittersum et al. 2012).

When focusing on environmental conditions that impact cotton production, the key factors are climate, water availability[71], and soil conditions (Jones et al. 2003; Stewart et al. 2010; van Ittersum et al. 2012). These key factors are time and location-specific as they are highly variable across regions and years (Bange & Constable 2006; van Ittersum et al. 2012).

Crop production typically consists of six main production operations, including (i) soil preparation (tillage), (ii) planting, (iii) nutrient and pest management, (iv) irrigation, (v) harvest, and (vi) post-harvest (Chen & Baillie 2009; Khabbaz 2010). Figure 5.1 illustrates the main production processes in an Australian cotton farming system[72]. Each production process involves various management practices and decisions, and the choices between these practices will drive economic and environmental outcomes (Keating et al.(2003) [73]. More specifically, management decisions and practices involved in the irrigation operation are considered as key to determining economic yield and crop quality, and water use efficiency of a crop (Hochman, Holzworth & Hunt 2009; Keating et al. 2003; Stewart et al. 2010; van Ittersum et al. 2012).

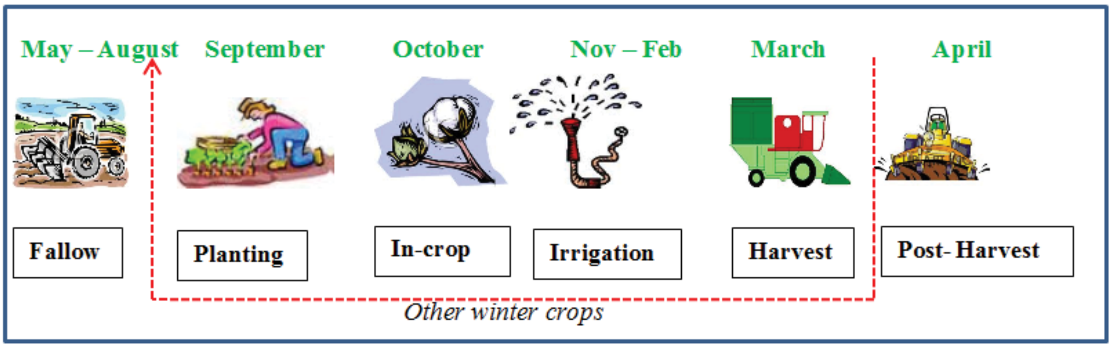

Figure 5.1 Example of six typical cotton production operations in an Australian cotton farming system

[69] For a fibre crop, such as cotton, crop quality is characterised by fibre length, strength, micronaire, colour, purity, uniformity, moisture content and chemical content (Abbott et al. 2010; Long et al. 2010). For grain crop, crop quality is characterized by protein content, grain size (Roer et al. 2012; Zhao et al. 2010).
[70] Genotype is the combination of genes that particular living things carry.
[71] Including rainfall amount and irrigation accessibility
[72] See Appendix B1 for detailed description of the six cotton production operations.
[73] For example, total sales revenue earned from a crop, total water use for a crop, and crop yield produced per unit of water (Cammarano et al. 2012; Naramngam & Tong 2013) .

The relationships between *G* x *E* x *M* interactions and crop output are non-linear relationships. There are two reasons for this. First, many of the physiological processes are non-linear, in the sense that they often exhibit a threshold response where plant performance is unaffected over some range of stimulus and then declines as the range of stimulus extends (Avissar et al. 1985; Forbes & Watson 1992). Crop response to soil water deficit is an example of this. Second, plants exhibit a high degree of homeostasis even in an environment rich in both abiotic and biotic stimuli. Part of the reason for this is the high degree of interdependency among growth processes. As a result, crop production is, by nature, a non-linear and complex process for which simple analytical descriptions are only approximations (Avissar et al. 1985; Forbes & Watson 1992).

As discussed in Chapters 3 and 4, information required from a cropping system for quantifying the summary crop water and economic sustainability measures includes crop water supplied (rainfall and irrigation), productive water (plant transpiration), non-productive water components (such as deep drainage, water runoff, soil evaporation), and economic yield of the crop (for example lint yield and cotton seed yield from cotton production). Due to the nature of crop production described above, the value of these input and output data of a crop production process are variable across regions and years, and dependent on *G* × *E* × *M* interactions. Such variability has important consequences. I argue that it represents the risk to which farmers are exposed, particularly for variation in *E*. Agriculture is much more exposed to the effects of environmental variation than other industries. In agriculture, *E* is also one of the major driving variables and farmers have essentially no control over it. Any valid research method that addresses the above question must accommodate this variation.

5.2.2 Research method alternatives

Given the above context, there are three methods that can be used; field experiments, publicly available data, and crop simulation modelling (Keating et al. 2003; van Ittersum et al. 2012). The advantages and disadvantages of these methods are now discussed, followed by a discussion about why crop simulation modelling method is the most appropriate method to be applied in this thesis.

5.2.2.1 Field experiments

Field experimentation is generally defined as a scientific method applied by researchers to experimentally examine an intervention in the real world as opposed to in the laboratory. In the context of crop production, a field experiment involves the process of replication of crop production operations including soil preparation, planting, fertiliser treatments, irrigation applications and crop harvesting, conducted in a cropping system (Zhang, Walker & Dawes 2002). In addition, in a field experiment, one or more variables or practices is varied in a systematic way while all other factors are held constant. During a field experiment, a range of crop data are collected, including collection of information on plant growth, soils, water and nitrogen (Cassman et al. 2003; van Ittersum et al. 2012; Zhang, Walker & Dawes 2002). The field experiment is of crucial importance in crop exploratory studies (for example, exploring the effect of a new crop variety on crop performance) as well as crop simulation model validation studies (Jones et al. 2003; Keating et al. 2003; van Ittersum et al. 2012).

However, the crop literature has identified a number of limitations of the field experimental method, especially for topics related to the choices of management practices to obtain optimal yield (Hochman, Holzworth & Hunt 2009; van Ittersum et al. 2012) and the effect of various management choices on crop yield, and the economic and environmental outcomes of the crop business (Cammarano et al. 2012; Naramngam & Tong 2013), making it difficult (and sometimes impossible) to generate required crop data in an accurate and valid manner. First, a field experiment is an expensive, time-consuming and labour intensive technique for examining crop yield under a range of choices of management practices (Braunack, Bange & Johnston 2012; Cammarano et al. 2012). Second, field experiments are conducted at particular points in time and space (Jones et al. 2003; van Ittersum et al. 2012). This means crop data and information derived from field experiments is site and season specific. As a result, examinations of crop performance (both economic and environmental performance) are limited by the small number of field trials in terms of soil type, time and space. Third, this method requires well-managed field studies and replications over several years to obtain a robust estimate of average yield (Cassman et al. 2003). Fourth, it is difficult to know for certain if all biotic and abiotic stresses (such as water deficit, nitrogen deficit) are controlled when determining optimal yield in a specific location (van Ittersum et al. 2012). Finally, it is difficult (if not impossible) to quantify one of the key crop water parameters – plant transpiration – using a field experiment approach (Avissar et al. 1985).

5.2.2.2 Historical/ public data collection

Another approach to collecting crop information is from publicly available information. Some economic and environmental information including crop yield, irrigation applications and irrigation cost, crop revenue and operating costs, can be collected from public data sources (e.g. from consulting firms[74] or the crop literature). They include industry reports (Cotton Australia 2008; Samson & Cotton CRC 2009; The Cotton Industry Development and Delivery Team 2012), research papers (Braunack, Bange & Johnston 2012; Cammarano et al. 2012), case studies and conference proceedings (Baillie 2009; Baillie & Chen 2008), and farm data collected from surveys.

While crop data collected from public sources are less expensive, less time-consuming, and less labour intensive compared to field experiment methods, the public data collection approach also has several limitations. First, the data collected are historical data, which means information needed for crop production planning and forecasting is not available. Second, information needed for evaluating the effect of management decision choices on crop economic and environmental performance of a crop business cannot be obtained if such management practices have not been used. For example, studies considering how a crop business can move towards more sustainable decision making from the current state cannot be examined if the proposed more sustainable practices have not been conducted in practice. Third, similar to the field experiment method, information related to plant transpiration, one of the key crop parameters that is used as an input for calculating the crop water use index, is not available from public data sources.

Fourth, while some crop data can be derived from publicly available information, most of them represent averages across regions or for the whole industry (Boyce Chartered Accountants 2012), making it difficult (if not impossible) to examine the relationship between two key crop variables, total water supplied and crop yield. This is because crop production is site-specific, contingent on various environmental factors and *G* x *E* x *M* interactions, resulting in different irrigation applied to and different economic yield produced from different cropping systems. In this respect, averages are not suitable.

[74] For example, Australian cotton comparative analysis crop reports provided by Boyce Chartered Accountants (Boyce Chartered Accountants 2012).

Finally, most of the publicly available crop data provide aggregate information – at the organisational level. This limits examination of the effect of different operational management decisions on crop performance.

5.2.2.3 Crop simulation modelling

The third approach that can be considered to collect crop information is crop simulation modelling. Crop simulation models are generally defined as "*mathematical representations of our current understanding of biophysical crop processes (phenology, carbon assimilation, assimilate partitioning) and of crop responses to environmental factors*" (van Ittersum *et al.* 2012, p.4).

For cotton production studies, crop simulation models (also called cropping system simulation models) have been used since the 1970s with an attempt to simulate fundamental cropping system processes including soil water redistribution, plant transpiration and soil evaporation, nutrient dynamics, crop growth and development (Thorp et al. 2014). To do so, developers of crop simulation models have synthesised the knowledge gained from crop science, laboratory, field, and controlled-environment experiements accumulated over several decades in order to produce computer algorithms that simulate the real world (Thorp et al. 2014). Crop simulation models also need to be validated by comparing simulated results against measured experimental data with various treatments to ensure they can represent the real world (Jones et al. 2003; Keating et al. 2003; Thorp et al. 2014; Wang et al. 2002). Once model developers are confident that the models can provide scientifically defensible results, particularly sound scientific calculations of key parameters of cropping system processes, and simulate the real world adequately, the models can be applied to integrate knowledge about soil, climate, crops and management at any point in time and space (Jones et al. 2003).

The need to develop process-based simulation models for cotton production stems from limited information available from traditional agronomic experiments and public sources of information about agricultural decision making and control (Jones et al. 2003; Thorp et al. 2014). Many of the issues that are facing the cotton industry and cotton crop businesses include issues related to the use of natural resources (such as land, water, energy), environmental and economic risks, profitabilility, and sustainability of practices, can all be better understood and managed by applying process-based cropping system simulation models. They are unlikely to be addressed using field experiments or public data colection methods (Thorp et al. 2014). Furthermore, information needs for environmental and economic sustainability- related decision making and control within the cotton industry are increasingly urgent due to increased pressures on land, water, energy and other natural resources. This impacts on both quantity and costs, making crop simulation models important and powerful tools for manging risks and guiding cotton management and research to make better decisions and move towards sustainability (Cammarano et al. 2012; Jackson et al. 2011; Jones et al. 2003; Thorp et al. 2014).

The simulation modelling method is not only being applied in natural science research but also in accounting research. For example, a body of costing systems, product pricing and capacity planning decisions research applies analytical and simulation[75] modelling methods to address questions that relate to efficiency of various decision rules (i.e. cost-based decision rules), performance of various planning rules (i.e. capacity planning rules), and optimisation decisions (Balachandran, Balakrishnan & Sivaramakrishnan 1997; Balakrishnan & Sivaramakrishnan 2001, 2002; Christensen & Demski 1995; Dhavale 2005; Hansen & Banker 2002; Kaplan & Thompson 1971; Labro & Vanhoucke 2007; Noreen & Burgstahler 1997). Furthermore, compared to the analytical method, the simulation method is an appropriate method when dealing with a complex environment as the complexity of the phenomenon or problem makes it difficult to mathematically compare the performance of the rules (Balachandran, Balakrishnan & Sivaramakrishnan 1997).

5.2.2.4 Crop simulation method as the most appropriate method

Based on the discussion in Section 5.2.1 regarding the nature of the phenomenon being studied, I argue that crop simulation modelling is the most appropriate method to be applied in this thesis.

Compared to field experiments method, computer simulations can perform thousands of scenarios in a short period (i.e. several hours), making crop simulation modelling a less expensive, less-time consuming and less labour-intensive technique to examine the effect of

[75] Balakrishnan and Sivaramakrishnan (2002, p. 24) define that "*To simulate is to attempt to duplicate the features, appearance, and characteristics of a real system. Scientists often use physical models to investigate phenomenon (e.g. airplane wind tunnel simulations). In a similar manner, accounting researchers use computational experiments (with mathematical models) to estimate the effects of various alternatives. The idea behind simulation is to model a situation mathematically, use numerical methods to study its properties, and to draw conclusions and make decisions based on the results of the simulation*".

various management decision choices on economic and environmental performance of a crop business (Cammarano et al. 2012; Jones et al. 2003; Keating et al. 2003; Thorp et al. 2014; van Ittersum et al. 2012).

In order to study long-term performance of a crop business[76], or predict the impact of climate change and local weather conditions on crop performance which can be used to support crop managers in making a wide range of decisions (i.e. asset maintenance, risk management, cost-benefit analysis), it is neccesary to collect crop data and information over long periods of weather data, the primary uncontrolled driver of crop output. As discussed earlier, crop production is subject to uncontrollable variation in input variables, particularly the weather. This means the data required by a manager is stochastic, not only in terms of mean performance under any given set of management conditions, but also the in terms of the variability of the result. Therefore, generating these data from public data is simply not possible. Field experiments are also inadaquate since a sufficient number of experiments must be run to test an adequate range of weather data. Crop simulation modelling allows the researchers do analysis using many yeas of weather data. Preliminary simulations in the experimental section of this thesis demonstrate that a 90-year range of weather data was just sufficient to capture rare events on both tails of the weather distribution. In this respect, estimating the possible outcomes over a hundred years of crop production without simulation modelling may prove exhausting and time consuming (if not impossible). Therefore, valid simulation models provide the most accesible, if not the only, way of providing stochastic data for managers.

Apart from some rare examples, e.g. the Rothamsted l Rotation, long-terrm field experiments are not feasible(Zhang, Walker & Dawes 2002). Apart from cost, the climate itself is now changing and genetic change will also occur in respose to biotic pressure. For example, the evolution of a new strain of disease part way through such a series of field experiments will probably mean that the original genoypes cannot be used for the duration of the study. Using crop model simulation, biotic and abiotic stresses can be captured to allow increased precision in quantification of crop yield and resource use efficiency (Cheeroo-Nayamuth et al. 2000; Grassini, Hall & Mercau 2009; Hochman, Holzworth & Hunt 2009; Lisson et al. 2005; van Ittersum et al. 2012).

[76] By definition, sustainability relates to the concept of long-term performance

Finally, crop simulation modelling is also considered extremely helpful when field experimental data are not available (Keating et al. 2003). For example, plant transpiration, one of the key parameters for water and economic sustainability analysis, can be estimated accurately via well-calibrated and validated simulation models(Hearn 1994; Wells & Hearn 1992).

In summary, crop simulation modelling is the most appropriate method for this research as it overcomes the serious limitations of other methods[77]. However, one of the key challenges of crop production simulation modelling research is selecting good (valid and reliable) models that enable model users to determine meaningful and reliable estimates of several crop parameters and predict the behaviours of the crop system under given conditions for better decision making and control.

5.3 Selection of cotton production simulation model

5.3.1 Overview of cotton production simulation models

The development and application of cotton production simulation models initially began in the US in the 1960s (Thorp et al. 2014) . Building upon a range of crop functions, associated fundamental equations were developed by scientists in an attempt to capture different aspects of cotton growth and development. The GOSSYM simulation model was first developed and used across the US cotton belt in the 1980s to provide guidance about on-farm cotton management (Thorp et al. 2014). Since then, several cotton production simulation models have been developed, continuously refined and applied to major cotton production regions globally, including GOSSYM, Cotton2K, COTCO2, OZCOT and CSM-CROPGRO-Cotton, respectively (Thorp et al. 2014).

The common characteristics of these five cotton simulation models are they are *mechanistic* (describing plant growth and development processes with a significant level of scientific understanding), *dynamic* (including a time dimension in their equations when quantifying crop variables and parameters, such as plant transpiration and plant growth), and *deterministic* (rather than stochastic with probability distribution based-calculations for crop

[77] I recognise that the simulation models are built upon field experiments data and public data. However, the primary method that I use to test the two scenarios in thesis is simulation since it would take a very long time to test my two scenarios using field experiments or case studies.

variables) (Thorp et al. 2014). As process-based models, these models share the same goal of estimating crop output (i.e. crop yield) by simulating plant growth and developmental processes over time (daily or hourly) in response to weather conditions, soil water and other soil characteristics, and crop management actions (Jones et al. 2003; Keating et al. 2003; Thorp et al. 2014). However, simulation approaches for these processes and their associated factors, including phenology, potential carbon assimilation, respiration, partitioning, canopy size, yield components, plant stress factors, and atmospheric and soil processes, vary widely among these models (Jones et al. 2003; Keating et al. 2003; Thorp et al. 2014).

In relation to management impacts on cotton production, the five models mentioned above share several common simulated management practices, including sowing date, cultivar selection, row spacing, plant density, irrigation, fertiliser (except COTCO2), defoliation (except COTCO2), and insect damage. Other management considerations, such as skip rows, crop residue, tillage, growth regulators, disease impact, climate change, cropping sequences, and geospatial analysis, vary among these models (Thorp et al. 2014).

Of the five existing crop production simulation models described above, APSIM-OZCOT model (the OZCOT module embedded in the APSIM system) and CROPGRO-Cotton – DSSAT model (the CROPGRO-Cotton module embedded in the DSSAT system) are widely used in Australia (Keating et al. 2003) and internationally (Jones et al. 2003), respectively. In Section 5.3.2 below, an analysis and evaluation of the two models are performed to provide a theoretical justification as to which cotton production simulation model is the most appropriate model to be used in this thesis.

5.3.2 Comparison and evaluation of APSIM-OZCOT model and CROPGRO-Cotton-DSSAT model

5.3.2.1 APSIM-OZCOT model

The Agricultural Production Systems Simulator (APSIM) cropping system modelling software was developed by the Agricultural Production Systems Research Unit in Australia to simulate biophysical processes of a crop incorporating the dynamics of plant-soil-management interactions (Keating et al. 2003; Wang et al. 2002). The development of APSIM in the 1990s arose from a need for crop modelling tools that "*provided accurate predictions of crop production in relation to climate, genotype, soil and management factors,* *whilst addressing long-term resource management issues in farming systems*" (Keating et al. 2003, p.268).

APSIM is described as a modular modelling framework, providing a range of crop modules for the majority of the grain and fibre crops grown in temperate and tropical areas (Keating et al. 2003). In the context of cotton production simulation, the original cotton plant model, which is named OZCOT, was developed by CSIRO Plant Industry (Wells & Hearn 1992) and embedded into the APSIM framework as a particular module for cotton crop simulation in an Australian setting (Keating et al. 2003). The integration of the plant aspect of the OZCOT model in the generic soil model in APSIM (named SOILWAT) makes it available for cotton crop simulation (Keating et al. 2003; Wang et al. 2002). In this respect, the term APSIM-OZCOT model is used in this thesis referring to the APSIM framework with the OZCOT model for cotton crop simulation.

In preliminary use of the APSIM-OZCOT model, estimation of transpiration was closely observed given its importance in the crop water process model described in Chapter 3. Serious underestimates of transpiration were found (see detailed description in Appendix B2), for which there was no theoretical basis, so the decision was made not to use the APSIM-OZCOT model in this thesis.

5.3.2.2 CROPGRO-Cotton-DSSAT model

The Decision Support System for Agrotechnology Transfer (DSSAT), a software application program comprising crop simulation models for simulating more than 42 crops[78], has been well-recognised and widely-used by researchers, crop managers, growers, consultants and policy makers in over 100 countries (Hoogenboom et al. 2015; Jones et al. 2003; Thorp et al. 2014) . DSSAT was originally developed from the International Benchmark Sites Network for Agrotechnological Transfer (IBSNAT) Project funded by the US Agency for International Development in the period of 1982-1993 (Thorp et al. 2014). The DSSAT system has been continuously developed and redesigned through interdisciplinary research collaboration among scientists worldwide to allow simulation of a wide range of crops and various applications to meet increased information needs for agricultural decision making (Hoogenboom et al. 2015; Jones et al. 2003; Thorp et al. 2014).

[78] As of Version 4.6 released on September 1, 2015

One of the key features of DSSAT is the design of the cropping system model (DSSAT-CSM) with a modular structure (similar to APSIM). The CSM model allows dynamic simulation of soil, plant growth and development, and yield for individual crops, as well as continuous simulation of crop rotations using different crop modules (Jones et al. 2003; Thorp et al. 2014). Also, similar to the APSIM framework, the CROPGRO-Cotton-DSSAT model has a generic structure and uses a daily time step to simulate key underpinning physiological processes in response to climate, soil conditions, and crop management actions (Thorp et al. 2014).

This model was subjected to the same evaluation as that of the APSIM-OZCOT model. The results of the evaluation are set out in Appendix B3. As the results show that there were no estimates of transpiration in conflict with the underlying science, so the conclusion was made that DSSAT provided a more reliable estimate of this key parameter. Consequently this model was selected for this thesis.

5.4 The links between DSSAT, the crop water process model and WESM

In previous chapters (Chapters 3 and 4), the designed WESM integrated with the crop water process model were developed. The discussion of why and how the selected cotton production simulation model – DSSAT model – can be used to simulate the real world (i.e. the crop water process model) to generate information needed for WESM analysis is also provided in the previous sections in this chapter. This section integrates these three models and discusses how they link together.

The scope of the devised WESM covers events from the abstraction of water from the environment to the declaration of a profit from cultivating cotton, with many of the processes between these steps being mediated by biological processes in a managed ecosystem. No single extant simulation model has this scope. Consequently, the WESM model requires that several discrete modules be linked and relevant data passed between them to enable the necessary quantitative links to be established. Figure 5.2 illustrates the links between DSSAT, the crop water process model and WESM.

The DSSAT model plays a role as a cropping system simulator to replicate a real-world cropping system in order to facilitate evaluation of environmental and economic sustainability performance from different crop management practices. As discussed above, crop simulation modelling is a method that mathematically captures biological and physiological processes of crop growth and crop responses to environmental factors and management decisions (Keating et al. 2003; Wang et al. 2002). Therefore, the DSSAT model is applied in this thesis as a mechanism to simulate crop growth and production in response to this range of environmental factors and management decisions. This provides an estimate of crop output (e.g. the key components of the crop water process model) to feed into the WESM model to enable calculations of the aggregate water and economic sustainability performance indicators. The integration of the DSSAT model into the crop water process model and the WESM model enables the process of creating targets, which is the second feature of a cybernetic control.

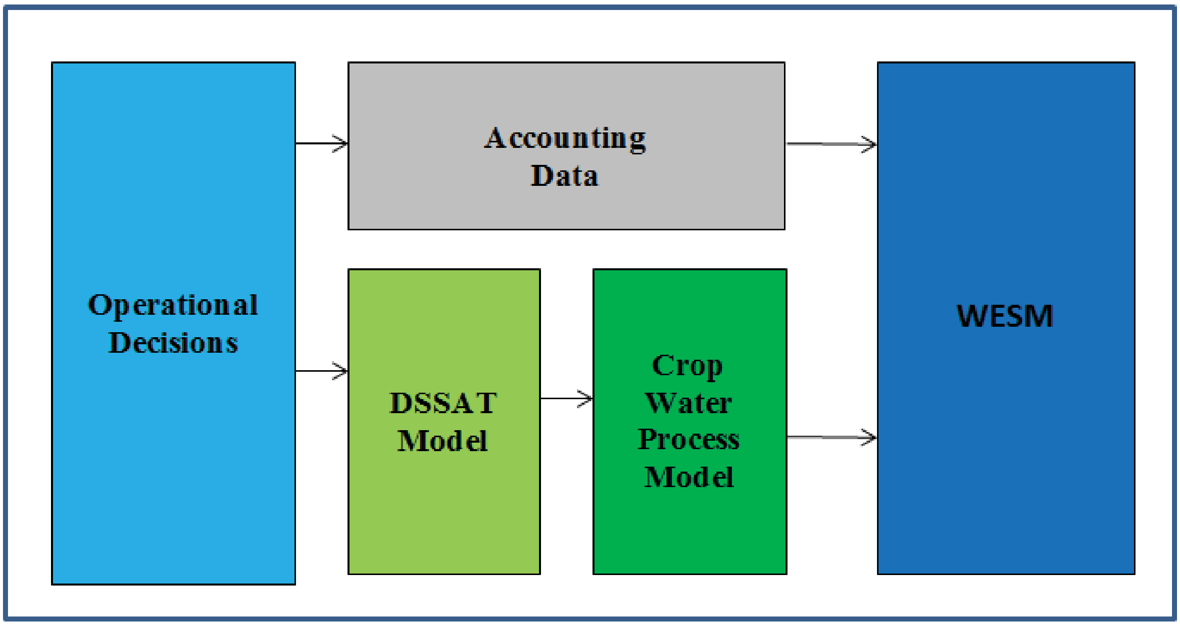

Figure 5.2 The links between DSSAT, the crop water process model and WESM

Greater detail of the links between DSSAT, the crop water process model and WESM are shown in Figure 5.3. A key feature not readily illustrated in each of these figures is the exposure of agricultural process to the weather. Temperature, for example, not only directly influences water flow processes but also influences plant growth which also control key steps in the flow. Fluctuations in temperature occur in short timeframes and repeat sequences are rare. The same considerations apply to other weather parameters. Such variation in key driving variables underpins the high levels of risk and uncertainty associated with agriculture.

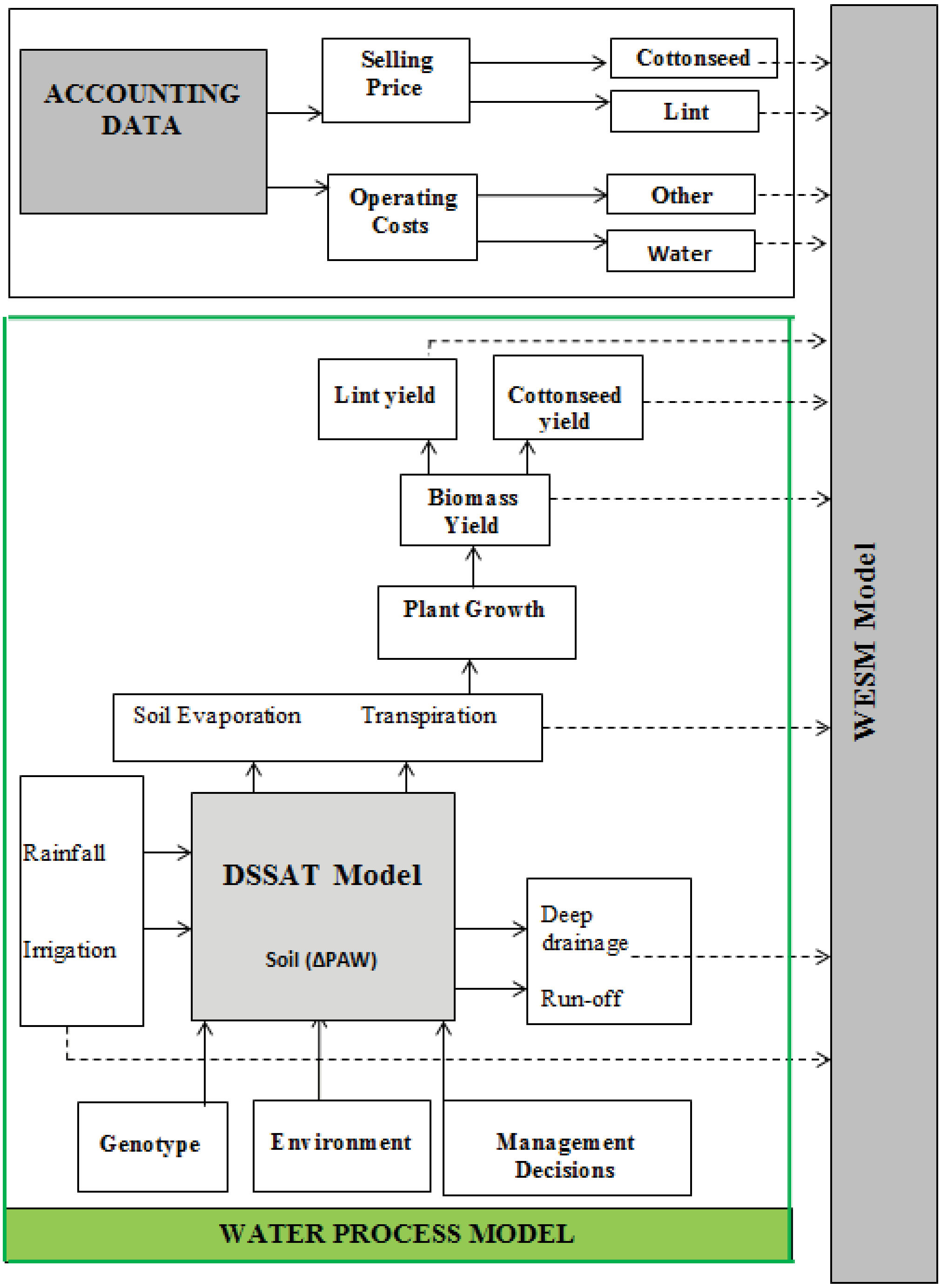

Figure 5.3 Detailed links between DSSAT, the crop water process model and WESM

DSSAT integrates this variable input data into the parameters that determine, for each season, the volume of water abstracted from the environment and the mass of saleable product generated. Consequently, it occupies a key role in the WESM, for which no real substitutes exist (Figure 5.4).

Figure 5.4 describes the key input data required for and output data resulting from cotton simulation modelling with the DSSAT model. These key crop parameters, which are driven by various management practices (given a specific crop variety, at a particular location and in a particular season), will be passed to the WESM model for environmental and economic sustainability analysis.

Another key feature not evident in Figures 5.2, 5.3 and 5.4 is the alignment of scales between models. The final summation is performed on unit area (hectare) and for a single season, symbolised by year of harvest. Input data are not necessarily provided at these scales (e.g. rainfall in mm, radiation in rad/m^2, temperature in average per day) and much of the scale alignment on which the WESM depends, is performed within DSSAT.

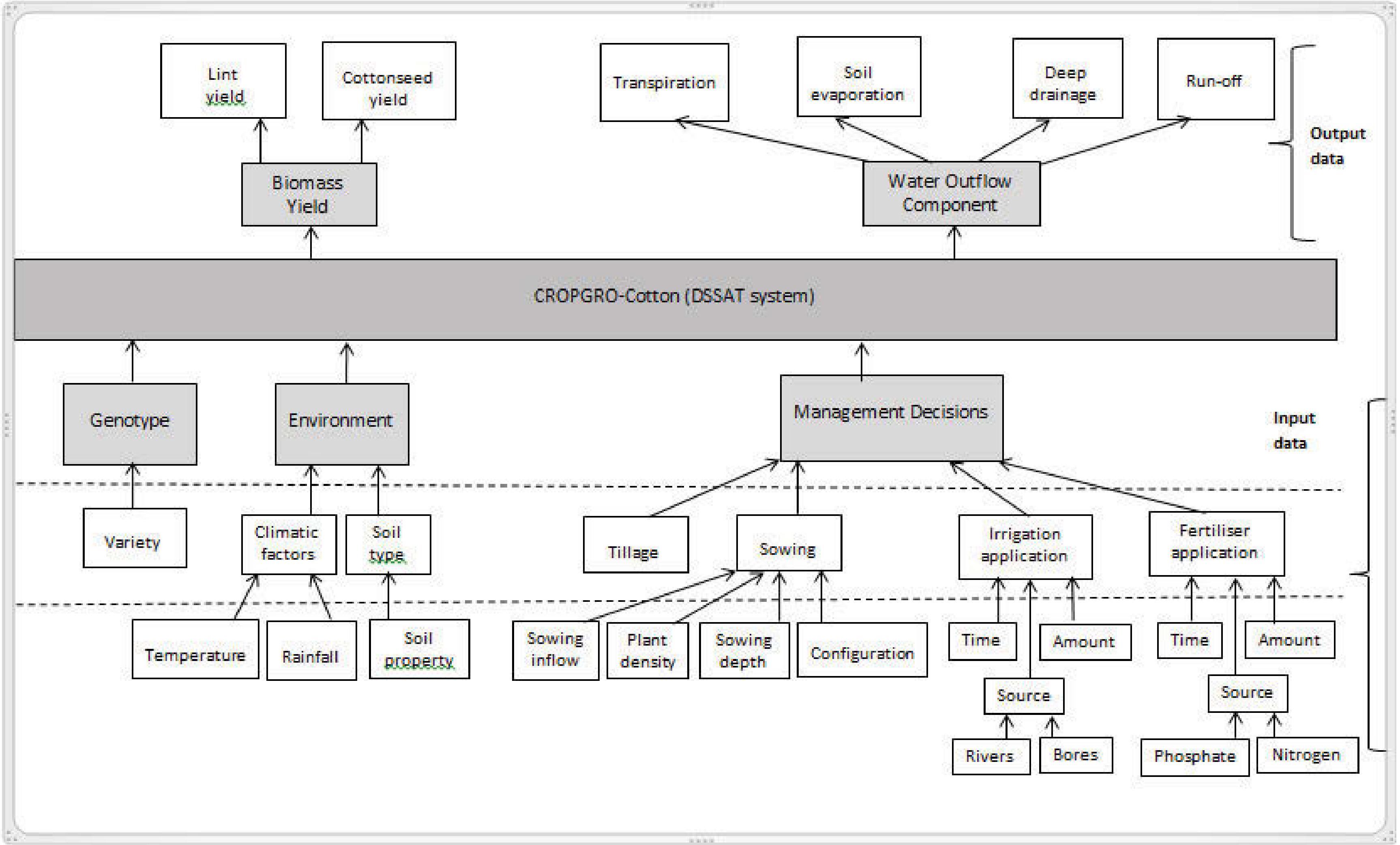

Figure 5.4 Description of input and output data of DSSAT model

5.5 Conclusion

This chapter outlines the research method applied in this thesis. The crop production simulation modelling is argued to be the most appropriate method to address the research question considered in this thesis. More specifically, the DSSAT model is selected as the most appropriate crop simulation model since it is well-recognised and widely-used by researchers worldwide. The model is proven to generate valid and reliable crop information which can facilitate the evaluation of water and economic sustainability performance of a crop business from various crop management decision choices.

The integration of the DSSAT model into the crop water process model and WESM model, incorporated with accounting data, enables the process of creating targets, which is the second feature of a cybernetic control. This will benefit cotton growers in a number of ways; to provide growers the ability to access simulations of different scenarios of cotton production to analyse and improve on-farm decision making and control for environmental and economic crop management, asset maintenance, and cost benefit analysis.

Building on Chapter 5, in Chapter 6, a furrow irrigation system is selected as an irrigation method applied in this thesis to examine the second component of the research question, how the designed EPMS can be *used* in an agricultural setting to support managers in water and economic sustainability-related decision making and control. To do this, the crop production simulation model (DSSAT) will be incorporated into a furrow irrigation simulation model. This will enable capture of a more comprehensive picture of a real-world cropping system, and hence, generation of more accurate and higher quality information under various scenarios of G x E x M conditions and over a long period of time to support belter sustainability-related decision making and control.

Chapter 6. Experimental Design for Furrow Irrigation Simulation

6.1 Introduction

The second part of the thesis focuses on the second component of the research question, which is how the designed WESM can be *used* in an agricultural setting to support managers in water and economic sustainability-related decision making and control.

Section 6.2 starts with an explanation of furrow irrigation systems and practices. Furrow irrigation systems are currently the most common irrigation systems used in cotton production making it an appropriate empirical example. In Section 6.3 I address some limitations of the DSSAT model in simulating cotton production systems with furrow irrigation management practices. This identifies the need for incorporating a furrow irrigation simulation model – SIRMOD – into the DSSAT model. Consequently, I build a two-phased crop simulation model which enables us to capture of a more comprehensive picture of a real-world cropping system, and provides more accurate and valid crop information.

Sections 6.4 and 6.5 describes the details and rationale for an experimental design of the two cropping system scenarios using a current furrow irrigation practice (Scenario 1) and an improved furrow irrigation practice (Scenario 2), respectively. Results of furrow irrigation and crop simulation modelling are also presented in these sections.

The final section (Section 6.6) summarises the chapter, including how the designed two-phased simulation modelling allows the generation of more accurate and reliable crop information. This enables analysis and evaluation of crop sustainability performance from the analysis which will be outlined in Chapters 7 and 8. Overall this provides an empirical example demonstrating how the WESM designed in this thesis can be used to support crop managers in more sustainable decision making and control.

6.2 Furrow irrigation systems: research and practice

6.2.1 Overview of furrow irrigation systems

It is estimated that around 85% of Australian cotton crops are irrigated (Cammarano et al. 2012; Jackson, Khan & Hafeez 2010). There are three main types of irrigation systems that are being used in cotton cultivation, furrow irrigation, subsurface (drip) irrigation systems, and lateral move (centre pivot) irrigation systems (Chen & Baillie 2009; Jackson, Khan & Hafeez 2010; Khabbaz 2010). Of those three irrigation systems, furrow irrigation systems are currently the most common method for irrigated cotton production (Smith, Raine & Minkevich 2005; Walker 2003). Figure 6.1 provides an example of furrow irrigation systems applied in an Australian cotton farm.

Figure 6.1 An example of furrow irrigation systems in a cotton farm (Source: Khabbaz 2010)

As illustrated in Figure 6.1, a furrow irrigation system works by simply supplying water from a head ditch, which is filled with water from a bore, river or storage with a pump, into the furrows where water is distributed over the field by gravity flow (Walker 2003). More specifically, furrow irrigation systems applied in Australian cotton regions, which are mostly characterised by cracking clay soils, are typically designed with relatively long furrows, low flow rates, and long irrigation application time (or cut-off time) (Smith, Raine & Minkevich 2005). As a gravity-fed irrigation system, one of the key advantages of the furrow irrigation system is that it requires less energy compared to other pressurised irrigation systems such as subsurface irrigation systems[79] or lateral move irrigation systems[80] which require increased head pressure to operate (Khabbaz 2010). Furthermore, capital investment in furrow irrigation systems is currently much lower than the other two irrigation systems.

However, compared to modern irrigation systems like subsurface irrigation and lateral move irrigation systems, the traditional furrow irrigation systems are considered the least efficient with respect to water use (Jackson, Khan & Hafeez 2010). While it was assumed for a long time within the Australian cotton industry that furrow irrigation systems on clay soils only resulted in a small amount of deep drainage, and hence these systems were relatively water use efficient, recent research has proven that these assumptions are invalid (Jackson, Khan & Hafeez 2010; Smith, Raine & Minkevich 2005) . One of the major problems of furrow irrigation systems that have been addressed in recent research is that there is substantial water loss from furrow irrigation to deep drainage (i.e. in average 42.5 mm per irrigation event or 2.5 ML per ha), leading to low irrigation application efficiency[81] (as low as 50%) (Smith, Raine & Minkevich 2005). This results in two problems. First, the environmental issues of deep drainage under irrigated crops leading to serious soil degradation and salinity. Second, the economic costs arising from the loss of an economic resource (water). The costs are two fold, (i) the direct cost of water, and (ii) lost opportunity costs of producing more crops (where the amount of water available to the farmer is capped or subject to a step-cost function).

[79] See Appendix C.1 for an example of subsurface (drip) irrigation systems.
[80] See Appendix C.2 for an example of lateral move and centre pivot irrigation systems.
[81] Irrigation application efficiency is defined as "*the depth or volume of water added to the root zone store expressed as a ratio of the depth or volume of water applied to the field*" (Smith, Raine & Minkevich 2015, p.118).

6.2.2 The effect of furrow irrigation practices

One way to improve water use efficiency in irrigated cotton production is shifting from furrow irrigation systems to more efficient irrigation systems, such as subsurface irrigation or lateral move irrigation systems which are proven to offer significant water savings from irrigation of up to 2.2ML/ha (Pratt Water 2004). Despite significant reduction in water application of modern irrigation systems, they have not yet been used widely in practice but may be feasible if the cost of water becomes higher than the cost of the investment. Another way to reduce the amount of deep drainage and improve water use efficiency in furrow irrigation systems is refining the design of furrow irrigation systems to improve their efficiency and/or changing furrow irrigation practices of cotton businesses.

Smith, Raine & Minkevich (2005) studied the effect of 79 furrow irrigation events on a range of soils under a range of irrigation management conditions (such as flow rate, time to cut-off, furrow length, soil moisture deficit) on crop irrigation performance. The study applied the surface irrigation model SIRMOD for each irirgation event. It was empirically shown that given soil conditions (type, hydraulic properties/texture/clay content, moisture deficit) and furrow chararcteristics (furrow length and slope), flow rates and irrigation time are the two key driving factors that influence the maginitude of deep drainage and irrigation application efficiency (Smith, Raine & Minkevich 2005). While the Smith, Raine & Minkevich (2005) study recognised the role of irrigation management in controlling the depth of deep drainage, and demonstrates the possibility of significant improvements in irrigation performance by the application of more advanced irrigation management practices (through the optimisation of the flow rate and irrigation time for a particular soil type and furrow design), it does not provide an end to end connection between irrigation management practices and water resource utilisation and crop profitability.

6.3 Water and crop production simulation modelling design: Two-phased crop simulation modelling

6.3.1 Limitations of DSSAT model in simulating furrow irrigated crop production

As discussed in Chapter 5, the DSSAT model can be used to simulate biophysical process of a cotton crop under the dynamics of plant-soil-management. However, there are two limitations of DSSAT in simulating furrow irrigated crop production which prevent the model from generating accurate crop water and yield components for a field.

The first limitation is that the DSSAT model treats the entire furrow as a single point. This means field characteristics, including field length, which are evident as driving factors of irrigation performance, are not captured in the crop simulation. More importantly, while water distributed through the surface of the land (infiltration) varies along the furrow, leading to the potential for variance in yield and fibre quality among different points of the furrow, this is not captured in DSSAT and a single yield value is generated.

The second limitation is that, because DSSAT does not itself calculate infiltration in a rigorous way, the effect of furrow irrigation on rewetting the soil profile and generating runoff is not reliable[82]. For these reasons, when using DSSAT as a stand-alone model to simulate the effect of irrigation strategies and/or management practices on irrigation performance, that DSSAT isn't sensitive enough to recognise differences in some irrigation strategies. Accordingly, DSSAT users will face the validity issue with crop data generation (inaccurate irrigation water outflow components and hence crop yield).

However, a solution is available. DSSAT is a modular system and many of the current modules may have begun as stand-alone models which were gradually incorporated into the DSSAT code. In this thesis, I propose to simulate the furrow irrigation event separately and manually transferring the necessary data to DSSAT as input data to its routines – thereby creating an additional module. This is essentially what existing modules do internally within DSSAT.

There are three stages to this. First, I simulate the irrigation event. Second, I simulate the crop response to the event. Finally, I aggregate results and account, at the field scale, for all water inputs and losses, and crop outputs.

[82] More specifically, the DSSAT model only simulates the movement of irrigation water applied to the field under the soil surface, from the first layer of the soil profile to the root zone area, not along the furrow. This means the DSSAT model can only capture the vertical dimension of water movement but not the horizontal dimension. Therefore, given irrigation water inflow, DSSAT cannot simulate how much irrigation water will go through the surface of the soil and how much irrigation water will go out of the system as runoff. Typically, DSSAT users will make an assumption of how much infiltration water and how much runoff there is given the amount of irrigation applied to the field. Furthermore, two different irrigation strategies, having different irrigation input conditions (for example, inflow rate and cut-off time), can lead to the same irrigation in the model. While it is evident that changing inflow rates and cut-off-times affect the magnitude and variation of infiltration along the furrow, the amount of runoff from irrigation, as well as deep drainage (Smith 2005), the DSSAT model itself does not capture this and will generate the same yield figure given a particular irrigation application. Consequently, DSSAT does not recognize the role of irrigation management/strategies in determining or controlling the irrigation performance of a crop.

6.3.2 Simulating a furrow irrigation event

6.3.2.1 Characteristics of furrow irrigation

In furrow irrigation, water is applied to the soil in the furrow at the upslope end. The water begins to infiltrate into the soil. Assuming that the application (or inflow) rate is greater than the infiltration rate of the initial soil surface, there will be excess water which will run, under gravity, along the furrow to initiate infiltration at the adjacent downslope soil surface. This process effectively repeats until the aggregate infiltration rate of the wetted soil equals the application rate. The advancing water front may not have reached very far down the furrow at this point.

Infiltration at any point along the wetted surface is initially rapid for the dry soil but the rate of infiltration declines with time as the soil wets, so that the furrow system, as described above, is never in equilibrium. As infiltration in the first wetted soil slows, a water excess is created in the furrow which causes the water front to advance further down the furrow. Eventually, the advancing water front reaches the furrow end and runoff begins.

For each irrigation event, the relationship between water inflow (irrigation applied) and water outflow (infiltration and runoff from irrigation) can be expressed as follow.

$$\begin{aligned} &\text{Irrigation applied per event}_{\text{it}}\left(\frac{\text{ML per event}}{\text{ha}}\right) \\ &\quad = \text{Irrigation infiltrated per event}_{\text{it}}\left(\frac{\text{ML per event}}{\text{ha}}\right) \\ &\quad + \text{Runoff from irrigation per event}_{\text{it}}\left(\frac{\text{ML per event}}{\text{ha}}\right) \end{aligned} \qquad [6.1]$$

Furrow irrigation therefore has a number of characteristics which may lead to suboptimal performance. First, wetting is sequential along the furrow with the rate of advance depending, inter alia, on the application rate. Second, soil at the upslope end of the furrow is able to infiltrate for a longer time than soil at the downslope end. Even though the infiltration rate declines with time, the general result is that more water infiltrates into the upslope soil than the downslope soil, resulting in the variable infiltration with furrow distance shown in Figure 6.2.

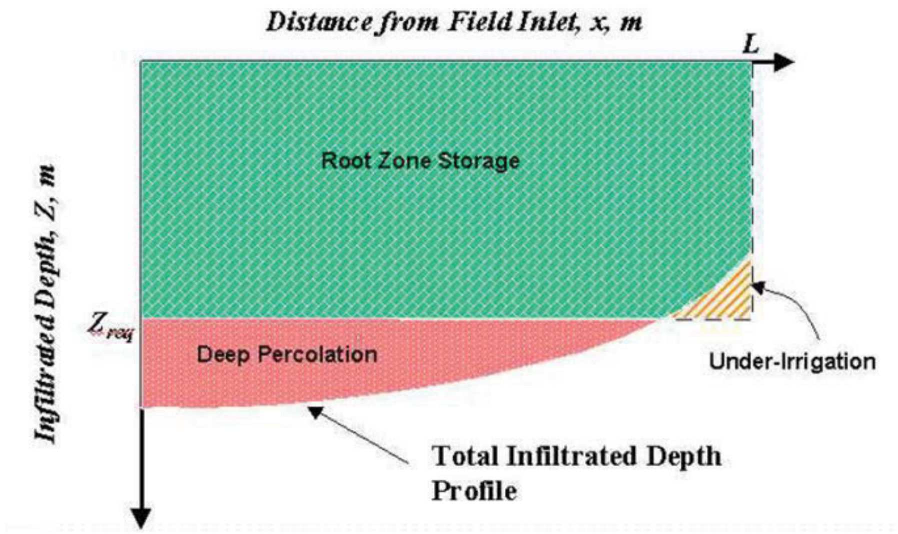

Figure 6.2 Infiltrated depth profile under furrow irrigation (Source: Walker 2003)

Irrigation management with furrow irrigation is therefore something of a compromise. If water is allowed to run in the furrow long enough (by adjusting irrigation time or cut-off time) that soil at the downslope end is adequately rewet, then excess water will have been applied at the upslope end. This will result in deep drainage from that part of the field. Alternatively, inadequate water supplied to the downslope crop area may result in crop water deficit, and hence poor crop growth there.

6.3.2.2 Furrow irrigation simulation modelling

A well-recognised model for simulating furrow irrigation is SIRMOD, which has been used to simulate the hydraulics of surface[83] irrigation systems at the field level (Gillies 2008; Gillies & Smith 2005; Smith, Raine & Minkevich 2005; Walker 2003). One of the key features of SIRMOD is its simulation of the irrigation event along the furrow, estimating depth of water infiltrated at each point of the furrow and aggregate runoff from the furrow end (see Figure 6.2).

Three key inputs of SIRMOD are field topography and geometry (field length and slope), inflow controls (inflow, time of cut-off) and infiltration characteristics (infiltration

[83] The term 'surface irrigation' represents a broad category of irrigation methods, including basin irrigation, border irrigation and furrow irrigation, in which water spreads over the field due to gravity and the slope of the field. As explained earlier, I focus on the furrow irrigation method, which is the most common surface method used in practice.

coefficients which are driven by soil characteristics)(Walker 2003). Based on these input parameters, SIRMOD simulates the hydraulics of the furrow irrigation system and reports water outflow components (infiltration, runoff) and irrigation performance (distribution uniformity, tailwater fraction) (Walker 2003).

SIRMOD can be applied in crop water management research and practice for identifying optimal irrigation strategies that would lead to improvements in irrigation efficiency and reductions in deep drainage losses (Smith, Raine & Minkevich 2005; Walker 2003). The applications include studies of the effect of changes of characteristics of the furrow system (furrow characteristics, soil properties) and the effect of changes of input conditions of an irrigation event (inflow controls and cut-off time) on irrigation performance of the system. Extant research shows evidence that changing these factors can lead to improvements in furrow irrigation performance (Gillies & Smith 2005; Smith, Raine & Minkevich 2005; Walker 2003). While factors that are related to soil type and soil properties, and physical characteristics of the furrow (length, slope, cross-section shape), are not easy to change in the short-term, factors that are related to irrigation management at the operational level, including inflow and irrigation time (or time to cut-off), can be changed in the short-term by crop managers to increase irrigation efficiency and reduce water loss due to deep drainage.

6.3.2.3 Design for simulation of a furrow irrigation event

As discussed above, three key inputs of SIRMOD are field topography and geometry, inflow controls, and infiltration characteristics. In this thesis, only one cropped field with one soil type is examined. Accordingly, input parameters associated with field topography, and geometry and infiltration characteristics, remain constant and are presented in Table 6.1 below. In Sections 6.4 and 6.5, two cropping system scenarios using two different sets of inflow controls, representing two different furrow irrigation management practices/strategies, will be discussed.

SIRMOD was run for a single irrigation event, assuming that all events would be the same, on the same soil type with the same inflow. Data[84] transferred to DSSAT and WESM were as follows. First, for each 10 metre length of furrow, average infiltration was calculated and passed to DSSAT as irrigation water infiltrated at that point. Second, runoff data was passed

[84] Water and crop parameters in SIRMOD and DSSAT are presented on a per ha basis.

to the WESM to be included with runoff from rainfall simulated by DSSAT as an input for calculating volume of recycled runoff.

Table 6.1 SIRMOD Input: Field and infiltration characteristics

Field Topography and geometry[85]		Infiltration Characteristics (clay vertosol)[86]	
Field length, m	710.00	a	0.238000
Field width, m	800.00	K, $m^3/m/mn^a$	0.018180
Furrow spacing, m	2.00	Fo, $m^3/m/mn$	0.000120
Slope of the field	0.08	C, m^3/m	0.000000

6.3.3 Simulating crop response to furrow irrigation

6.3.3.1 Design for simulation of crop response to furrow irrigation

As discussed in Section 6.3.1, SIRMOD can simulate the movement of irrigation water applied to the field (inflow) in both vertical and horizontal dimensions simultaneously. However, for the vertical movement of water, SIRMOD can only simulate the total amount of irrigation water going down through the first layer of the soil (infiltration) but not how much water will go through each layer of the soil profile, how much water will stay in the root zone, or how much water will go beyond the root zone (deep drainage). In contrast, the DSSAT model can simulate, given the total amount of infiltration, how water is distributed through several layers of the soil profile and how water is used by the root zone for carbon assimilation.

Therefore, I integrate the SIRMOD irrigation modelling software with the DSSAT crop production modelling software. This provides a more comprehensive picture of the hydraulics of furrow irrigation systems and overcome a validity issue of the DSSAT model by generating more accurate crop output data (crop yield and crop water components).

Furthermore, as crop water supplied by irrigation, the amount of water infiltrating the soil, varies with distance along the furrow, it follows that crop response should also vary.

[85] J. Purcell, Aqua-Tec Consulting (http://www.aquatechconsulting.com.au/jim-purcell.htm), personal communication, 2015.
[86] Details of this soil type and its properties will be discussed in Section 6.3.3.2.

Accordingly, the furrow was considered to consist of 71 x 10 metre length or 72 furrow points. For each of these, irrigation infiltration for each furrow point was calculated by SIRMOD. Rainfall was assumed to be constant across each length.

DSSAT was then run, in parallel, 72 times to generate a total yield (lint yield and cotton seed yield), transpiration, soil evaporation and deep drainage profile along the furrow, with 72 data points for each parameter, for each year of weather records. This was considered to be a more valid and accurate simulation of crop response than simply using, in a single annual simulation, the average infiltration amount, as it could respond to nonlinearities in crop response to crop water supply. A simple average would not do this.

In addition, in reality, these furrow points should share the same planting date, irrigation dates and harvest date. In order to capture this realism, there are two steps were considered. First, a particular furrow point[87] was selected to allow DSSAT to simulate planting dates, irrigation dates and harvest dates over 86 years of weather records, based on the management rules described in Table 6.2. Second, DSSAT was run, in parallel, 72 times using the fixed planting dates, irrigation dates and harvest dates determined in step 1.

6.3.3.2 DSSAT Setup

This section provides a brief description of DSSAT setup with respect to choices of cotton location, soil type, cultivar and crop management practices (i.e. scheduling planting, irrigation, nitrogen application and harvest). Details of DSSAT setup is shown on Table 6.2.

Cotton simulation were performed using CROPGRO-Coon model in DSSAT 4.6 (Hoogenboom et al. 2015).

[87] In this thesis, I selected furrow point 24, which is 240 metres from the top end of the furrow, 1/3 of the furrow length, for doing step 1. Future research could select other furrow points, for example the furrow points in the middle or at 2/3 of the furrow length in the process of finding planting, irrigation and harvest dates and examine a better strategy to gain improved output of the crop as a whole.

Table 6.2 DSSAT set up

Soil	Soil type	Vertosol
	Surface texture	Clay
	Depth, cm	180
Cultivar	Crop	Cotton
	Cultivar type	Deltapine 555 B
Planting rule		
Sowing window	Start date	1st October
	End date	30th November
Soil temperature for planting	Maximum soil temperature, ^{0}C	40
	Minimum soil temperature, ^{0}C	10
Soil water for planting	Soil depth, cm	20
	Lower soil water percentage, %	40
	Upper soil water percentage, %	100
Planting management	Planting method	Dry seed
	Planting distribution	Rows
	Planting population at seeding	12 plants/m^2
	Row spacing, cm	100
	Plant depth, cm	5
Fertiliser management	Fertiliser material	Urea
	Fertiliser application method	Bended beneath surface
	Soil depth, cm	60
First fertiliser application	Date	On planting date
	Amount, kg N/ha	250
Second fertiliser application	Date	60 days after planting date
	Amount, kg N/ha	50 kg
Irrigation management	Irrigation option	Fixed amount applied
	Management depth	40 cm
	Threshold, % of max available	60
	Method	Furrow
	End of application	GS009 (50% of bolls have attained 0.5 final size)
Harvest management	Harvest option	At maturity

Daily weather data used as an input to the model were recorded at the Myall Vale Weather Station, New South Wales, Australia (30^{0}200'S, 149^{0}600'E) by the Australian Bureau of Meteorology (wwww.longpaddock.qld.gov.au/silo/) for the period 1924–2014[88]. Weather data comprised rainfall (mm day^{-1}), maximum and minimum air temperature (^{o}C), and solar radiation (MJm^{-2}day^{-1}).

Clay Vertosol[89] is selected. Details of soil properties are provided in Appendix C –Table C1.

Deltapine 555 B cultivar was selected. This is a US cultivar available in DSSAT, which has similar characteristics of Bollgard II cultivars, the most common cultivar used in the Australian cotton industry (more than 90%) (Braunack, Bange & Johnston 2012).

Cotton was planted 0.05 m deep in 1 m rows with a plant density of 12 plants (Braunack, Bange & Johnston 2012).

Nitrogen was applied two times during a crop season; 250 kg N/ha on the planting date and an additional 50kgN/ha 60 days after planting. The way the nitrogen management was set up in this thesis also ensures that cotton was not nitrogen stressed at any point during the growing season (D. Johnston, CSIRO Agriculture[90], personal communication, 2015).

The furrow irrigation scheduling was constructed based on the irrigation rule of refilling the soil profile when 40% of the plant-available water (PAW) was depleted. The way the furrow irrigation was set up in the scenarios modelled ensures that cotton was not water stressed at any point during the growing season[91].

When the threshold of 60% was reached, 72 different irrigation depths (infiltration amount, mm) generated by SIRMOD were applied for each furrow point for each crop season; this

[88] 90 cotton crop-year observations were obtained, from1924-1925 cotton crop year to 2013 - 2014 cotton crop year.
[89] The soil information was obtained from https://researchdata.ands.org.au/south-eastern-australia-vertosol-partical-size-dirtibution/155154.
[90] CSIRO Agriculture Flagship, Locked Bag 59, Narrabri NSW 2390 michael.bange@csiro.au, david.b.johnston@csiro.au, michael.braunack@csiro.au
[91] In Australia, a cotton growing season is typically from September to June, depending on cotton locations(Braunack, Bange & Johnston 2012).

provided 6,192 simulations run under DSSAT (86[92] crop years x 72 irrigation furrow points). In the next section (Section 6.3.4), I will discuss how simulated data from DSSAT are aggregated and passed to the WESM model.

The DSSAT model used simulated phenology to estimate harvest date. For each crop season, daily values of each of key crop parameters (i.e. rainfall, transpiration, soil evaporation, deep drainage, runoff from rainfall, total yield) were cumulated from the planting date to the harvest date.

6.3.4 Data aggregation

The data aggregation and passing of parameter values to the WESM model followed the paths described in Figure 6.3. A statistical software package (STATA)[93] was used to aggregate and pass data from SIRMOD and DSSAT to WESM. Values averaged over 72 stations were passed to WESM and included economic yield, soil evaporation, transpiration and deep drainage. Irrigation was calculated for WESM as average infiltration plus runoff from irrigation, estimated by SIRMOD. Runoff from rainfall, which is calculated within DSSAT, does not consider slope length and is considered the same across the furrow. Therefore, runoff from rainfall was taken into WESM from the last station in the furrow.

Preliminary simulations showed that the irrigation events did not induce deep drainage themselves. Rain, followed closely by an irrigation event might, however, exhibit more deep drainage as a result of an initially wet soil profile.

[92] DSSAT results show that of 90 crop-year runs there are four years (1928, 1940, 1945 and 2002) which had no crop production due to severe drought.
[93] StataCorp. 2015. *Stata Statistical Software: Release 14*. College Station, TX: StataCorp LP.

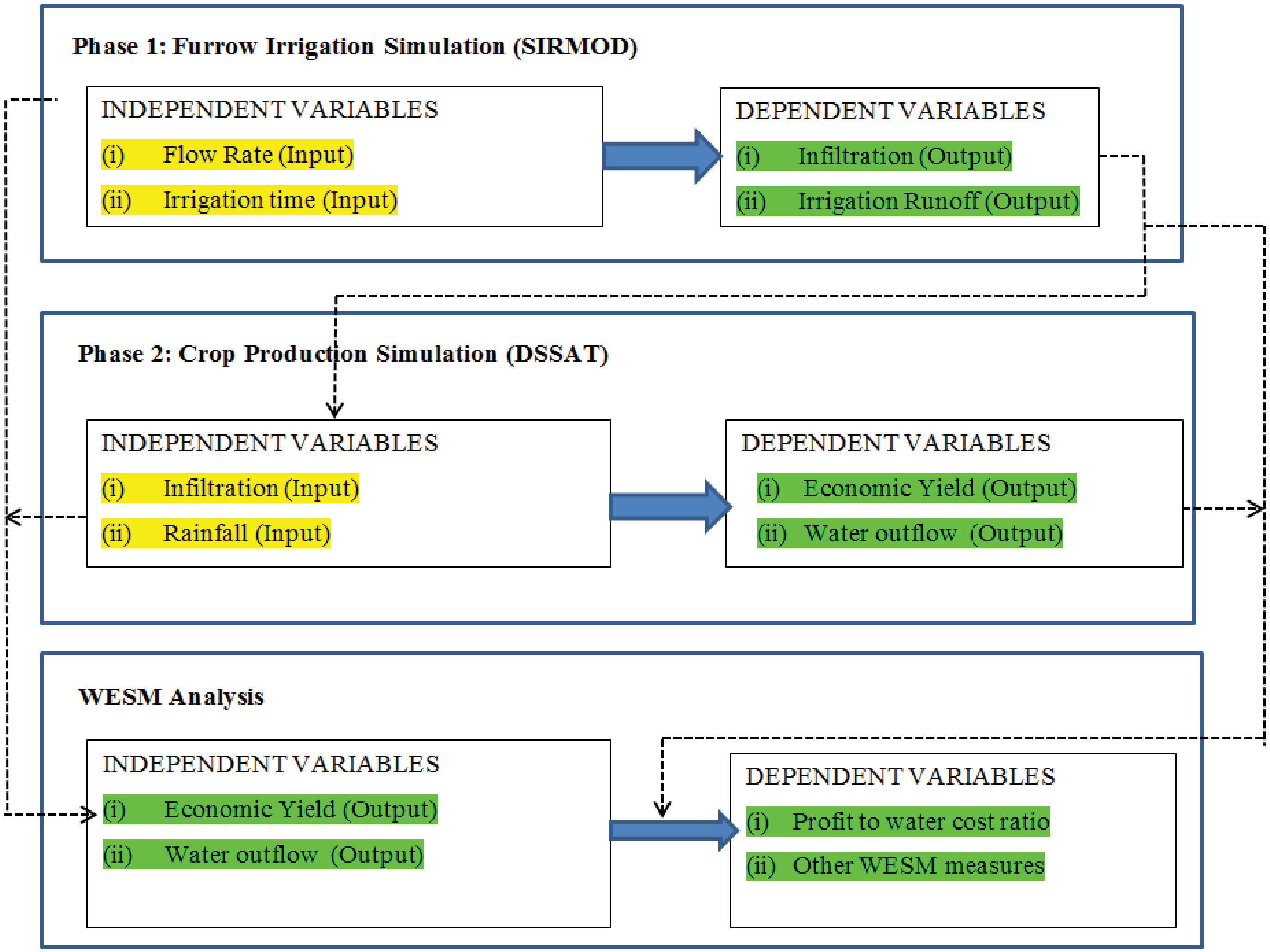

Figure 6.3 The link between key water and crop parameters between the two phased-crop simulation process and WESM

6.3.5 Water balance of a cropping system

As discussed in Section 6.2.3, SIRMOD can simulate the movement of irrigation water applied to the field (inflow) in both the vertical dimension and horizontal dimension simultaneously. However, for the vertical movement of water, SIRMOD can only simulate the total amount of irrigation water going down through the first layer of the soil (infiltration) but not how much water will go through each layer of the soil profile, how much water will stay in the root zone, and how much water will go beyond the root zone (deep drainage). In contrast, the DSSAT model can simulate, given the total amount of infiltration, how water is distributed through several layers of the soil profile and how water is used by the root zone for carbon assimilation. Therefore, in this thesis, I will integrate the SIRMOD irrigation modelling software with the DSSAT crop production modelling software to provide a more comprehensive picture of the hydraulics of furrow irrigation systems. This overcomes the validity issue of the DSSAT model by generating more valid/accurate crop output data (crop yield and crop water components). By doing this, I will provide more valid, useful and reliable information that can support Australian crop managers in better water and economic sustainability decision making.

6.3.5.1 Water balance under the SIRMOD system

The model starts by considering the field and the water crossing that boundary for an irrigation event. When we consider water crossing that boundary for an irrigation event at the field level, for each irrigation event, SIRMOD provides three simulated parameters; irrigation applied to the upslope end of the furrow (water inflow, in ML), irrigation infiltrated (infiltration, in mm) at any point along the furrow, and runoff from irrigation at the downslope end of the furrow (in ML/ha). Based on the mass balance, water inflow to the system should be equal to water outflow of the system.[94]

$$\text{Irrigation applied per event}_{it}\left(\frac{\text{ML per event}}{\text{ha}}\right) = \text{Irrigation infiltrated per event}_{it}\left(\frac{\text{ML per event}}{\text{ha}}\right) + \text{Runoff from irrigation per event}_{it}\left(\frac{\text{ML per event}}{\text{ha}}\right) \quad [6.2]$$

[94] Given the length and the width of the furrow, volume of irrigation applied and runoff from irrigation (ML) can be converted into depth of water (mm). Then all parameters are converted into ML/ha (1 ML/ha = 100 metre).

The inflow and outflow parameters in Equation 6.1 can be aggregated for a crop season. Given a number of irrigation events:

$$\begin{aligned}\text{Irrigation applied}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)\\ &= \text{Irrigation applied per event}_{\text{it}}\left(\frac{\text{ML per event}}{\text{ha}}\right)\\ &\times \text{Number of irrigation events}_{\text{it}}\\ &= \text{Irrigation infiltrated}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Runoff from irrigation}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)\end{aligned} \quad [6.2]$$

Whereas total infiltration (irrigation infiltrated) and total runoff from irrigation for a crop season can be calculated by:

$$\begin{aligned}\text{Irrigation inflitrated}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)\\ &= \text{Irrigation infiltrated per event}_{\text{it}}\left(\frac{\text{ML per event}}{\text{ha}}\right)\\ &\times \text{Number of irrigation events}_{\text{it}}\end{aligned} \quad [6.3]$$

$$\begin{aligned}\text{Runoff from irirgation}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)\\ &= \text{Runoff from irrigation per event}_{\text{it}}\left(\frac{\text{ML per event}}{\text{ha}}\right)\\ &\times \text{Number of irrigation events}_{\text{it}}\end{aligned} \quad [6.4]$$

6.3.5.2 Water balance under the DSSAT system

For DSSAT, I am replacing the DSSAT infiltration calculations with SIRMOD because, as discussed above, that gives use better realism, particularly down the furrow. For each of 72 furrow stations, infiltration at that point is input from SIRMOD and partitioned into soil evaporation (ML/ha), deep drainage (ML/ha) and transpiration (ML/ha). Infiltration is therefore simply an internal parameter that has bearing outside this data exchange.

Given rainfall supplied to the cropping system, I use the DSSAT runoff calculation to calculate runoff from rainfall, as it is the only one on offer.

Therefore, for all points in the field, rainfall is input by DSSAT and infiltration is input from SIRMOD, and the result in transpiration, soil evaporation, deep drainage, runoff from rainfall[95] and change in soil water is simulated.

$$\begin{aligned} \text{Rainfall}_{\ it} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{ Irrigation infiltrated}_{\ it} \left(\frac{\text{ML}}{\text{ha}}\right) \\ = \text{ Transpiration}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{ Soil evaporation}_{\ it} \left(\frac{\text{ML}}{\text{ha}}\right) \\ + \text{ Deep drainage}_{\ it} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{Runoff from rainfall}_{\ it} \left(\frac{\text{ML}}{\text{ha}}\right) \\ + \text{Change in soil water}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) \end{aligned} \qquad [6.5]$$

6.3.5.3 Water balance for the field

In order to examine the water balance for the field for each year of weather data, there are two steps involved. First, for each year, average transpiration, soil evaporation, deep drainage, runoff from rainfall and change in soil water over the 72 furrow stations are calculated. Second, the water balance under the DSSAT model needs to be integrated into the water inflow (irrigation applied) and the water outflow (runoff from irrigation) components of SIRMOD to establish the overall water balance for the field.

This can be done by simply adding the runoff from irrigation component to both the left and right hand-sides of Equation 6.5, such that:

[95] Because the runoff calculation does not involve slope length, we use just the runoff from the last station in the furrow.

$$\text{Rainfall}_{it}\left(\frac{ML}{ha}\right) + \text{Irirgation infiltrated}\left(\frac{ML}{ha}\right) + + \text{Runoff from irrigation}_{it}\left(\frac{ML}{ha}\right)$$
$$= \text{Transpiration}_{it}\left(\frac{ML}{ha}\right) + \text{Soil evaporation}_{it}\left(\frac{ML}{ha}\right)$$
$$+ \text{Deep drainage}_{it}\left(\frac{ML}{ha}\right) + \text{Runoff from rainfall}_{it}\left(\frac{ML}{ha}\right)$$
$$+ + \text{Runoff from irrigation}_{it}\left(\frac{ML}{ha}\right) + \text{Change in soil water}_{it}\left(\frac{ML}{ha}\right) \qquad [6.6]$$

Given irrigation applied is the sum of irrigation infiltrated and runoff from irrigation, and total water runoff is a sum of runoff from rainfall and runoff from irrigation:

$$\text{Rainfall}_{it}\left(\frac{ML}{ha}\right) + \text{Irirgation applied}\left(\frac{ML}{ha}\right)$$
$$= \text{Transpiration}_{it}\left(\frac{ML}{ha}\right) + \text{Soil evaporation}_{it}\left(\frac{ML}{ha}\right)$$
$$+ \text{Deep drainage}_{it}\left(\frac{ML}{ha}\right) + \text{Total water runoff}_{it}\left(\frac{ML}{ha}\right)$$
$$+ \text{Change in soil water}_{it}\left(\frac{ML}{ha}\right) \qquad [6.7]$$

If we move the boundary out to the farm, as discussed in Chapter 3, a portion of total water runoff needs to be recycled to supplement rainfall and reduce the water impost of cotton cultivation on the environment.

$$\text{Irrigation applied}_{it}\left(\frac{ML}{ha}\right)$$
$$= \text{Irrigation abstracted}_{it}\left(\frac{ML}{ha}\right) + \text{Recycled runoff}_{it}\left(\frac{ML}{ha}\right) \qquad [6.8]$$

$$\text{Total water runoff}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Recycled runoff}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Loss from water runoff}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [6.9]$$

Therefore, crop water supply and crop water loss are defined in Equations 6.10 and 6.11

$$\text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Rainfall}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Irrigation abstracted}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Recycled runoff}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [6.10]$$

$$\text{Crop water loss}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) = \text{Soil evaporation}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Deep drainage}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Loss from water runoff}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Change in soil water}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right) \quad [6.11]$$

6.4 Current irrigation practice

This simulation, as described earlier, requires two phases. The key input data for each phase are described below.

For current practice, a water inflow rate of 2.8 L/s was used for each irrigation event. Water was cut-off to the furrow at 745 minutes (see Table 6.3 – Panel A). The data were initially recorded in commercial cotton fields and kindly provided to me for this study (J. Purcell, Aqua-Tec Consulting[96], personal communication, 2015).

[96] http://www.aquatechconsulting.com.au/jim-purcell.htm

Table 6.3 Furrow irrigation data – Scenario 1

Panel A: SIRMOD Input – Scenario 1	
Inflow controls	
SIRMOD Input Variables	Value
Furrow Inflow, l/s	2.80
Time of Cut-off, min	745.00

Panel B: Simulated results (SIRMOD Output) – Scenario 1	
Irrigation performance	
SIRMOD Out Variables	Value
Advance time, min	572.10
Distribution Uniformity, %	85.45
Tailwater Fraction	10.42
Average irrigation amount per event, ML/ha	0.79
Runoff from irrigation per event, ML/ha	0.09

Panel C: Furrow irrigation input to WESM – Scenario 1

WESM Input Variables	**Value**	**Information source**	**Note**
Irrigation per event $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	0.79	SIRMOD Output	Scenario 1 – Current irrigation management practice
Runoff from irrigation per event $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	0.09	SIRMOD Output	Scenario 1 – Current irrigation management practice
Ratio of recycled runoff	75%	Assumption	Scenario 1 – Current irrigation management practice

Infiltration as a function of furrow distance for current practice is illustrated in Figure 6.4. This represents a distribution uniformity of 85%. The average infiltration amount was 0.79 ML/ha, with runoff to the tailwater drain of 0.09 ML/ha (Table 6.3 – Panel B). From Figure

6.4, an infiltration or irrigation supplied for each of the 71 stations was calculated as input to DSSAT (Table 6.3 – Panel C). Details of infiltration amounts of each of the 71 stations under Scenario 1 are presented in Appendix C -Table C2.

Using DSSAT for simulating cotton production over 86 years, a range of crop production and water components are generated (Table 6.4). WESM analysis for the current irrigation practice will be outlined in Chapter 7.

Table 6.4 WESM Input Variables – Scenario 1(Simulated Data)

Variable	**Information Source**	**Value (Mean-S1)**
Panel A: Furrow irrigation simulated data		
Irrigation required per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	SIRMOD	0.79 ML/ha
Runoff from irrigation per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	SIRMOD	0.09 ML/ha
Panel B: Crop production simulated data		
Biomass yield$_{it}$ $\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	DSSAT	11,948 kg/ha
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	DSSAT	4,507 kg/ha
Panel C: Crop water simulated data		
Rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	4.57ML/ha
Transpiration$_{it}$ $\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$	DSSAT	4.61 ML/ha
Soil evaporation $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	6.24 ML/ha
Deep drainage$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	1.01 ML/ha
Runoff from rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	0.52 ML/ha
Change in soil water$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	-0.06 ML/ha
Number of irrigation events $_{it}$ $\left(\frac{\text{events}}{\text{crop season}}\right)$	DSSAT	9.8 irrigation events per season

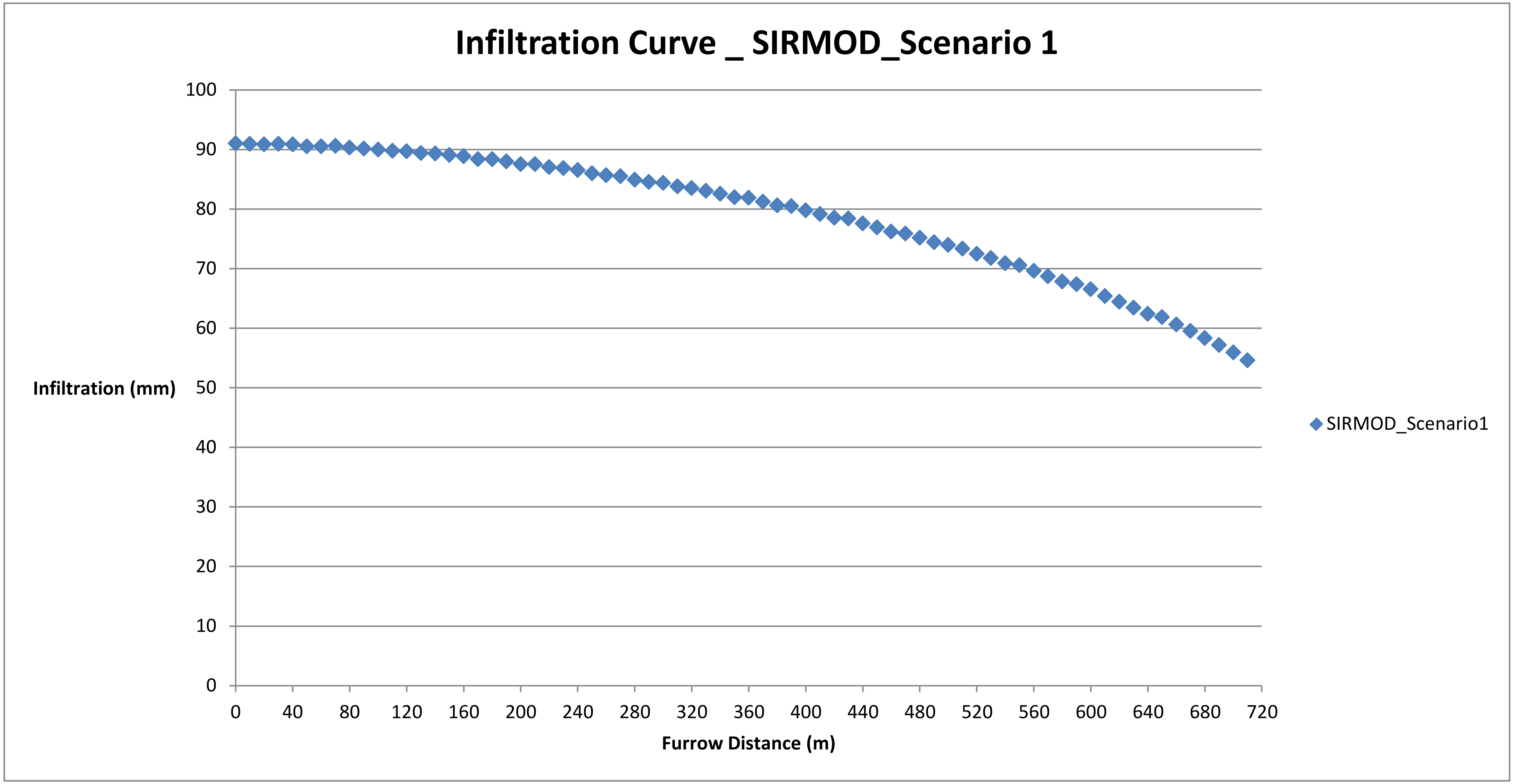

Figure 6.4 Infiltration curve_ Scenario 1

6.5 Improved irrigation practice

The SIRMOD input data provided to me for this study (J. Purcell, Aqua-Tec Consulting, personal communication, 2015) also included an altered inflow management which resulted in a more uniform water distribution. The resulting infiltration along the furrow is shown in Figure 6.5. Details of infiltration amounts of each of the 71 stations under Scenario 2 are presented in Appendix C -Table C2.

The altered management parameters were an inflow of 6.0 L/s and a cut-of time of 310 minutes (Table 6.5 - Panel A). This gave, as output, the average infiltration amount of 0.55 ML/ha, with runoff to the tailwater drain of 0.24 ML/ha (Table 6.5 - Panel C).

The DSSAT simulation and data aggregation was as described earlier (Section 6.3) except that altered infiltration values for each station were calculated from Fig. 6.5. A range of crop production and water components are generated (Table 6.6). In Chapter 8, simulated results generated by DSSAT for Scenario 2 are presented to show input data for WESM analysis and comparison between the two scenarios.

Table 6.5 Furrow irrigation data – Scenario 2

Panel A: SIRMOD Input – Scenario 2	
Inflow controls	S2
Furrow Inflow, l/s	6.00
Time of Cutoff, min	310.00

Panel B: Simulated results (SIRMOD Output) – Scenario 2	
Key SIRMOD Output Variables	S2
Irrigation performance	
Advance time, min	225.50
Distribution Uniformity, %	93.23
Tailwater Fraction	30.72
Volume Balance	
Inflow, m^3	111.60
Infiltration, m^3	**77.30**
Outflow, m^3	34.20

Panel C: Furrow irrigation input to WESM – Scenario 2		
WESM Input Variables	S2	Information source
Irrigation required per event $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	**0.55**	Calculated based on SIRMOD Output
Runoff from irrigation per event $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	**0.24**	Calculated based on SIRMOD Output
Ratio of recycled runoff	**85%**	Assumption
Deep drainage per event $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	**0.004**	DSSAT Simulated Output (Average over 86 years)

Table 6.6 WESM Input Variables – Scenario 2 (Simulated Data)

Variable	Information Source	Value (Mean-S2)
Panel A: Furrow irrigation simulated data		
Irrigation required per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	SIRMOD	0.55 ML/ha
Runoff from irrigation per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	SIRMOD	0.24 ML/ha
Panel B: Crop production simulated data		
Biomass yield$_{it}$ $\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	DSSAT	12,270 kg/ha
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	DSSAT	4,514 kg/ha
Panel C: Crop water simulated data		
Rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	4.57 ML/ha
Transpiration$_{it}$ $\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$	DSSAT	4.69 ML/ha
Soil evaporation $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	6.10 ML/ha
Deep drainage$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	0.04 ML/ha
Runoff from rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	0.53 ML/ha
Change in soil water$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	-1.19 ML/ha
Number of irrigation events $_{it}$ $\left(\frac{\text{events}}{\text{crop season}}\right)$	DSSAT	10.2 irrigation events per season

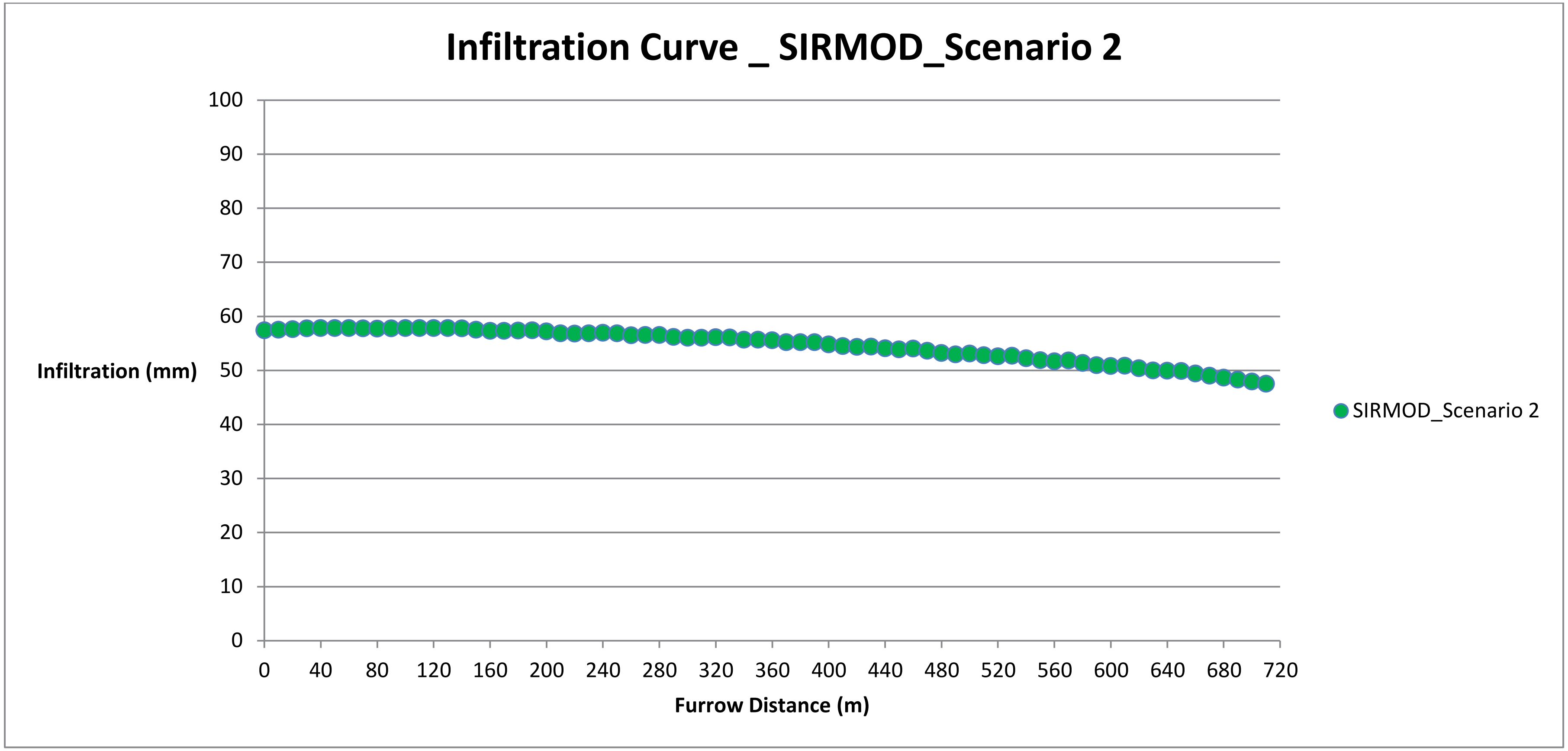

Figure 6.5 Infiltration curve_Scenario 2

6.6 Conclusions

The example used in this chapter to illustrate the utility of the WESM developed and described in Fig. 5.2 is that of a conventionally (furrow) irrigated cotton crop, because this is the most common form of irrigation used in the industry. The chapter describes furrow irrigation practices, sets up DSSAT to simulate this practice accurately, and considers its application to current furrow irrigation practice and to improved irrigation management.

The two-phased crop simulation modelling approach is designed with an attempt to provide a more comprehensive picture of the hydraulics of furrow irrigation systems and to overcome the validity issue of the DSSAT model. By doing this, I will provide more valid, useful and reliable information which enables the second component of the research question posed in this thesis to be addressed.

The data generated from SIRMOD and DSSAT for current and improved practices will be input to the WESM model for analysis in Chapters7 and 8, respectively.

Chapter 7. The Analysis of Water and Economic Sustainability – An empirical example of WESM Analysis

7.1 Introduction

This chapter does two things. First, it outlines an empirical example of the how the developed WESM model works, demonstrating the theoretical development of the model as contained in earlier chapters of the thesis. The data includes how information is presented at seven levels of the WESM model and how they are linked together in a clear, logical and structured way. The output from this model, as explained earlier, has the potential to enable crop managers to make more informed sustainability- related decision making and control.

Second, this chapter contains an initial set of outputs of performance measures so as to inform target construction, further contributing to the design of the EPMS. As argued in Chapter 1, the construction of targets is a key cybernetic control feature; however, in the initiation of the system it is impossible to specify targets in many instances as the model is designed from the ground up. While some targets are informed by scientific theory (such as water input efficiency, water resource efficiency) or estimated by simulation (such as transpiration), and some data inputs are supplied from market sources (such as lint price, and the cost of irrigation water), many of the measures are completely new theoretical developments; as a result, the construction of targets without initialising the model is impossible. This chapter therefore contains a set of output data that creates an initial set of targets to be used for future target setting and demonstrates the use of the model for cybernetic control.

In order to illustrate how the WESM model works, a sample year (Year 2012) is selected as the sample. Section 7.2 contains crop water and production data that result from furrow irrigation simulation modelling (using SIRMOD software) and crop production simulation modelling (using DSSAT software) for the year 2012. In addition, economic data that is obtained from a sample budget for furrow irrigated cotton in 2014–2015 provided by the NSW Department of Primary Industries are used for this example. These data will be fed into the WESM model for quantifying all the measures presented in the WESM model. Furthermore, a summary of calculated low-level measures (Level 7 and Level 6) are also presented to support the analysis of the five main levels of the WESM model (Level 1 to Level 5) in Section 7.3.

In Section 7.3, the analysis of the summary water and economic sustainability – the profit to water cost ratio – over the five levels (Level 1 to Level 5) is presented. Using the empirical example selected, this section illustrates how changes in a higher level measure are driven by changes in the lower level.

Section 7.4 concludes the chapter and contains the implications of WESM model analysis for better management decisions in relation to water and economic sustainability performance.

7.2 Selection of the empirical example

The current furrow irrigation practice that is described in Chapter 6 (see Table 6.3) is applied in this chapter for generating irrigation and crop data for the WESM model analysis. Based on WESM input data (mean value) described in Table 6.4, all WESM measures across seven levels of WESM are calculated. The mean of the summary water and economic sustainability measure – profit to water cost ratio – is *2.62*.

In order to illustrate how the WESM model works, a sample year is selected to create the sample. The year 2012 is selected for two reasons. First, its profit to water cost ratio value (*2.57*) is close to the profit to water cost ratio of the Scenario 1 sample. Second, the economic data is obtained from a sample budget for furrow irrigated cotton in 2014 -2015(NSW Department of Primary Industries 2015), therefore a sample year that is as close as possible to 2014–2015 is preferable. Table 7.1 reports the SIRMOD and DSSAT output simulated for the sample year 2012.

Table 7.2 summarises the economic data and irrigation management data, accompanied by simulated water and crop data to input to the WESM model, to enable quantification of WESM measures across seven levels. For the sample year 2012, Table 7.3 – Panel F and Panel G, accompanied by figure 7.1, present the calculations of low-level (levels 6 and 7) economic measures and low-level (levels 6 and 7) environmental measures, respectively. The data outlined in Tables 7.1, 7.2 and Panel F and Panel G of Table 7.3 are used for quantifying all high-level WESM measures that are analysed in Section 7.3.

Table 7.1 WESM Input Variables – year 2012 (Simulated Data)

Variable	Information Source	Value
Panel A: Furrow irrigation simulated data		
Irrigation infiltrated per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	SIRMOD	0.79 ML/ha
Runoff from irrigation per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	SIRMOD	0.09 ML/ha
Panel B: Crop production simulated data		
Biomass yield$_{it}$ $\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	DSSAT	12,201 kg/ha
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	DSSAT	4,734 kg/ha
Panel C: Crop water simulated data		
Rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	4.17 ML/ha
Transpiration$_{it}$ $\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$	DSSAT	4.82 ML/ha
Soil evaporation $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	5.83 ML/ha
Deep drainage$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	1.87 ML/ha
Runoff from rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	0.38 ML/ha
Change in soil water$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	-0.02 ML/ha
Number of irrigation events $_{it}$ $\left(\frac{\text{events}}{\text{crop season}}\right)$	DSSAT	11 irrigation events per season

Table 7.2 WESM Input Variables (Non-Simulated Data)

Panel A: Accounting data			
WESM input variables	**Value**	**Information source**	**Note**
Lint $\text{price}_{it}\left(\frac{\$}{\text{kg}}\right)$	**\$2.09/kg of lint**	NSW Department of Primary Industries (2015)	Equivalent to \$474/bale (1 bale = 227 kg) This is the 5-year average cotton lint price 2010–2015
Seed $\text{price}_{it}\left(\frac{\$}{\text{kg}}\right)$	**\$0.32/kg of seed**	NSW Department of Primary Industries (2015)	Equivalent to \$320/t
Fixed operating $\text{cost}_{it}\left(\frac{\$}{\text{ha}}\right)$	**\$2,812/ha**	NSW Department of Primary Industries (2015)	Only considers fixed operating cost on a per ha basis. Overhead costs and permanent labour are not considered in calculation of operating profit per ha. Fixed operating cost is determined using the regression technique[97] based on the sample budget for furrow irrigated cotton in **2014–2015** for Central and Northern NSW area.
Unit other variable $\text{cost}_{it}\left(\frac{\$}{\text{kg of lint}}\right)$	**\$0.12/kg of lint**	NSW Department of Primary Industries	Equivalent to \$27.33 /bale of lint. Exclusive

[97] Details of the calculations are presented in the Appendix D1

		(2015)	irrigation cost. Unit other variable cost is determined using the regression technique[98] based on the sample budget for furrow irrigated cotton in **2014–2015** for Central and Northern NSW area.
Unit licensed irrigation cost$_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	**$60.30/ML**	NSW Department of Primary Industries (2015)	Including licence fees of $32.24 /ML and pumping cost of $28.06/ML
Unit traded irrigation cost$_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	**Not applicable**		Assuming that traded irrigation to irrigation abstracted ratio is equal to zero
Panel B: Other input data			
WESM input variables	**Value**	**Information source**	**Note**
Licensed irrigation to Irrigation infiltrated ratio$_{it}$ (%)	**100%**	Assumption	Water management practice: Irrigation allocation assumption
Traded irrigation to Irrigation infiltrated ratio$_{it}$ (%)	**0%**	Assumption	Water management practice: Irrigation allocation assumption
Lint percentage$_{it}$ (%)	**40%**	Cotton Seed Distributors (2013)	Crop variety assumption: SICOT 43BRF

[98] Details of the calculations are presented in the Appendix D1.

Table 7.3 WESM Analysis (year 2012) – Panel G (Level 6 and Level 7: Low-Level Environmental Measures)

Panel G1– Calculation of Irrigation required		
Variable	WESM Level	Formula
Irrigation infiltrated $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \text{Irrigation required per event}_{it} \left(\frac{\text{ML per event}}{\text{ha}}\right) \times \text{Number of irrigation events}_{it}$ = 0.79 * 11 = **8.69 ML/ ha**
Irrigation infiltrated per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	WESM Input	SIRMOD Output (Simulation) 0.79 ML/ ha
Number of irrigation events	WESM Input	DSSAT Output (Simulation) 11 irrigation events
Panel G2– Calculation of Runoff from irrigation		
Runoff from irrigation $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \text{Runoff from irrigation per event}_{it} \left(\frac{\text{ML per event}}{\text{ha}}\right) \times \text{Number of irrigation events}$ = 0.09 * 11 = **0.99 ML/ ha**
Runoff from irrigation per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	WESM Input	SIRMOD Output (Simulation) 0.09 ML/ ha
Number of irrigation events	WESM Input	DSSAT Output (Simulation) 11 irrigation events

Panel G3– Calculation of Irrigation applied		
Irrigation applied $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \text{Irrigation infiltrated}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{Runoff from irrigation}_{it} \left(\frac{\text{ML}}{\text{ha}}\right)$ = 8.69 + 0.99 = **9.68 ML/ ha**
Irrigation infiltrated $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	**Level 7**	Calculated in Panel G1 = 8.69 ML/ ha
Runoff from irrigation $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	**Level 7**	Calculated in Panel G2 = 0.99 ML/ ha
Panel G4– Calculation of Total water runoff		
Total water runoff $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \text{Runoff from rainfall}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) + \text{Runoff from irrigation}_{it} \left(\frac{\text{ML}}{\text{ha}}\right)$ = 0.38 + 0.99 = **1.37 ML/ ha**
Runoff from rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	WESM Input	DSSAT Output (Simulation) 0.38 ML/ ha
Runoff from irrigation $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	Calculated in Panel G3 = 0.99 ML/ ha

Panel G5– Calculation of Recycled runoff		
Recycled runoff $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \text{Total water runoff}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) \times \text{Ratio of recycled runoff}$ = 1.37 x 75% = **1.02 ML/ ha**
Total water runoff $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	Calculated in Panel G4 = 1.37 ML/ ha
Ratio of recycled runoff $_{it}$ (%)	WESM Input	Water management practice (assumption – Current Farming Practice) = 75%
Panel G6– Calculation of Irrigation abstracted		
Irrigation abstracted $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \text{Irrigation applied}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) - \text{Recycled runoff}_{it} \left(\frac{\text{ML}}{\text{ha}}\right)$ = 9.68 – 1.02 = **8.66 ML/ ha**
Irrigation applied $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	Calculated in Panel G3 = 9.68 ML/ ha
Recycled runoff $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	Calculated in Panel G5 = 1.02 ML/ ha

Panel G7– Calculation of Loss from water runoff		
Loss from water runoff $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 6**	$= \text{Total water runoff}_{it} \left(\frac{ML}{ha}\right) - \text{Recycled runoff}_{it} \left(\frac{ML}{ha}\right)$ = 1.37 - 1.02 = **0.35 ML/ ha**
Total water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel G4 = 1.37 ML/ ha
Recycled runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel G5 = 1.02 ML/ ha
Panel G8– Calculation of Crop water loss		
Crop water loss $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 6**	$= \text{Soil evaporation}_{it} \left(\frac{ML}{ha}\right) + \text{Deep drainage}_{it} \left(\frac{ML}{ha}\right) + \text{Loss from water runoff}_{it} \left(\frac{ML}{ha}\right) + \text{Change in soil water}_{it} \left(\frac{ML}{ha}\right)$ = 5.83 + 1.87 + 0.35 – 0.02 = **8.03ML/ ha**
Soil evaporation $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (Simulation) 5.83 ML/ ha
Deep drainage $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (Simulation) 1.87 ML/ ha

Loss from water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel G7 = 0.35 ML/ ha
Change in soil water$_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (Simulation) = - 0.02 ML/ha
Panel G9– Calculation of Crop water supplied		
Crop water supply$_{it}$ $\left(\frac{ML}{ha}\right)$	**Level 6**	$= \text{Rainfall}_{it} \left(\frac{ML}{ha}\right) + \text{Irrigation abstracted}_{it} \left(\frac{ML}{ha}\right) + \text{Recycled runoff}$ = 4.17 ML/ha + 8.66 ML/ha + 1.02 ML/ha = **13.85 ML/ha**
Rainfall $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (Simulation) = 4.17 ML/ha
Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel G6 = 8.66 ML/ha
Recycled runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel G5 = 1.02 ML/ha
Panel G10– Calculation of Rainfall to crop water supplied ratio (%)		
Rainfall to crop water supplied ratio (%)	**Level 6**	$= \text{Rainfall}_{it} \left(\frac{ML}{ha}\right) \div \text{Crop water supplied}_{it} \left(\frac{ML}{ha}\right)$ = 4.17 ML/ha ÷ 13.85 ML/ha = **30.1%**
Rainfall $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (Simulation) = 4.17 ML/ha

Crop water $\text{supplied}_{it}\left(\frac{ML}{ha}\right)$	Level 6	Calculated in Panel G9 = 13.85 ML/ha
Panel G11– Calculation of Recycled runoff to crop water supplied ratio (%)		
Recycled runoff to crop water supplied ratio (%)	**Level 6**	$= \text{Recycled runoff}_{it}\left(\frac{ML}{ha}\right)$ $\div \text{Crop water supplied}_{it}\left(\frac{ML}{ha}\right)$ = 1.02 ML/ha ÷ 13.85 ML/ha = **7.36%**
Recycled runoff $_{it}\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel G5 = 1.02 ML/ha
Crop water $\text{supply}_{it}\left(\frac{ML}{ha}\right)$	Level 6	Calculated in Panel G9 = 13.85 ML/ha
Panel G12– Calculation of Crop water loss to crop water supplied ratio (%)		
Crop water loss to crop water supply ratio (%)	**Level 6**	$= \text{Crop water loss}_{it}\left(\frac{ML}{ha}\right)$ $\div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)$ = 8.03 ML/ha ÷ 13.85 ML/ha = 58.19%
Crop water loss $_{it}\left(\frac{ML}{ha}\right)$	Level 6	Calculated in Panel G8 = 8.03 ML/ha
Crop water $\text{supply}_{it}\left(\frac{ML}{ha}\right)$	Level 6	Calculated in Panel G9 = 13.85 ML/ha

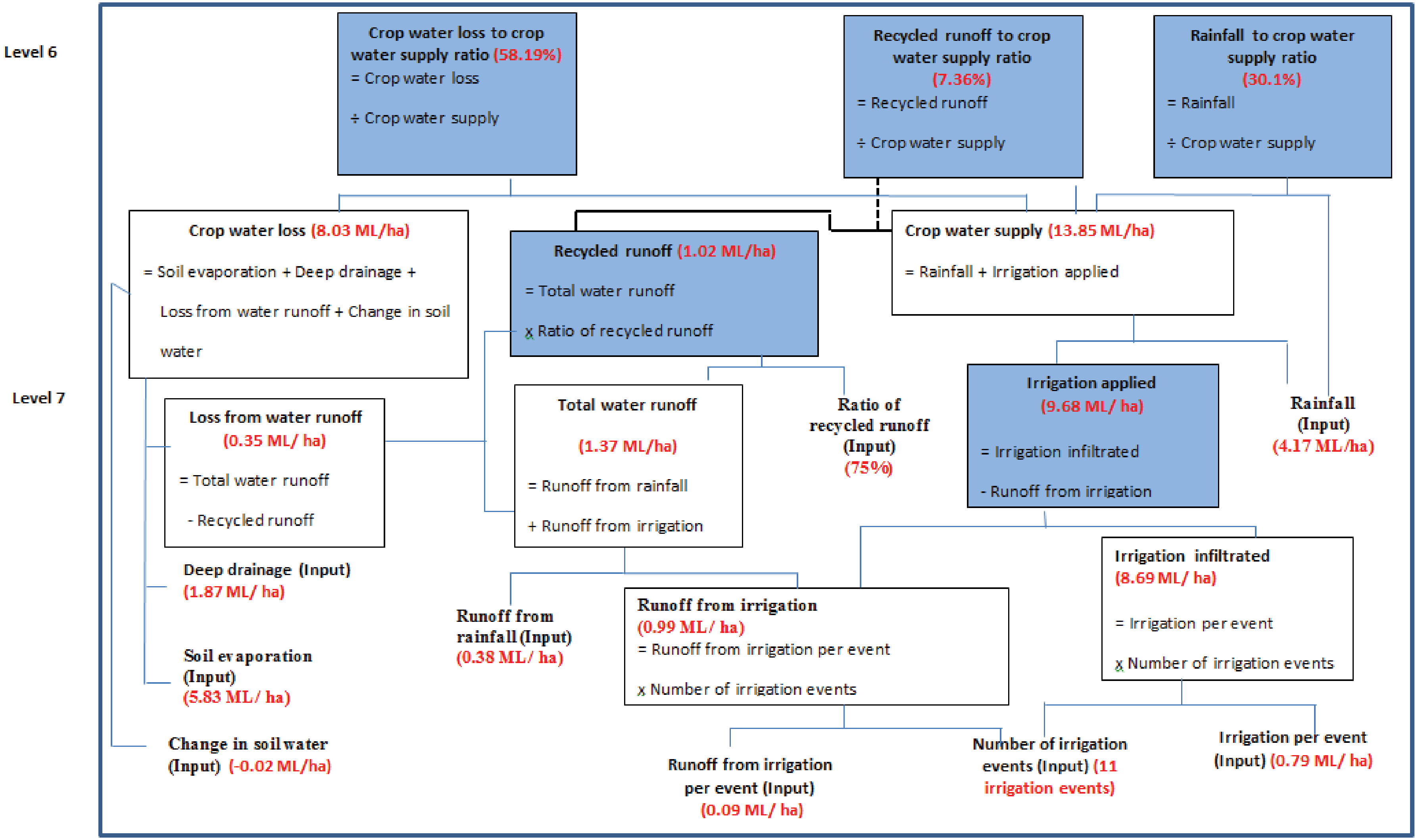

Figure 7.1 Levels 6 to 7 of the WESM model (environmental low-level measures)

Table 7.3 WESM Analysis (year 2012) – Panel F (Level 6 and Level 7: Low-Level Economic Measures)

Panel F1– Calculation of Lint yield		
Variable	WESM Level	Formula
Lint yield$_{\mathbf{it}}$ $\left(\frac{\mathbf{kg}}{\mathbf{ha}}\right)$	**Level 7**	$=$ Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$ $\times$ Lint percentage$_{it}$ (%) = 4734 kg/ha x 40% = **1894 kg/ha** (equivalent to 8.4 bales/ha)
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation) = 4734 kg/ha
Lint percentage$_{it}$ (%)	WESM Input	Crop Variety (assumption: SICOT 43BRF) = 40%
Panel F2– Calculation of Seed yield		
Seed yield$_{\mathbf{it}}$ $\left(\frac{\mathbf{kg}}{\mathbf{ha}}\right)$	**Level 7**	$=$ Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$ $\times$ Seed percentage$_{it}$ (%) = 4734 kg/ha x 60% = **2840 kg/ha**
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation) = 4734 kg/ha
Seed percentage$_{it}$ (%)	WESM Input	Accounting Data (assumption) = 100% - Lint percentage$_{it}$ (%) = 100% - 40% = 60%

Panel F3– Calculation of Sales revenue (lint)		
Sales revenue$_{it}$(lint) $\left(\frac{\$}{\mathbf{ha}}\right)$	**Level 6**	$= \text{Lint yield}_{it} \left(\frac{kg}{ha}\right) \times \text{Lint price}_{it} \left(\frac{\$}{kg}\right)$ = 1894 kg/ha x \$2.09/kg = **\$3959 / ha**
Lint yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	Calculated in Panel F1 = 1894 kg/ha
Lint price$_{it}$ $\left(\frac{\$}{kg}\right)$	WESM Input	Accounting Data (Assumption) = \$2.09/ kg of lint
Panel F4– Calculation of Sales revenue (cotton seed)		
Sales revenue$_{it}$(cotton seed) $\left(\frac{\$}{\mathbf{ha}}\right)$	**Level 6**	$= \text{Seed yield}_{it} \left(\frac{kg}{ha}\right) \times \text{Seed price}_{it} \left(\frac{\$}{kg}\right)$ = 2840 kg/ha x \$0.32/ kg = \$909/ha
Seed yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	Calculated in Panel F2 = 2840 kg/ha
Seed price$_{it}$ $\left(\frac{\$}{kg}\right)$	WESM Input	Accounting Data (Assumption) = \$0.32/ kg of seed

Panel F5– Calculation of Traded irrigation volume		
Traded irrigation volume$_{it}$ $\left(\frac{ML}{ha}\right)$	**Level 7**	$= \text{Irrigation abstracted}_{it} \left(\frac{ML}{ha}\right)$ $\times$ Traded irrigation to Irrigation abstracted ratio$_{it}$ (%) = 8.66 ML/ha x 0% = **0 ML/ha**
Irrigation withdrawn $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel G6 = 8.66 ML/ha
Traded irrigation to Irrigation abstracted ratio$_{it}$	WESM Input	Water management practice (assumption – Current Farming Practice) = 0%
Panel F6– Calculation of Licensed irrigation volume		
Licensed irrigation volume$_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$ =	**Level 7**	$= \text{Irrigation withdrawn}_{it} \left(\frac{ML}{ha}\right)$ $\times$ Licensed irrigation to Irrigation withdrawn ratio$_{it}$ (%) = 8.66 ML/ha x 100% = **8.66 ML/ha**
Irrigation withdrawn $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel G6 = 8.66 ML/ha
Licensed irrigation to Irrigation abstracted ratio$_{it}$	WESM Input	Water management practice (assumption for – Current Farming Practice) = 100%
Panel F7– Calculation of Traded irrigation cost		
Traded irrigation cost$_{it}$ $\left(\frac{\$}{\mathbf{ha}}\right)$	**Level 6**	$= \text{Traded irrigation volume}_{it} \left(\frac{ML}{ha}\right) \times \text{Unit traded irrigation cost}_{it} \left(\frac{\$}{ML}\right)$ = **\$0/ha**

Traded irrigation volume$_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel F5 = 0 ML/ha
Unit traded irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$	WESM Input	Accounting Data (assumption) Not applicable since Traded irrigation to Irrigation withdrawn ratio is assumed zero
Panel F8– Calculation of Licensed irrigation cost		
Licensed irrigation cost$_{it}$ $\left(\frac{\$}{ha}\right)$	**Level 6**	$=$ Licensed irrigation volume$_{it}$ $\left(\frac{ML}{ha}\right)$ $\times$ Unit traded irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$ = 8.66 ML/ha x \$60.30 = **\$522 /ha**
Licensed irrigation volume$_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel F6 = 8.66 ML/ha
Unit licensed irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$	WESM Input	Accounting Data (assumption) = \$60.30/ ML
Panel F9– Calculation of Total water cost		
Total water cost$_{it}$ $\left(\frac{\$}{ha}\right)$	**Level 6**	$=$ Licensed irrigation cost$_{it}$ $\left(\frac{\$}{ha}\right)$ $+$ Traded irrigation cost$_{it}$ $\left(\frac{\$}{ha}\right)$ = \$522.2 /ha + \$0 /ha = **\$522 /ha**
Licensed irrigation cost$_{it}$ $\left(\frac{\$}{ha}\right)$	Level 6	Calculated in Panel F8 = \$522 /ha

Traded irrigation $\text{cost}_{it}\left(\frac{\$}{\text{ha}}\right)$	Level 6	Calculated in Panel F7 = $0 /ha
Panel F10 – Calculation of Other variable cost		
Other variable $\mathbf{cost}_{it}\left(\frac{\$}{\mathbf{ha}}\right)$	**Level 6**	$= \text{Unit other variable cost}_{it}\left(\frac{\$}{\text{kg of lint}}\right) \times \text{Lint yield}_{it}\left(\frac{\text{kg}}{\text{ha}}\right)$ = $0.12/kg x 1894 kg/ha = **$227/ha**
Unit other variable $\text{cost}_{it}\left(\frac{\$}{\text{kg of lint}}\right)$	WESM Input	Accounting Data (assumption) = $0.12/kg of lint
Lint $\text{yield}_{it}\left(\frac{\text{kg}}{\text{ha}}\right)$	Level 7	Calculated in Panel F1 = 1894 kg/ha

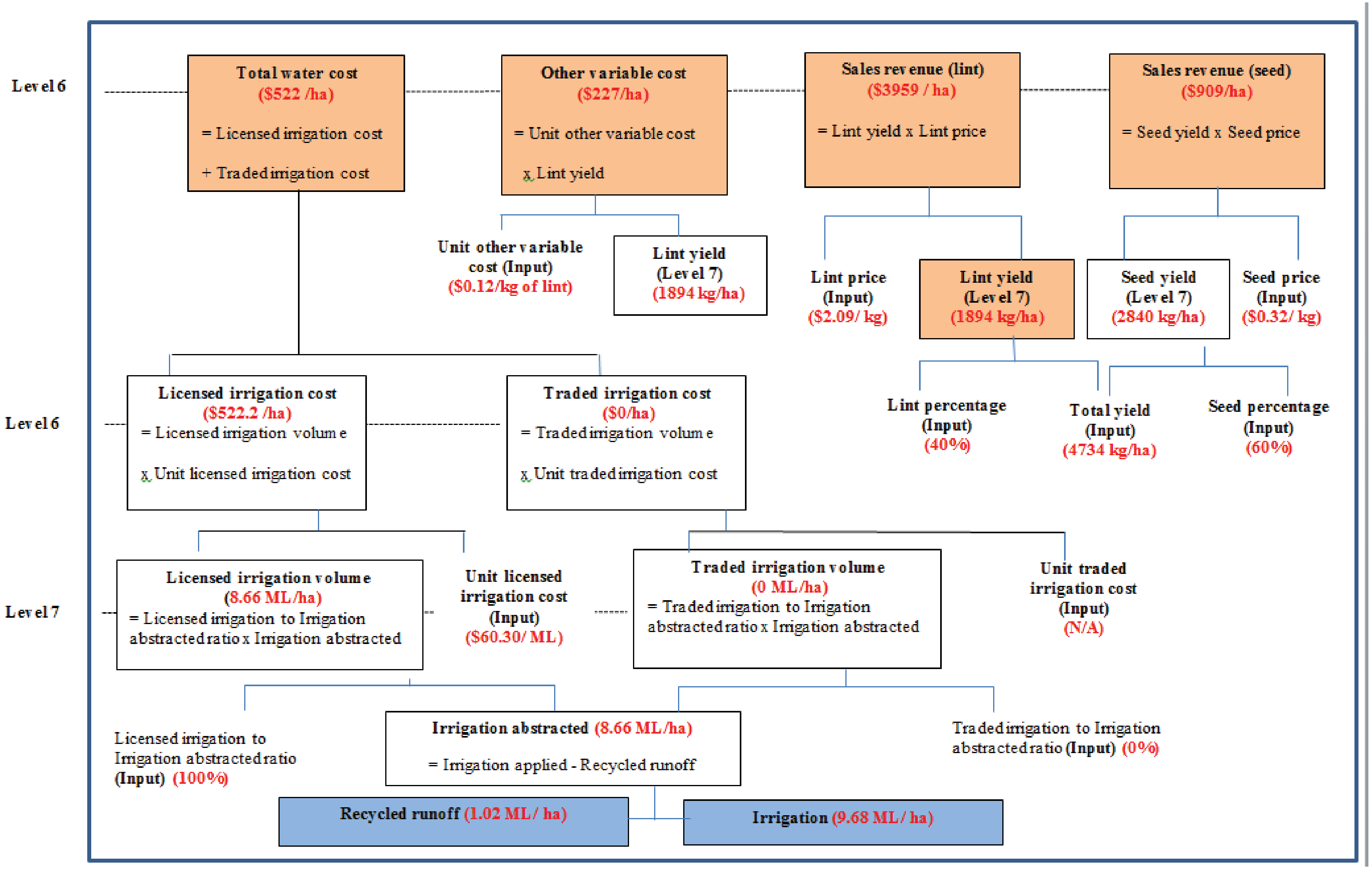

Figure 7.1 Levels 6 to 7 of the WESM model (economic low-level measures)

7.3 Analysis of water and economic sustainability

Running the WESM model using data provides an opportunity to discuss the analysis of the drivers of profit to water cost ratio, thereby enabling the analysis of water and economic sustainability performance.

The value of a crop business is generated by economic and environmental factors. In Chapter 4, it is theorised that the profit to water cost ratio is a valuable summary measure of the environmental (with regard to water resource use) and economic sustainability of crop businesses. However, in order to understand how to improve water and economic sustainability performance of a crop business, it is essential to analyse drivers of profit to water cost ratio to gain insights into what drives this summary measure, how it will change as a result of a particular decision, and how the change translates into meaningful implications for management decisions.

In this section, following the five levels of analysis that are laid out in Chapter 4, the analysis of profit to water cost ratio of crop production under current management practice for year 2012 is used to demonstrate how the WESM model works.

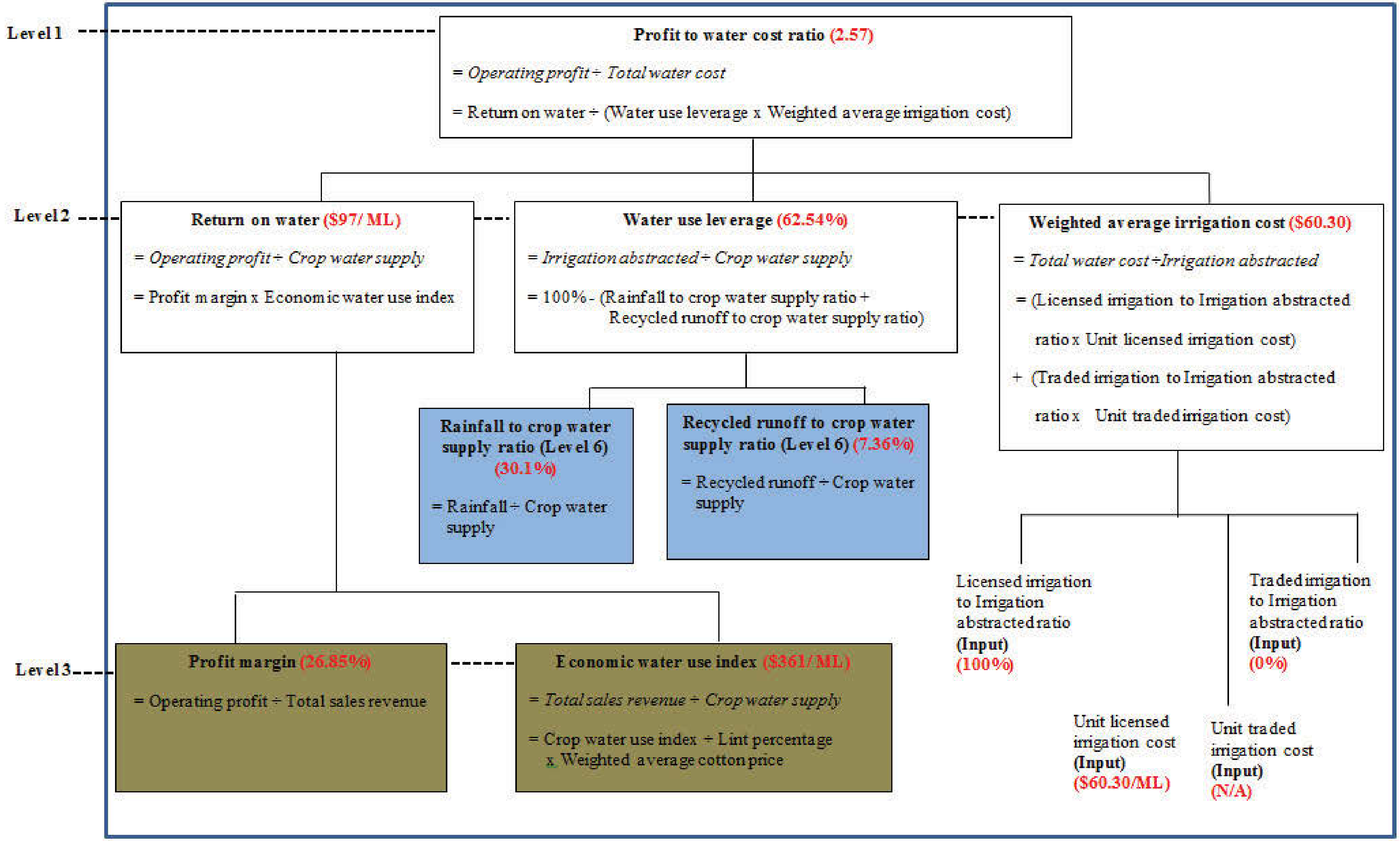

Figure 7.1 Levels 1 to 3 of the WESM model

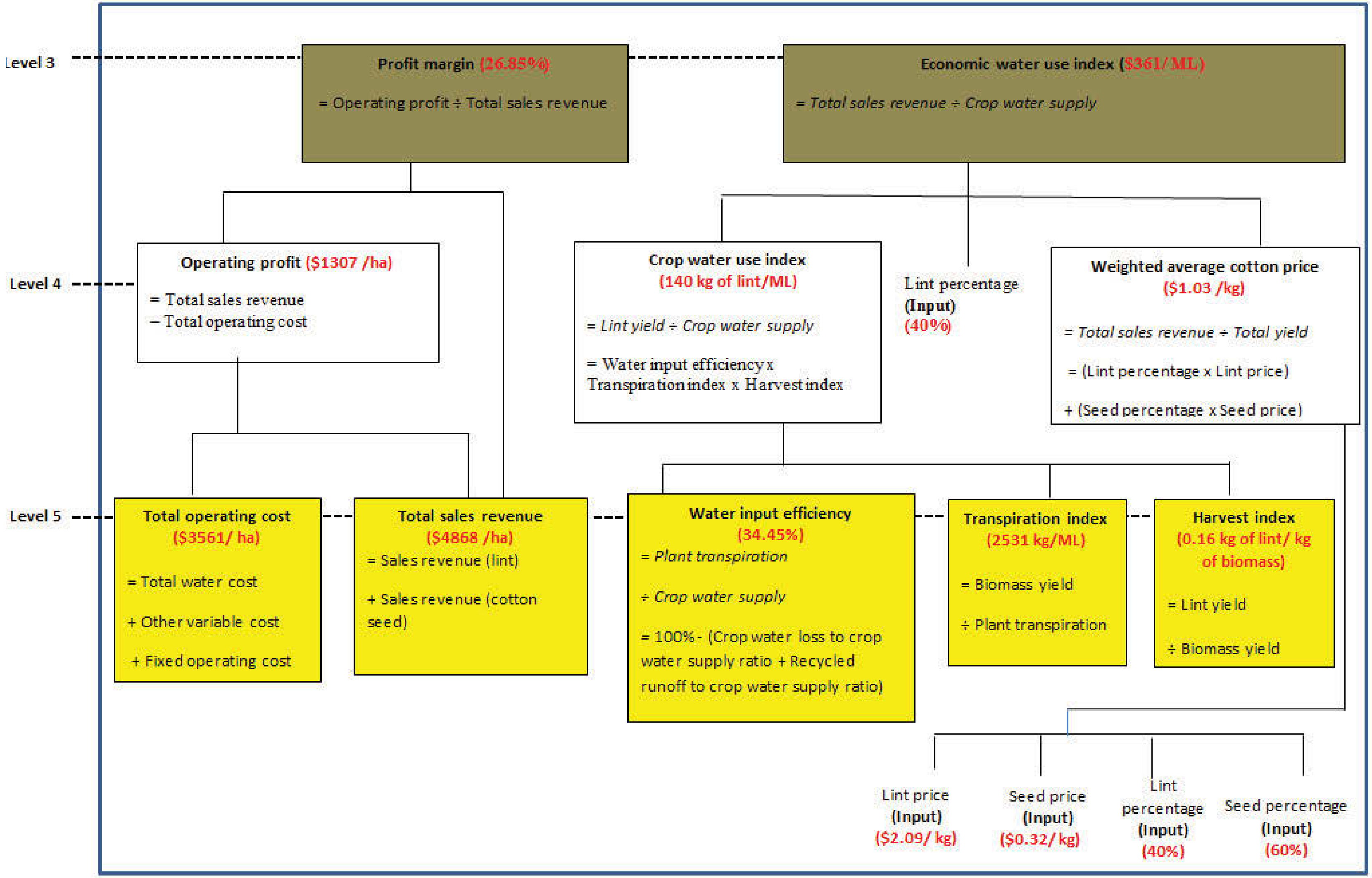

Figure 7.1 Levels 3 to 5 of the WESM model

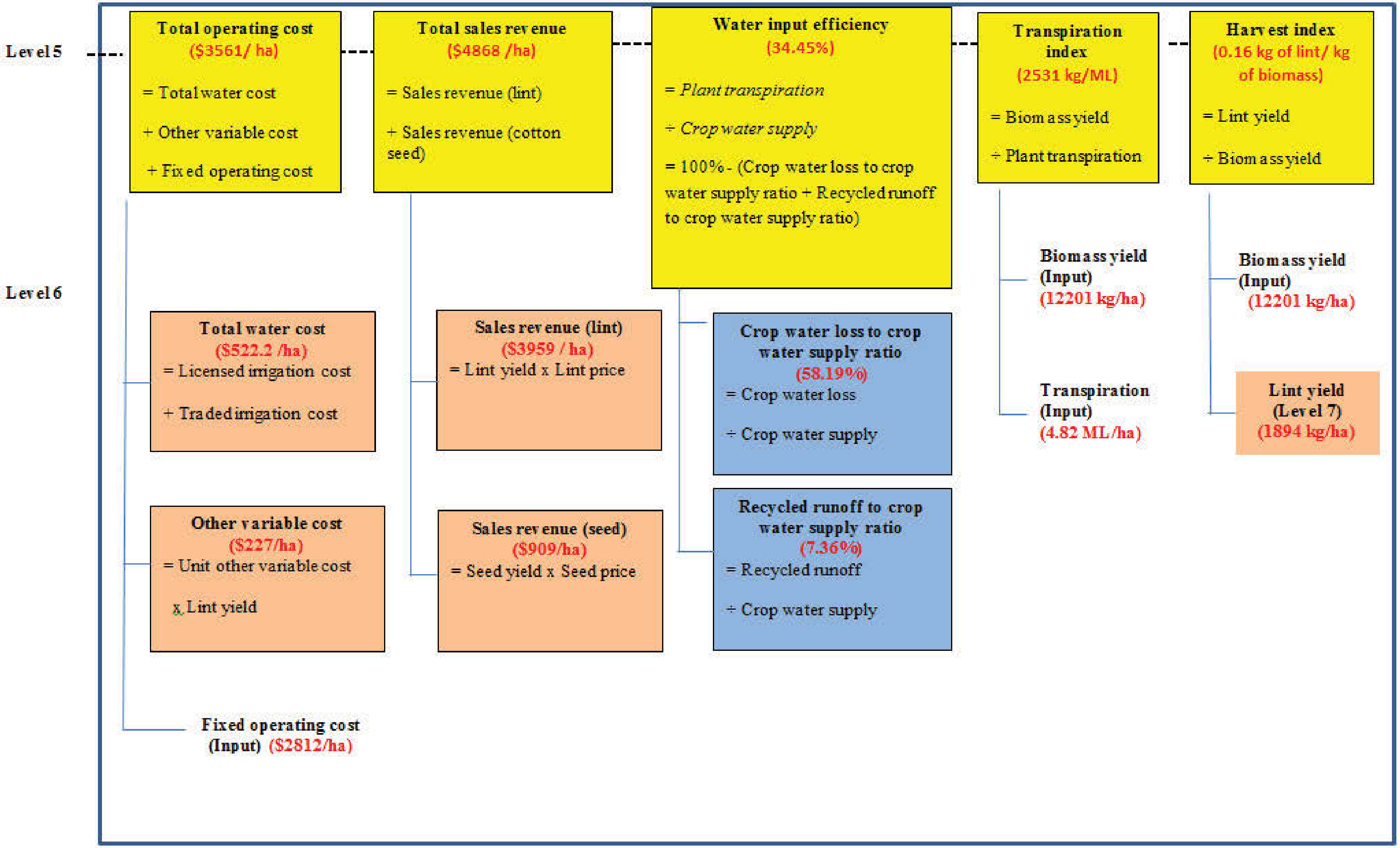

Figure 7.1 Levels 5 to 6 of the WESM model

7.3.1 First-level of analysis

In Table 7.3, Panel A, it is shown that profit to water cost ratio is 2.57. This means for every dollar spent on water, the crop business creates an operating profit of $2.57. However, by merely looking at the profit to water cost ratio, the crop manager does not know explicitly how efficiently the business uses the water resource to create its economic value and how water is sourced.

In the first-level of analysis, the profit to water cost ratio of 2.57 is produced by a return of $97 on one ML of water supplied to the cropping system, 63% of which is sourced by abstracted water which costs $60.30/ML to obtain. In other words, for every one ML of water supplied to the cropping system, 0.63 ML is sourced from water abstracted from the environment. As it costs $60.30 to obtain one ML of irrigation water, the business has to incur a cost of $38 for irrigation water (= 0.63ML x $60.30/ML) to generate $97 of operating profit.

Though the first-breakdown of the profit to water cost ratio explains the effect of return on water, water use leverage and weighted average irrigation cost on the summary figure, it is still not clear what drives return on water, how water management practices affect water use leverage, and how irrigation water is sourced. Therefore, it is necessary to further decompose the three drivers of profit to water ratio into their components.

Table 7.3 WESM Analysis (year 2012) – Panel A (Level 1 of WESM)

Analysis of Profit to water cost ratio		
Variable	Level	Formula
Profit to water cost ratio$_{it}$	**Level 1**	$= \text{Return on water}_{it}\left(\frac{\$}{\text{ML}}\right) \div \left[\text{Water use leverage}_{it}\ (\%) \times \text{Weighted average irrigation cost}_{it}\left(\frac{\$}{\text{ML}}\right)\right]$ = \$97/ ML ÷ (62.54% x \$60.30) = **2.57**
Return on water$_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	Level 2	Calculated in Panel B1 = \$97 / ML
Water use leverage$_{it}$ (%)	Level 2	Calculated in Panel B2 = 62.54%
Weighted average irrigation cost$_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	Level 2	Calculated in Panel B3 = \$60.30

7.3.2 Second-level of analysis

7.3.2.1 Decomposition of return on water

In Table 7.3, Panel B1, it is demonstrated that a return of $97 per ML of water resource is explained by economic water use index of $361 per ML of water resource and profit margin of 27%. This means for every ML of crop water supply, the business generates $361 of total sales revenue, 27% of which remains after operating costs have been deducted.

The decomposition of return on water into the economic water use index and profit margin reveals the ability of water resource use in crop production to generate sales and the extent to which economic return can be created from each dollar of sales. However, at this level, the crop manager still does not know how the value of the economic water use index (i.e. $361 per ML of water resource) will change as a result of crop management decisions. By gaining insights into the factors affecting this measure, it helps the crop manager to identify areas for continuous improvement in economic value created for the business with regard to water resource use.

Furthermore, while the profit margin – a ratio of operating profit to total sales revenue – is a useful measure of assessing whether a business stays in business, this measure per se (i.e. 27% in this example) only reveals, in a relative term, the profitability of each dollar of sales the crop business generates. By decomposing the profit margin ratio into its two terms, crop managers can further examine how changes in one or both terms involved affect its change. Accordingly, in the third-level of analysis, economic water use index and profit margin will be further broken into their components.

7.3.2.2 Decomposition of water use leverage

Table 7.3, Panel B2, explains how crop water supply for crop production is sourced. For every 1 ML of water resource used, 30% of it is rainfall, 7.4% of it comes from recycled irrigation water, and the remaining 62.6% is abstracted as irrigation water.

In respect to water resources for crop irrigation, rainfall is considered an uncontrollable water resource, varying across years. In this example, in 2012, the amount of rainfall provided to the business only contributed to 30% of the total crop water needs to be supplied to its cropping system. One way to reduce dependence on irrigation water and reduce the risk of crop yield loss due to insufficient water availability is improving the management of water runoff from rainfall and furrow irrigation systems. In other words, the more water runoff being recycled by the farm, the less water needs to be abstracted from the environment for crop production.

In this case 68% of crop water is provided by abstracted irrigation water. The higher the percentage of recycled water runoff, the lower the water use leverage. Under current water management practice, it is assumed that the business recycles only 75% of its total water runoff. If the business improves its water management practice by increasing the ratio of recycled water towards 100%, the water use leverage figure will decrease.

7.3.2.3 Decomposition of weighted irrigation water cost

Weighted irrigation water cost represents the average water cost per ML of irrigation water that a crop business has to pay for its two irrigation water sources; licensed irrigation and traded irrigation. The value of this measure is determined by four factors, including licensed irrigation to irrigation abstracted ratio (%), unit licensed irrigation cost ($/ML), traded irrigation to irrigation abstracted ratio (%), and unit traded irrigation cost ($/ML).

With an attempt to provide a simple example to illustrate how the developed WESM works, it is assumed that irrigation water is only sourced by licensed irrigation. This means that weighted average irrigation cost and unit licensed irrigation cost are identical.

Given that unit licensed irrigation cost is assumed $60.30/ML (see Table 7.2), Table 7.3 (Panel B3) reports weighted average irrigation cost value at $60.30/ML.

In this respect, the effect of irrigation sources and weighted irrigation water cost on the profit to water cost ratio is isolated in this analysis. Therefore, the two key drivers of profit to water cost ratio considered in this example are return on water and water use leverage, the components of which will be further analysed in the lower levels of analysis.

Table 7.3 WESM Analysis (year 2012) – Panel B (Level 2 of WESM)

Panel B1-Analysis of Return on water		
Variable	**Level**	**Formula**
Return on water$_{it}\left(\frac{\$}{ML}\right)$	**Level 2**	$= \text{Profit margin}_{it}(\%) \times \text{Economic water use index}_{it}\left(\frac{\$}{ML}\right)$ = 26.85% x \$361 /ML = **\$97/ ML**
Profit margin$_{it}(\%)$	Level 3	Calculated in Panel C1 = 26.85%
Economic water use index$_{it}\left(\frac{\$}{ML}\right)$	Level 3	Calculated in Panel C2 = \$361 /ML
Panel B2-Analysis of Water use leverage		
Water use leverage (%)	**Level 2**	$= 100\% - $ [Rainfall to crop water supplied ratio (%) $+$ Recycled runoff to crop water supplied ratio (%)] = 100% - (30.1% + 7.36%) = 62.54%
Rainfall to crop water supplied ratio (%)	Level 6	Calculated in Panel G10 = 30.1%
Recycled runoff to crop water supplied ratio (%)	Level 6	Calculated in Panel G11 = 7.36%
Panel B3- Analysis of Weighted average irrigation cost		

Weighted average irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$	**Level 2**	$= \left[\text{Licensed irrigation to Irrigation withdrawn ratio}_{it}\ (\%) \times \text{Unit licensed irrigation cost}_{it} \left(\frac{\$}{ML}\right)\right] + \left[\text{Traded irrigation to Irrigation withdrawn ratio}_{it}\ (\%) \times \text{Unit traded irrigation cost}_{it} \left(\frac{\$}{ML}\right)\right]$ = 100% x \$60.30 = **\$60.30**
Licensed irrigation to Irrigation withdrawn rati (%)	WESM Input	Water management practice (assumption for – Current Farming Practice) = 100%
Traded irrigation to Irrigation withdrawn ratio (%)	WESM Input	Water management practice (assumption for – Current Farming Practice) = 0%
Unit licensed irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$	WESM Input	Accounting Data (assumption) = \$60.30/ ML
Unit traded irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$	WESM Input	Accounting Data (assumption) Not applicable since Traded irrigation to Irrigation withdrawn ratio is assumed zero

7.3.3 Third-level of analysis

7.3.3.1 Decomposition of profit margin

In Table 7.3, Panel C1, a profit margin of 27% is explained by the operating profit of $1,307 per ha and the total sales revenue of $4,868 per ha.

The profit margin ratio shows that for every dollar of sales, the business earns 27 cents of operating profit. In addition, the decomposition of profit margin reveals that the economic value the crop business generates for each unit of land is $1,307/ha. As an absolute measure of profitability, operating profit provides a means of translating changes in profitability into value created for the business. However, in order to understand how this profitability figure can be improved as a result of a particular crop management decision, it is essential to understand what drives its two components: total sales revenue and total operating cost. This will be explained in the fourth level of analysis (Section 7.3.4).

7.3.3.2 Decomposition of economic water use index

Table 7.3, Panel C2, explains that an economic water use index of $361 of sales revenue for one ML of crop water supply is produced by a crop water use index of 140 kg of lint per ML of crop water supply, which is scaled up to total yield by the lint percentage of 40% and then translated into a dollar term by incorporating the weighted average cotton price of $1.02/kg of total yield.

More specifically, there are two steps involved in the decomposition of the economic water use index. First, a crop water use index of 140 kg of lint per ML of crop water supply is converted to 350 kg of total yield per ML of crop water supply by dividing 140 by the lint percentage of 40% (e.g. 140/0.4 = 350). Second, for each ML of crop water supply, total sales revenue generated is a product of 350 kg of total yield and the weighted average cotton price of $1.02/kg of total yield, which is $375 of sales revenue (e.g. $350 x 1.02 =$357[99]).

The decomposition of the economic water use index helps to explain the effect of the crop water use index, lint percentage and weighted average cotton price on it. However, at this level, we do not know what factor(s) determine the level of production of the primary crop

[99] Slight difference in Economic water use index value occurs between two calculating approaches (e.g., based on its definition versus its decomposition components) due to rounding.

product (i.e. lint yield) produced by each ML of crop water supply. In addition, by only looking at the average figure of cotton price, we do not know the extent to which the value of each of product components affect the average value of the crop products and/or how to determine the break-even points (in lint yield or lint price) for evaluating business risks.

Given that lint percentage is assumed constant (e.g. 40%, see Table 7.2), in the next level of analysis (Section 7.3.4), the two key drivers of economic water use index – crop water use index and weighted average cotton price – are decomposed into their drivers.

Table 7.3 WESM Analysis (year 2012) – Panel C (Level 3 of WESM)

Panel C1-Analysis of Profit Margin		
Variable	Level	Formula
Profit margin$_{\mathbf{it}}$(%)	**Level 3**	$= \left[\mathbf{Opearating\ profit_{it}}\left(\frac{\$}{\mathbf{ha}}\right) \div \mathbf{Total\ sales\ revenue_{it}}\left(\frac{\$}{\mathbf{ha}}\right)\right] \times 100\%$ = \$1307 /ha ÷\$4868 /ha = **26.85%**
Operating profit$_{it}\left(\frac{\$}{ha}\right)$	Level 4	Calculated in Panel D1 = \$1307 /ha
Total sales revenue$_{it}\left(\frac{\$}{ha}\right)$	Level 5	Calculated in Panel E4 = \$4868 /ha

Panel C2-Analysis of Economic water use index		
Variable	Level	Formula
Economic water use index$_{\mathbf{it}}\left(\frac{\$}{\mathbf{ML}}\right)$	**Level 3**	$= \text{Crop water use index}_{it}\left(\frac{\text{kg of lint}}{\text{ML}}\right) \div \text{Lint percentage}_{it}(\%)$ $\times \text{Weighted average cotton price}_{it}\left(\frac{\$}{\text{kg of total product}}\right)$ = 140 kg/ML ÷ 40% x \$1.03 /kg = **\$361 /ML**
Crop water use index$_{it}\left(\frac{\text{kg of lint}}{\text{ML}}\right)$	Level 4	Calculated in Panel D2 = 140 kg of lint/ML

Lint percentage$_{it}$ (%)	WESM Input	Crop Variety (assumption: SICOT 43BRF) = 40%
Weighted average cotton price$_{it}\left(\frac{\$}{\text{kg of total yield}}\right)$	Level 4	Calculated in Panel D3 = \$1.03 /kg

7.3.4 Fourth-level of analysis

7.3.4. 1 Decomposition of operating profit

Table 7.3, Panel D1, shows that the business's operating profit $1,307 per ha resulted from $4,868/ha of total sales revenue after deducting $3,561/ha of operating cost. As total sales revenue and operating cost are the two drivers of operating profit and profit margin, the break-down of the operating profit figure is useful for looking at potential increases in economic return for the crop business by increasing sales revenue and/or cutting operating cost.

However, by only viewing total sales revenue and operating cost figures, we do not know how total sales revenue and/or operating cost change as a result of management decision(s) and how the change(s) add value to the business. Therefore, in the fifth-level of analysis (Section 7.3.5), information of sales revenue and operating cost is drilled down into more detailed information to allow us to gain more insights into what drives the two quantitative terms that determine profitability of the crop business.

7.3.4.2 Decomposition of crop water use index

Table 7.3, Panel D2, explains that a crop water use index of 140 kg of lint per ML of crop water supply is a product of a transpiration index of 2,531 kg of biomass/ML of transpiration, a harvest index of 0.16 kg of lint /kg of biomass, and a water input efficiency of 35%.

More specifically, there are two steps involved in the decomposition of the crop water use index. First, by multiplying 2,531 kg of biomass/ML of transpiration (transpiration index value) and 0.16 kg of lint /kg of biomass (harvest index value), the relationship between the primary crop product produced and the amount of water that contributed to crop production is quantified, which is 405 kg of lint produced per ML of transpiration (2,531 x 0.16 = 405). Second, incorporation of water input efficiency into the ratio of lint to transpiration allows us to quantify the ability of the crop business to generate primary crop product from each unit of water volume supplied to the cropping system. More particularly, a water input efficiency of 35% indicates that for every 1 ML of water resource that is supplied to the cropping system, only 0.37 ML is actually used by plants for producing biomass. This means the amount of lint product produced from 1 ML of crop water supply is 142 kg of lint (e.g., 405 x 0.35 = 142[100]).

Of the three components of the crop water use index, the transpiration index and harvest index are driven by nitrogen management and pest and disease management, respectively, while the water input efficiency measure is driven by water management decisions. In order to gain more insights into how well crop managers manage and use water for their crop production, as well as to quantify the impact of water management decisions, particularly irrigation scheduling decisions on water input efficiency, it is assumed that nitrogen is applied sufficiently for crop production and pest and disease are well controlled. This leaves the key component that drives the crop water use index, and hence economic water use index, water input efficiency. In the next section, (Section 7.3.5), the water input efficiency figure is further broken down into its productive and non-productive water components.

7.3.4.3 Decomposition of weighted average cotton price

The decomposition of weighted average cotton price into its components in Table 7.3, Panel D3, realises that the average cotton price of $1.02 per kg of total cotton product is driven by the lint percentage of 40%, the lint price of $2.09/kg, and cotton seed price of $0.32/kg.

As presented in Table 7.2, lint price and cotton seed price used for this example are obtained from the sample budget for furrow irrigated cotton in 2014–2015 for the Central and Northern NSW area, reported by NSW Department of Primary Industries (NSW Department of Primary Industries 2015). In practice, lint price is reported in dollar per bale of lint[101], while cotton seed price is reported in dollar per tonne of cotton seed. Accordingly, $2.09/kg of lint is equivalent to $474/bale of lint, and $0.32/kg of cotton seed is equivalent to $320/tonne of cotton seed.

As illustrated in Table 7.3, Panel C2, the economic water use index is driven by three components, including crop water use index, weighted average cotton price, and percentage lint. In order to isolate the effect of economic factors (for example, lint price and cotton seed price) and variety factors (for example, lint percentage) from the effect of crop management

[100] Slight difference in crop water use index value occurs between two calculating approaches (e.g. based on its definition versus its decomposition components) due to rounding.
[101] 1 bale = 227 kg

decisions (which are captured by the crop water use index) on the economic water use index, in this example, it is assumed that lint price, cotton seed price, and lint percentage remain constant.

Table 7.3 WESM Analysis (year 2012) – Panel D (Level 4 of WESM)

Panel D1-Analysis of Operating profit		
Variable	Level	Formula
$\mathbf{Operating\ profit_{it}}\left(\frac{\$}{\mathbf{ha}}\right)$	**Level 4**	$= \text{Total sales revenue}_{it}\left(\frac{\$}{\text{ha}}\right) - \text{Total operating cost}_{it}\left(\frac{\$}{\text{ha}}\right)$ = \$4868 /ha - \$3561 /ha = **\$1307 /ha**
$\text{Total sales revenue}_{it}\left(\frac{\$}{\text{ha}}\right)$	Level 5	Calculated in Panel E4 = \$4868 /ha
$\text{Total operating cost}_{it}\left(\frac{\$}{\text{ha}}\right)$	Level 5	Calculated in Panel E5 = \$3561/ ha
Panel D2 - Analysis of Crop water use index		
$\mathbf{Crop\ water\ use\ index_{it}}\left(\frac{\mathbf{kg\ of\ lint}}{\mathbf{ML}}\right)$	**Level 4**	$= \text{Transpiration index}_{it}\left(\frac{\text{kg of biomass}}{\text{ML of tranpiration}}\right) \times \text{Harvest index}_{it}\left(\frac{\text{kg of lint}}{\text{kg of biomass}}\right) \times \text{Water input efficiency}_{it}(\%)$ = 2531 x 0.16 x 34.45% = **140 kg of lint/ML**
$\text{Transpiration index}_{it}\left(\frac{\text{kg of biomass}}{\text{ML of tranpiration}}\right)$	Level 5	Calculated in Panel E2 = 2531 kg/ML

Harvest index$_{it}$ $\left(\frac{\text{kg of lint}}{\text{kg of biomass}}\right)$	Level 5	Calculated in Panel E3 = 0.16 kg of lint/ kg of biomass
Water input efficiency$_{it}$(%)	Level 5	Calculated in Panel E1 = 34.45%
Panel D3 - Analysis of Weighted average cotton price		
Weighted average cotton price$_{it}$ $\left(\frac{\$}{\textbf{kg of total yield}}\right)$	**Level 4**	$= \left[\text{Lint percentage}_{it}\ (\%) \times \text{Lint price}_{it} \left(\frac{\$}{\text{kg}}\right)\right] + \left[\text{Seed percentage}_{it}\ (\%) \times \text{Seed price}_{it} \left(\frac{\$}{\text{kg}}\right)\right]$ = (40% x \$2.09) + (60% x \$0.32) = **\$1.03 /kg**
Lint percentage$_{it}$ (%)	WESM Input	Crop Variety (assumption: SICOT 43BRF) = 40%
Seed percentage$_{it}$ (%)	WESM Input	Accounting Data (assumption) = 100% - Lint percentage$_{it}$ (%) = 100% - 40% = 60%
Lint price$_{it}$ $\left(\frac{\$}{\text{kg}}\right)$	WESM Input	Accounting Data (Assumption) = \$2.09/ kg of lint
Seed price$_{it}$ $\left(\frac{\$}{\text{kg}}\right)$	WESM Input	Accounting Data (Assumption) = \$0.32/ kg of seed

7.3.5 Fifth-level of analysis

7.3.5.1 Decomposition of water input efficiency

The decomposition of water input efficiency presented in Table 7.3, Panel E1, reveals that of 13.85 ML/ha of water resource supplied to the cropping system, 58% of it (equivalent to 8.03 ML/ha) is lost from the cropping system and hence does not contribute to yield production. Given that 7.5% of water loss from runoff is recycled back to the farming system, only 34.5% of water supplied is actually used by the crop for transpiration to generate biomass and ultimately profit for the business.

Furthermore, Table 7.3, Panel G9, reports that of 13.85 ML/ha of crop water supply, 8.66 ML/ha is provided by irrigation water. This illustrates that reducing the amount of water lost will decrease the amount of water that needs to be abstracted from the environment (e.g. irrigation water). Alternatively, the savings can be used to increase crop production elsewhere on the farm assuming available land on site. Either way, minimising water loss provides positive economic and environmental outcomes for the crop business.

Water supplied to the cropping system can be lost via soil evaporation, deep drainage, runoff or change in soil water. In order to quantify the degree to which each of non-productive water components contribute to the total water lost from the cropping system for identifying areas for improving water efficiency, water loss is further decomposed into its components.

Table 7.3, Panel F2, shows that 8.03 ML/ha of water lost includes 5.83 ML/ha of soil evaporation, 1.87 ML/ha of water lost due to deep drainage, 0.35 ML/ha of loss from water runoff and a relatively small decrease in soil water (e.g., 0.02 ML/ha). For a particular soil type, soil evaporation does not vary significantly with regard to water management. Therefore, in order to improve water input efficiency, it is essential to reduce deep drainage and loss from water runoff.

7.3.5.2 Decomposition of total operating cost

Table 7.3, Panel E5, reports that the total operating cost of $3,561/ha consists of $522/ha of total water cost, $227/ha of other variable operating costs, and $2,812/ha of fixed operating costs.

As described in Table 7.3, Panel F5, $522/ha of total water cost (includes licensed irrigation costs in the example) is a product of irrigation volume of 8.66 ML/ha and the unit cost of licensed irrigation of $60.30/ML. In addition, $227/ha of other variable operating costs are obtained by multiplying the lint price of $0.12/kg by lint yield of 1894 kg/ha.

Given that operating fixed cost, lint price, and unit licensed irrigation costs are assumed constant, total operating cost is driven by the amount of irrigation abstracted and lint produced. Furthermore, since irrigation schedules are designed in DSSAT in a way to ensure sufficient water is supplied to the cropping system, lint yield does not vary significantly with regard to water management. Accordingly, the amount of irrigation abstracted is the key driving factor of operating cost.

Table 7.3 WESM Analysis (year 2012) – Panel E (Level 5 of WESM)

Panel E1 – Analysis of Water input efficiency		
Variable	WESM Level	Formula
Water input efficiency$_{it}$(%)	**Level 5**	$= 100\%$ $-$ [Crop water loss to crop water supplied ratio (%) $+$ Recycled runoff to crop water supplied ratio (%) = 100% - (58.19% + 7.36%) = **34.45%**
Crop water lost to crop water supplied ratio (%)	Level 6	Calculated in Panel G12 = 58.19%
Recycled runoff to crop water supplied ratio (%)	Level 6	Calculated in Panel G11 = 7.36%
Panel E2 – Analysis of Transpiration index		
Transpiration index$_{it}\left(\frac{\textbf{kg of biomass}}{\textbf{ML of tranpiration}}\right)$	**Level 5**	$= \text{Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$ $\div \text{Transpiration}_{it}\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$ = 12201 kg/ha ÷ 4.82 ML/ha = **2531 kg/ML**
$\text{Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation) = 12,201 kg/ha

$\text{Transpiration}_{it}\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation) = 4.82 ML/ha
Panel E3 – Analysis of Harvest index		
$\mathbf{Harvest\ index_{it}}\left(\frac{\mathbf{kg\ of\ lint}}{\mathbf{kg\ of\ biomass}}\right)$	**Level 5**	$= \text{Lint yield}_{it}\left(\frac{\text{kg of lint}}{\text{ha}}\right) \div \text{Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$ = 1,894 kg/ha ÷ 12,201 kg/ha = **0.16**
$\text{Lint yield}_{it}\left(\frac{\text{kg of lint}}{\text{ha}}\right)$	Level 7	Calculated in Panel F1 = 1,894 kg/ha
$\text{Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation) = 12,201 kg/ha
Panel E4-Analysis of Total sales revenue		
$\mathbf{Total\ sales\ revenue_{it}}\left(\frac{\$}{\mathbf{ha}}\right)$	**Level 5**	$= \text{Sales revenue}_{it}(\text{lint})\left(\frac{\$}{\text{ha}}\right) + \text{Sales revenue}_{it}\,(\text{cotton seed})\left(\frac{\$}{\text{ha}}\right)$ = \$3959 /ha + \$909 /ha = **\$4868 /ha**

Sales revenue$_{it}$(lint) $\left(\frac{\$}{ha}\right)$	Level 6	Calculated in Panel F3 = \$3959 /ha
Sales revenue$_{it}$(cotton seed) $\left(\frac{\$}{ha}\right)$	Level 6	Calculated in Panel F4 = \$909/ha
Panel E5-Analysis of Total operating cost		
Total operating cost$_{it}$ $\left(\frac{\$}{ha}\right)$	**Level 5**	$= \text{Total water cost}_{it}\left(\frac{\$}{ha}\right) + \text{Other variable cost}_{it}\left(\frac{\$}{ha}\right) + \text{Fixed operating cost}_{it}\left(\frac{\$}{ha}\right)$ = \$522 /ha + \$227/ha + \$2812/ha = **\$3561/ ha**
Total water cost$_{it}$ $\left(\frac{\$}{ha}\right)$	Level 6	Calculated in Panel F9 = \$522 /ha
Other variable cost$_{it}$ $\left(\frac{\$}{ha}\right)$	Level 6	Calculated in Panel F10 = \$227/ha
Fixed operating cost$_{it}$ $\left(\frac{\$}{ha}\right)$	WESM Input	Accounting Data (assumption) = \$2812/ha

7.3.6 Summary of WESM analysis

The analysis is conducted under the assumptions that economic factors, lint percentage, and irrigation allocation ratios remain unchanged while nitrogen practices and pest and disease are well managed. This allows the crop manager(s) to isolate the effect of water management on the overall water and economic sustainability performance of the crop business. It also enables crop managers to assess whether suboptimal performance of the business's sustainability performance is driven by water management decisions or other factors.

The first-level of analysis shows that the profit to water cost ratio is driven by return on water and water use leverage. In addition, in the second-level of analysis, it is demonstrated that water use leverage is driven by the ratio of recycled runoff. Moreover, the two drivers of return on water, the economic water use index and profit margin, are found to be impacted by crop water use index and total operating cost respectively (the third-level of analysis).

The fourth-level of analysis reveals that the crop water use index is mainly affected by water input efficiency, which is shown to be driven by the amount of deep drainage and loss from water runoff (the fifth and sixth levels of analysis). Furthermore, in the fifth-level of analysis, it is shown that total operating cost is affected by the amount of irrigation abstracted, which is driven by the irrigation infiltrated and ratio of recycled runoff.

The WESM model analysis shows that, in respect to water management, the two key factors that drive the profit to water cost ratio are the amount of water lost through deep drainage and runoff.

7.4 Conclusion

Chapter 7 provides an empirical example of the how the developed WESM model works and, based on the two-phased simulation modelling process, how the model generates valid, reliable and useful information that supports crop managers in better sustainability- related decision making and control.

More specifically, this chapter uses the sample year 2012 presented here (under current furrow irrigation practice) to quantify all measures across seven levels of the WESM model and conduct analysis to examine the relationship between high-level and low-level information. Through the analysis of the summary water and economic sustainability measure – the profit to water cost ratio – over seven levels of analysis for the sample year 2012, water lost from the system due to deep drainage and runoff are identified as the two key factors that drive the profit to water cost ratio. Furthermore, the analysis enables me to generate a first set of performance outputs that can be used for standard and target setting in decision making and control for researchers and farmers.

In the next chapter (Chapter 8), an improved furrow irrigation practice is tested in the same WESM model and the results are compared against that of the current furrow irrigation practice. This identifies both economic and environmental (water) sustainability implications of improving furrow irrigation practices.

Chapter 8. A step towards sustainability of crop businesses - Improving furrow irrigation management practices

8.1 Introduction

This chapter contains two key things. First, following Chapter 7, this chapter examines how the overall environmental and economic sustainability performance of a cotton business can be improved as a result of changing furrow irrigation management practice. To do this, I apply and test theory relating to how irrigation practice can be improved and the kind of impacts this has on environmental sustainability and economic performance.

Second, the output of Scenario 2 could provide the basis for better targets (compared to Scenario 1). By doing this, I further demonstrate the model's usefulness and provide an approach to overcome inherent target setting problems in PMS design.

Section 8.2 presents a comparison of furrow irrigation management practice (i.e. SIRMOD input) and furrow irrigation performance (i.e. SIRMOD output) between the current furrow irrigation practice (Scenario 1) and the improved furrow irrigation practice (Scenario 2).[102] As discussed in Chapter 6, SIRMOD output data are used for crop production simulation modelling (using DSSAT) to generate water and crop production input data for WESM analysis.

Section 8.3 reports the results of univariate tests (using the student *t*-test) on the statistical differences between the Scenario 2 sample (based on the improved furrow irrigation practice) and the Scenario 1 sample (based on the current furrow irrigation practice) across seven levels of WESM, following a bottom-up approach. Furthermore, Section 8.4 contains analyses of environmental and economic differences between the two scenarios. The comparisons between Scenario 1 and Scenario 2 provide insights into how changes in furrow irrigation decisions drive changes in the overall economic and environmental sustainability performance of a crop business, and how the changes can be translated into better

[102] While these furrow irrigation parameters were described and reported in Chapter 6 for each of scenarios, in Section 8.2, a comparison between the base line furrow irrigation practice (Scenario 1) and alternative (improved) furrow irrigation practice (Scenario 2) is presented to provide basis for variance analysis between two scenarios in this chapter.

environmental sustainability performance, as well as increased economic value for the crop business.

Finally, Section 8.5 summarises the chapter, including implications for better water management decisions to drive crop businesses to move towards sustainability. I find that moving from the current to the improved furrow irrigation practice improves both environmental and economic performance thereby making the activity more sustainable.

8.2 Comparisons of furrow irrigation management practice and furrow irrigation performance between Scenario 1 and Scenario 2

This section provides a comparison between the base line furrow irrigation practice (Scenario 1) and alternative, improved furrow irrigation practice (Scenario 2) to provide basis for variance analysis between two scenarios in later sections in this chapter.

Chapter 7 demonstrated that, given good nitrogen, pest and disease management, and constant economic factors[103], crop factors[104], and irrigation allocation ratios[105]; the two key factors that drive the profit to water cost ratio are the loss of water from the system due to deep drainage and water runoff. In addition, in Chapter 4, it is discussed that loss from water runoff can be managed through better water recycling management practices, while loss from deep drainage can be managed improved scheduling and management of irrigation.

As described in Table 8.1, the current furrow irrigation practice (Scenario 1) is characterised by the two irrigation factors; furrow inflow rate of 2.80 l/s and time of cut-off (irrigation time) at 745.00 minutes. As a result of such relatively low furrow inflow and the considerable time irrigating (e.g.173 minutes longer than the advance time[106]), infiltration (irrigation infiltrated) is not uniformly distributed along the furrow (see Figure 8.1). More particularly, there is a significant difference (36 mm) in the amount of irrigation applied between the top (i.e. 91 mm per irrigation) and the bottom (i.e. 55 mm per irrigation) of the furrow with the average of irrigation applied of 79 mm (or 0.79 ML/ha) per irrigation event (see Figure 8.1).

[103] Including lint price, cotton seed price, unit irrigation cost, unit other variable cost, operating fixed cost.
[104] For example, lint percentage and cotton seed percentage.
[105] For example, proportions of licensed irrigation traded irrigation.
[106] Advance time is defined as the time required for the irrigation water to reach the end of the furrow (Smith et al. 2005).

Furthermore, it was shown that a considerable deep drainage fraction (ratio of deep drainage to average irrigation applied) of 21% resulted from the current furrow irrigation practice (e.g. 0.17mm/0.79 mm = 21%). This loss of water to deep drainage not only impacts the environment but also represents a significant water and economic loss for the Australian cotton industry.[107]

In order to improve the distribution uniformity of furrow irrigation systems, which will reduce the amount of irrigation infiltrated per event as well as minimise the amount of crop water loss through deep drainage, a more advanced furrow irrigation practice is examined in this chapter. Increasing furrow inflow rates, while reducing time of cut-off below that of current furrow irrigation practices, result in improved irrigation performance[108] (Smith et al. 2005). More specifically, Smith et al. (2005) show that a flow rate of 6 l/s is considered a good irrigation management strategy for improving irrigation performance without inducing erosion. In respect to irrigation time (or cut-off time), it is suggested that stopping irrigation when irrigation water reaches the bottom of the furrow, in other words setting time to cut-off equal to the advance time, leads to significantly improved irrigation performance.

In this thesis, the value of two irrigation factors – the furrow inflow rate and irrigation time – that define the improved irrigation management practice for furrow irrigation on Vertosols were obtained from a real-world example by J. Purcell (Aqua-Tec Consulting[109], personal communication, 2015). Table 8.1, Panel A, shows that given the same cropping system that is used for Scenario 1 (e.g. same furrow characteristics, soil type and location), the improved irrigation management practice (Scenario 2) is defined by a furrow inflow rate of 6.00 l/s and cut-off time of 310 minutes. While Scenario 2 represents an improved situation compared to Scenario 1 in respect to economic and environmental performance (which will be discussed later in this chapter), it does not necessary reflect optimal water management conditions. In future research, an optimization process can be undertaken in order to determine optimal conditions for maximising the overall water and economic sustainability.

[107] Details of net environmental loss and net economic loss of the current irrigation management practice (compared to the improved irrigation management practice) are discussed in Section 8.4.4.

[108] Application efficiency and deep drainage losses are used as proxies for irrigation performance (Smith et al. 2005). Accordingly, increased application efficiency and reduced deep drainage losses indicate improvements in irrigation performance.

[109] http://www.aquatechconsulting.com.au/jim-purcell.htm

Table 8.1, Panel B, reveals that, by setting a higher flow rate (6 l/s in Scenario 2 as opposed to 2.80 l/s in Scenario 1) while reducing the gap between the cut-off time and the advance time (e.g. from 173 minutes in Scenario 1 to 85 minutes in Scenario 2), the distribution uniformity of irrigation applied is improved to 93%. Furthermore, as illustrated in Figure 8.1, there is a much smaller difference between the infiltration amount per event (less than 10 mm) between the top (e.g. 57 mm per irrigation event) and the bottom (e.g. 48 mm per irrigation event) of the furrow, with an average of infiltration of 55 mm (or 0.55 ML/ha) per irrigation event. Since the amount of water infiltrating along the furrow for Scenario 2 is less variable than that of Scenario 1, it was predicted there would be more uniform total yield produced along the furrow[110] for Scenario 2 than for Scenario 1. Most importantly, water loss from deep drainage was reduced substantially, reducing from 10.1 mm (or 0.101ML/ha) per irrigation event to 0.4 mm (or 0.004 ML/ha) per irrigation event (see Table 8.1, Panel C)

Though moving from the current irrigation management practice to the improved irrigation management practice leads to greater uniformity of irrigation across the furrow, reduced irrigation infiltrated per event, as well decreased loss to deep drainage, water runoff from irrigation increases significantly. Table 8.1, Panel B, shows that there is not much difference in inflow to the cropping system between Scenario 1 (with 125.20 m^3) and Scenario 2 (with 111.60 m^3), but the tailwater fraction increases considerably from 10.42% for Scenario 1 to 30.72% for Scenario 2 as a result of higher furrow inflow. Consequently, the amount of water runoff changes from 9 mm (or 0.09 ML/ha) per event for Scenario 1 to 24 mm (or 0.24 ML/ha) per event for Scenario 2 (see Table 8.1, Panel C). However, runoff from irrigated fields must be captured and recycled. Moreover, it is assumed that a better water recycling practice is used in Scenario 2 with 85% recovery compared to 75% in Scenario 1. This also reduces the amount of irrigation water needing to be abstracted from the environment (i.e. by adding water recycled from runoff to the cropping system).

In the next section, simulated results generated by DSSAT for Scenario 1 and Scenario 2 are presented to show the input data for WESM analysis and comparison between the two scenarios.

[110] This also results in potential improvement in fibre quality and hence economic value of the crop.

Table 8.1 Furrow irrigation data: Scenario 1 versus Scenario 2

	Scenario 1	Scenario 2	Information source
Panel A: SIRMOD Input – Scenario 1 versus Scenario 2			
SIRMOD Input Variables			
Inflow controls			
Furrow Inflow, l/s	2.80	6.00	
Time of Cut-off, min	745.00	310.00	
Panel B – Simulated results (SIRMOD Output) – Scenario 1 versus Scenario 2			
Irrigation performance			
Advance time, min	572.10	225.50	
Distribution Uniformity, %	85.45	93.23	
Tailwater Fraction	10.42	30.72	
Volume Balance			
Inflow, m^3	125.20	111.60	
Infiltration, m^3	112.40	77.30	
Outflow, m^3	12.80	34.30	
Panel C –Furrow irrigation input to WESM – Scenario 1 versus Scenario 2			
Irrigation infiltrated per event $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	**0.79**	**0.55**	Calculated based on SIRMOD Output
Runoff from irrigation per event $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	**0.09**	**0.24**	Calculated based on SIRMOD Output
Ratio of recycled runoff	**75%**	**85%**	Assumption
Deep drainage per event $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	**0.103**	**0.004**	DSSAT Simulated Output (average over 86 years)

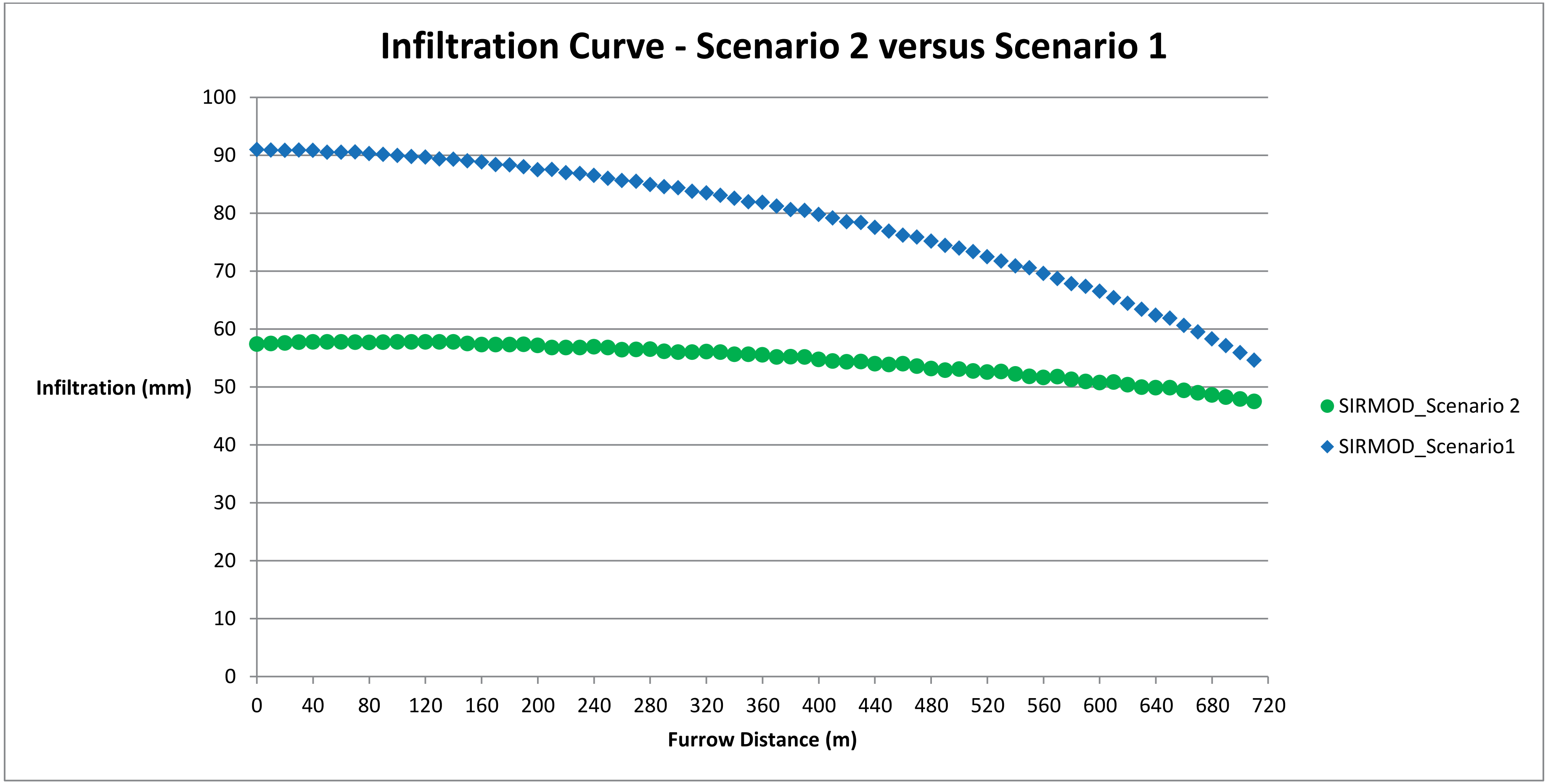

Figure 8.1 Infiltration curve_ Scenario 2 versus Scenario 1

8.3 Statistical test between Scenario 1 and Scenario 2

This section provides results of a statistical test *(t-test)* for the significance of the difference between the means of two samples – Scenario 1 and Scenario 2 as described above.

Each sample includes 90 crop-year observations obtained from DSSAT crop production simulation modelling, from 1924 to 2014. DSSAT results show that for this period there are four years (1928, 1940, 1945 and 2002) which had no crop production due to severe drought. As a result, for each of the two scenarios, the final sample includes 86 crop-years of observations.

Section 8.3.1 reports results of *t-test* for simulated variables of Scenario 1 and Scenario 2 which are used as WESM model input data, followed by results of the *t-test* for low-level environmental variables (Level 7 and Level 6, Section 8.3.2), low-level economic variables (Level 7 and Level 6, Section 8.3.3 and Level 5, Section 8.3.4), middle-level variables (Level 4 and Level 3) (Section 8.3.5), and high-level variables (Level 2 and Level 1) (Section 8.3.6).

The analysis and discussion of the significance of the difference between the means of two samples follows the bottom-up approach to demonstrate how changes in furrow irrigation management decisions at the operational level drive changes in middle-level measures and high-level measures of the WESM model, and eventually the economic and environmental sustainability performance of a crop business.

8.3.1 Description of the WESM input variables

In this section, the difference in the means of WESM simulated input variables between Scenario 1 and 2 are presented and discussed (see Table 8.2). More particularly, three sets of simulated data are reported as follows.

First, Table 8.2, Panel A, reveals that by switching from the current furrow irrigation management practice (represented by Scenario 1) to the improved one (Scenario 2), the amount of irrigation infiltrated (infiltration) per irrigation event is reduced by 30% (from 0.79 ML/ha per event to 0.55 ML/ha per event). In contrast, the amount of runoff from irrigation per event increases from 0.09 ML/ha per event to 0.24 ML/ha per event. However, unlike water loss due to deep drainage, a high proportion of water runoff from irrigation can be recycled to the cropping system, for example through water recycling management, to supplement rainfall and hence reduce the amount of irrigation water needing to be abstracted from the environment. It is assumed that for Scenario 2, better water recycling management allows 85% of runoff from irrigation to be recycled to the cropping system (as opposed to 75% in Scenario 1). In this respect, water loss to irrigation runoff in Scenario 2 is reduced considerably. Details of total water runoff, recycled runoff, and water lost from runoff of the two scenarios are reported in Section 8.3.2.

Second, in respect of economic yield of crop production, there is no statistically significant difference in the means of total yield between Scenario 1 and Scenario 2 (see Table 8.2, Panel B). This suggests that, on average, the crops did not grow any better in Scenario 2 conditions compared to Scenario 1, while it is not unreasonable to have expected the mean yield in Scenario 2 to be higher than the mean yield in Scenario 1. However, for ease of comparison, I chose a common irrigation management which, in preliminary trials, seemed appropriate for both scenarios. The more extensive dataset I now have suggests that Scenario 2 irrigation management might need further refinement to take advantage of the greater uniformity in water application. Since there is not much difference in total yield between Scenario 1 and Scenario 2[111], it is suggested that changes in economic value are a result of changes in the amount of irrigation abstracted from the environment between the two scenarios. This is explored in Section 8.3.2.

Third, Table 8.2, Panel C, reports a range of crop water components simulated by DSSAT. Since both Scenario 1 and Scenario 2 samples are examined under the same cropping system, same period of time (over the same 86 years), they share the same weather conditions and similar number of irrigation events. Therefore, it is not surprising that there is no statistical difference between parameter values for the two scenarios except for deep drainage and change in soil water status over each season. More specifically, deep drainage decreased by 96% (from 1.01 ML/ha for Scenario 1 to 0.04 ML/ha for Scenario 2) when implementing the improved irrigation management practice. In addition, change in soil water under S2 is -1.19 ML/ha while that for S1 is only -0.06 ML/ha. Accordingly, compared to S1, S2 demonstrates smaller water loss in respect to change in soil water, which means greater use is made of the soil water by the crop. This substantial reduction in deep drainage and change in soil water

[111] However, it is still a better management practice than S1 due to a substantial reduction in deep drainage and a greater ratio of recycled runoff, leading to a considerable decrease in total water lost to the cropping system.

helps to explain how the overall economic and environmental sustainability performance of a crop business can change as a result of irrigation management decisions at the operational level, as well as provide economic and environmental benefits, which will be discussed in later subsections of Section 8.3.

Apart from water and crop production input variables, which are obtained from SIRMOD and DSSAT simulation, economic data and crop data are input to WESM to allow quantification of the measures presented in WESM. In order to isolate the effect of water management decisions, it is assumed that economic data and crop data remains constant across the two scenarios. In addition, it is assumed that 100% of irrigation water is sourced from licensed irrigation water in both cases (see Table 7.3 for values of non-simulated WESM input variables).

Table 8.2 Statistical Test: Univariate Mean Differences in WESM Simulated Input Data between Scenario 1 and Scenario 2

Variable	**Information Source**	**Mean (Scenario 1)**	**Mean (Scenario 2)**	**Difference in mean** $\left(\frac{\mathbf{S2-S1}}{\mathbf{S1}}\right)\times\mathbf{100\%}$	***p-value***	
Panel A: Furrow irrigation simulated data[112]						
Irrigation infiltrated per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	SIRMOD	0.79 ML/ha per event	0.55 ML/ha per event	–30%		
Runoff from irrigation per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	SIRMOD	0.09 ML/ha per event	0.24 ML/ha per event	166%		
Ratio of recycled runoff (%)	Assumption	75%	85%	13%		
Panel B: Crop production simulated data (reported for a crop season period)						
Biomass yield$_{it}$ $\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	DSSAT	11,948 kg/ha	12,270 kg/ha	2.7%	*0.004*	**
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	DSSAT	4,507 kg/ha	4,514 kg/ha	0.1%	*0.880*	
Panel C: Crop water simulated data (reported for a crop season period)						
Rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	4.57 ML/ha	4.57 ML/ha	0%	*0.993*	
Runoff from rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	0.52 ML/ha	0.53 ML/ha	0.6%	*0.958*	
Soil evaporation $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	6.24 ML/ha	6.10 ML/ha	–2.3%	*0.254*	

[112] For each sample, value of each of furrow irrigation simulated variables presented in Panel A is constant across years.

$\text{Transpiration}_{it}\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$	DSSAT	4.61 ML/ha	4.69 ML/ha	1.6%	*0.259*	
$\text{Number of irrigation events }_{it}\left(\frac{\text{events}}{\text{crop season}}\right)$	DSSAT	9.8	10.2	4%	*0.111*	
$\text{Deep drainage}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	1.01 ML/ha	0.04 ML/ha	–95.7%	*0.000*	***
$\text{Change in soil water}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$	DSSAT	-0.06 ML/ha	-1.19 ML/ha	1,938%	*0.000*	***

This Table reports univariate tests using the student t**-test.** Two-tailed test of significance: ***< 0.001, **< 0.01 and *< 0.05.

8.3.2 Statistical test – Level 6 and Level 7 – Low-level environmental variables

This section reports results of *t-tests* for the low-level (e.g. Level 7 and Level 6) of WESM variables with regards to environmental measurement (see Table 8.3, Panel G).

8.3.2.1 Water inflow and outflow components in SIRMOD

Table 8.3, Panel G1 to G3, provide the three water inflow and outflow components given by SIRMOD: irrigation infiltrated, runoff from irrigation, and irrigation applied. First, there is statistically significant difference (*p-value* < 0.001) between the means of irrigation infiltrated [113] for Scenario 1 and Scenario 2. More specifically, there is, on average a substantial reduction (28%) of total irrigation infiltrated over a crop season when shifting from the current irrigation management practice to the improved one. There is also a statistically significant difference (*p-value* < 0.001) in the means of runoff from irrigation between the two scenarios: total runoff from irrigation over a crop season increases by 174% from Scenario 1 to Scenario 2. The significant changes in the amount of total irrigation infiltrated and total runoff from irrigation over a crop season can be explained by the significant decrease in the amount of irrigation infiltrated per event and the significant increase in runoff from irrigation per event, respectively (Section 8.3.1).

Since the irrigation applied to the field is the sum of the infiltration and runoff, it is not surprising that the irrigation applied to Scenario 2 is only 7% less than that applied to Scenario 1, but this difference is statistically different.

8.3.2.2 Water runoff, water recycling and irrigation abstracted

Table 8.3, Panel G4 to G7, shows water runoff components of the cropping system and the change in the amount of water abstracted from the environment as a result of recycling management practices.

First, total water runoff from the cropping system is from two sources; runoff from rainfall described in Table 8.2, Panel C, and runoff from irrigation, discussed above. Table 8.3, Panel G4, shows that there is no significant difference in the runoff from rainfall. However, in

[113] Note that for irrigation, I am effectively replacing the DSSAT irrigation infiltrated (or infiltration) calculations with SIRMOD's because that provides better realism, particular down the furrow as illustrated in Figure 8.1.

respect to total water runoff over a crop season, the value for Scenario 2 is significantly greater than for Scenario 1due to the substantial increase in runoff from irrigation of 174%.

Second, as discussed in Section 8.3.1, under the improved water management practice, 85% of water runoff is assumed to be recycled to the cropping system in Scenario 2, while only 75% of water runoff is recycled under the current water management scenario. It is also noted that these ratios of recycled runoff are applied for both runoff from irrigation and runoff from rainfall. Table 8.3, Panel G5, shows that when water recycling management is taken into account, a considerable amount of runoff is recycled to the cropping systems (e.g. 2.55 ML/ha for Scenario 2 compared with 1.07 ML/ha for Scenario 1).

Third, for the entire cropping system, which includes the cropped field and the dam for storing abstracted and recycled water, in an irrigation season, the farmer will have to irrigate the field, which will include both irrigation infiltrated (or infiltration) and runoff from irrigation. However, depending on the efficiency of his operations, and in particular his recycling of runoff, he will able to use a recoverable portion of total water runoff (which is referred to as ratio of recycled runoff) which is returned to the dam. This will reduce the amount of irrigation water that he needs to abstract from the environment. Thus, there is a significant reduction of 27% in irrigation water abstracted from the environment moving from Scenario 1 to Scenario 2 (see Table 8.3, Panel G6).

8.3.2.3 Crop water loss and its water components

Table 8.3, Panel G8, shows that there is a statistically significant difference in the amount of crop water lost (*p-value* < 0.001) over a crop season between the Scenario 1 and Scenario 2. Of the four components of crop water loss, including soil evaporation, deep drainage, loss from water runoff[114] and change in soil water, deep drainage and change in soil water are shown to be the key drivers of the reduction in total crop water loss. It is shown that moving from Scenario 1 to Scenario 2 results in a reduction of water lost from the cropping system of 2.15 ML/ha. This implies that the overall water management of S2 has been more effective than for S1. This is important because water lost to deep drainage is truly non-recoverable by the farmer and, in susceptible situations, is the source of irrigation-induced salinization.

[114] Loss from water runoff is a portion of total water runoff that is not recycled (calculated in Panel G7).

Detailed analysis and discussion of environmental and economic significance of Scenario 2 will be presented in Section 8.4.

8.3.2.4 Crop water supply and its water components

Table 8.3, Panel G9 to Panel G12, compare the means of crop water supply and a range of ratios of crop water components to crop water supply, which provide underpin the discussions of water input efficiency and water use leverage in the later subsections.

About one-third of crop water required (34% for Scenario 1 and 36% for Scenario 2), is provided by rainfall. It is evident that there is a significant difference in the means of recycled runoff to crop water supply ratio ($p\text{-}value < 0.001$) between Scenario 1 and Scenario 2 (see Panel G11). More specifically, when moving from Scenario 1 to Scenario 2, there is a significant increase in the means of recycled runoff to crop water supply ratio, from 8% for Scenario 1 to 20% for Scenario 2.

As a result of this, a significant reduction in the proportion of abstracted water in total crop water supply is expected when moving from Scenario 1 to Scenario 2. This relates to the water use leverage that will be discussed in Section 8.3.6.

Finally, Table 8.3, Panel G12, shows the crop water loss to crop water supply ratio. As shown in equation 6.10, crop water supply is equal to crop water loss, transpiration and recycled runoff. Mathematically, the ratios of crop water loss and recycled runoff are the complement of the ratio of transpiration to crop water supply (which is defined as water input efficiency). However, as crop water loss is reported to take up around half of crop water supply in both scenarios (57% for S1 and 43% for S2) (see Table 8.3, Panel G12), the ratio of crop water loss to crop water supply is considered as a key driver of water input efficiency. The lower the ratio of crop water loss to crop water supply, the more efficient the water resource is in producing crop production.

Table 8.3, Panel G12, shows a significant difference in the means of crop water loss to crop water supply ratio ($p\text{-}value < 0.001$) between Scenario 1 and Scenario 2.

Table 8.3 Statistical Test: Univariate Mean Differences between Scenario 1 and Scenario 2 – Panel G (Level 6 and Level 7: Low-Level Environmental Measures)

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Difference in means $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	*p*-value	
Panel G1: Calculation of irrigation infiltrated						
Irrigation infiltrated $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$ $= \text{Irrigation infiltrated per event}_{it} \left(\frac{\text{ML per event}}{\text{ha}}\right) \times \text{Number of irrigation events}_{it}$	**Level 7**	**7.76 ML/ha**	**5.59 ML/ha**	**–28%**	**0.000**	***
Irrigation infiltrated per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	WESM Input	0.79 ML/ha	0.55 ML/ha	–30%		
Number of irrigation events	WESM Input	9.8	10.2	4%	0.111	
Panel G2: Calculation of runoff from irrigation						
Runoff from irrigation $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right) =$ $= \text{Runoff from irrigation per event}_{it} \left(\frac{\text{ML per event}}{\text{ha}}\right) \times \text{Number of irrigation events}$	**Level 7**	**0.90 ML/ha**	**2.47 ML/ha**	**174%**	**0.000**	***
Runoff from irrigation per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	WESM Input	0.09 ML/ha	0.24 ML/ha	166%		
Number of irrigation events	WESM Input	9.8	10.2	4%	0.111	

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Difference in means $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	*p*-value	
Panel G3: Calculation of irrigation applied						
Irrigation applied $_{it}$ $\left(\frac{ML}{ha}\right)$ $= \text{Irrigation infiltrated}_{it} \left(\frac{ML}{ha}\right) + \text{Runoff from irrigation}_{it} \left(\frac{ML}{ha}\right)$	**Level 7**	**8.66 ML/ha**	**8.06 ML/ha**	**–7%**	**0.000**	**
Irrigation infiltrated $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	7.76 ML/ha	5.59 ML/ha	–28%	0.000	***
Runoff from irrigation $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	0.90 ML/ha	2.47 ML/ha	174%	0.000	***
Panel G4: Calculation of total water runoff						
Total water runoff $_{it}$ $\left(\frac{ML}{ha}\right) =$ $= \text{Runoff from rainfall}_{it} \left(\frac{ML}{ha}\right) + \text{Runoff from irrigation}_{it} \left(\frac{ML}{ha}\right)$	**Level 7**	**1.42 ML/ha**	**3.00 Ml/ha**	**110%**	**0.000**	***
Runoff from rainfall $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	0.52 ML/ha	0.53 ML/ha	0.6%	0.958	
Runoff from irrigation $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	0.90 ML/ha	2.47 ML/ha	174%	0.000	***

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Difference in means $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	*p*-value	
Panel G5: Calculation of recycled runoff						
Recycled runoff $_{it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$ $= \text{Total water runoff}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \times \text{Ratio of recycled runoff}$	**Level 7**	**1.07 ML/ha**	**2.55 ML/ha**	**138%**	**0.000**	***
Total water runoff $_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	1.43 ML/ha	3.00 Ml/ha	110%	0.000	***
Ratio of recycled runoff $_{it}$ (%)	WESM Input	75%	85%	13%		
Panel G6: Calculation of irrigation abstracted						
Irrigation abstracted $_{it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$ $= \text{Irrigation applied}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) - \text{Recycled runoff}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$	**Level 7**	**7.59 ML/ha**	**5.51 ML/ha**	**–27%**	**0.000**	***
Irrigation applied $_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	8.66 ML/ha	8.06 ML/ha	–7%	0.000	**
Recycled runoff $_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	1.07 ML/ha	2.55 ML/ha	138%	0.000	***
Panel G7: Calculation of loss from water runoff						

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Difference in means $\left(\frac{S2-S1}{S1}\right)\times 100\%$	*p*-value	
Loss from water runoff $_{it}\left(\frac{ML}{ha}\right) = \text{Total water runoff}_{it}\left(\frac{ML}{ha}\right) - \text{Recycled runoff}_{it}\left(\frac{ML}{ha}\right)$	**Level 7**	**0.36 ML/ha**	**0.45 ML/ha**	**26%**	**0.000**	***
Total water runoff $_{it}\left(\frac{ML}{ha}\right)$	Level 7	1.43 ML/ha	3.00 ML/ha	110%	0.000	***
Recycled runoff $_{it}\left(\frac{ML}{ha}\right)$	Level 7	1.07 ML/ha	2.55 ML/ha	138%	0.000	***
Panel G8: Calculation of crop water loss						
Crop water loss$_{it}\left(\frac{ML}{ha}\right) =$ Soil evaporation $_{it}\left(\frac{ML}{ha}\right)$ + Deep drainage$_{it}\left(\frac{ML}{ha}\right)$ + Loss from water runoff $_{it}\left(\frac{ML}{ha}\right)$ + Change in soil water $_{it}\left(\frac{ML}{ha}\right)$	**Level 6**	**7.55 ML/ha**	**5.40 ML/ha**	**–28%**	**0.000**	***
Soil evaporation $_{it}\left(\frac{ML}{ha}\right)$	WESM Input	6.24 ML/ha	6.10 ML/ha	–2.3%	0.254	
Deep drainage$_{it}\left(\frac{ML}{ha}\right)$	WESM Input	1.01 ML/ha	0.04 ML/ha	–95.7%	0.000	***
Loss from water runoff $_{it}\left(\frac{ML}{ha}\right)$	Level 7	0.36 ML/ha	0.45 ML/ha	26%	0.000	***
Change in soil water $_{it}\left(\frac{ML}{ha}\right)$	WESM Input	–0.06 ML/ha	–1.19 ML/ha	1938%	0.000	***

Panel G9: Calculation of crop water supply						
Crop water supply$_{it}$ $\left(\frac{ML}{ha}\right)$ $= \text{Rainfall}_{it}\left(\frac{ML}{ha}\right) + \text{Irrigation abstracted}_{it}\left(\frac{ML}{ha}\right) + \text{Recycled runoff}$	**Level 6**	**13.23 ML/ha**	**12.63 ML/ha**	**–5%**	**0.000**	***
Rainfall $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	4.57 ML/ha	4.57 ML/ha	0%	0.993	
Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	7.59 ML/ha	5.51 ML/ha	–27%	0.000	***
Recycled runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	1.07 ML/ha	2.55 ML/ha	138%	0.000	***
Panel G10: Calculation of rainfall to crop water supply ratio (%)						
Rainfall to crop water supply ratio (%) $= \text{Rainfall}_{it}\left(\frac{ML}{ha}\right) \div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)$	**Level 6**	**34%**	**36%**	**5%**	***0.000***	***
Rainfall $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	4.57 ML/ha	4.57 ML/ha	0%	0.993	
Crop water supply$_{it}$ $\left(\frac{ML}{ha}\right)$	Level 6	13.23 ML/ha	12.63 ML/ha	–5%	0.000	***
Panel G11: Calculation of recycled runoff to crop water supply ratio (%)						
Recycled runoff to crop water supply ratio (%) $= \text{Recycled runoff}_{it}\left(\frac{ML}{ha}\right) \div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)$	**Level 6**	**8%**	**20%**	**151%**	**0.000**	***

Recycled runoff $_{it}\left(\frac{ML}{ha}\right)$	Level 7	1.07 ML/ha	2.55 ML/ha	138%	0.000	***
Crop water supply$_{it}$ $\left(\frac{ML}{ha}\right)$	Level 6	13.23 ML/ha	12.63 ML/ha	–5%	0.000	***
Panel G12: Calculation of crop water loss to crop water supply ratio (%)						
Crop water loss to crop water supply ratio (%) $= \text{Crop water loss}_{it}\left(\frac{ML}{ha}\right) \div \text{Crop water supply}_{it}\left(\frac{ML}{ha}\right)$	**Level 6**	**57%**	**43%**	**–23%**	**0.000**	***
Crop water loss$_{it}\left(\frac{ML}{ha}\right)$	Level 6	7.55 ML/ha	5.40 ML/ha	–28%	0.000	***
Crop water supply$_{it}$ $\left(\frac{ML}{ha}\right)$	Level 6	13.23 ML/ha	12.63 ML/ha	–5%	0.000	***

This Table reports univariate tests using the student t**-test.** Two-tailed test of significance: ***< 0.001, **< 0.01 and *< 0.05.

8.3.3 Statistical test – Level 6 and Level 7 – Low-level economic variables

This section provides results of *t-test* for the low-level (e.g. Level 7 and Level 6) of WESM variables with regards to measurement of economic variables, including operating cost and sales revenue components. This is summarised in Table 8.3, Panel F.

8.3.3.1 Measurement of sales revenue

For cotton crops, lint and cotton seed are the two products that can create value for a crop business. Of these two products, lint is considered a higher value product with a selling price of $2.09/kg, compared with $0.32/kg for cotton seed (see Table 7.3). Assuming that lint selling price and cotton seed selling price remains unchanged across years and between the two samples, sales revenues generated from lint product and from cotton seed product are driven by lint yield and cotton seed yield respectively.

Furthermore, both lint yield and cotton seed yield are driven by the total yield produced per hectare of land, assuming that lint percentage and seed percentage are constant for a particular variety grown, for example 40% and 60% respectively for SICOT 43BRF (see Table 7.3). Since there is no significant difference in the means of total yield between the two scenarios (as discussed in Section 8.3.1), there is no significant difference in the means of lint yield and cotton seed yield, or the sales revenue of lint and cotton seed, between the two scenarios (See Table 8.3, Panel F1 to F4).

8.3.3.2 Measurement of total water cost

In the Chapters 3 and 4, I discussed how irrigation abstracted can be sourced from licensed irrigation and traded irrigation, and therefore, total irrigation cost comprises licensed irrigation cost and traded irrigation cost. Since unit licensed irrigation cost and unit traded irrigation cost are typically not the same, how irrigation is allocated (which is reflected by the ratios of licensed irrigation and traded irrigation to total irrigation abstracted) will determine the irrigation cost.

To make it simpler, in the empirical chapters of this thesis (Chapter 7 and Chapter 8), it is assumed that 100% of irrigation is sourced from licensed irrigation, equal to the amount of irrigation abstracted calculated in Section 8.3.2 (see Table 8.3, Panel F5 and F6). Furthermore, zero rainfall cost and zero recycling costs are assumed. As a result, the irrigation cost represents total water cost[115] incurred by a crop business for crop production, reported in Table 8.3, Panel F9.

There is a significant difference in the means of total water cost (*p-value* < *0.001*) between the two scenarios, with a substantial reduction of total water cost (27%) when moving from Scenario 1 to Scenario 2.

8.3.3.3 Measurement of other variable costs

Table 8.3, Panel F10, shows that other variable cost is a product of unit other variable cost and lint yield. Since there is no significant difference in the means of lint yield, there is no significant difference in other variable costs when moving from Scenario 1 to Scenario 2.

Sections 8.3.2 and 8.3.3 lay out the cause and effect of changes in the means of environmental and economic measures at the low level (e.g. Level 7 and 6) of WESM. This allows further analysis of changes in the means of middled-level and high-level variables of WESM in the next sections (Sections 8.3.4 to 8.3.6).

[115] Water cost will change as a result of changes in irrigation abstracted which is dependent on water management decisions.

Table 8.3 Statistical Test: Univariate Mean Differences between Scenario 1 and Scenario 2 – Panel F (Level 6 and Level 7: Low-Level Economic Measures)

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $\left(\frac{S2-S1}{S1}\right)\times 100\%$	*p-value*	
Panel F1: Calculation of lint yield						
Lint yield$_{it}$ $\left(\frac{kg}{ha}\right)$ $= \text{Total yield}_{it}\left(\frac{\text{kg of total product}}{\text{ha}}\right) \times \text{Lint percentage}_{it}\ (\%)$	**Level 7**	**1,803 kg/ha** (= 8.0 bales/ha)	**1,806 kg/ha** (= 8.0 bales/ha)	**0.1%**	**0.880**	
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	WESM Input	4,507 kg/ha	4,514 kg/ha	0.1%	0.880	
Lint percentage$_{it}$ (%)	WESM Input	40%	40%	0%		
Panel F2: Calculation of seed yield						
Seed yield$_{it}$ $\left(\frac{kg}{ha}\right)$ $= \text{Total yield}_{it}\left(\frac{\text{kg of total product}}{\text{ha}}\right) \times \text{Seed percentage}_{it}\ (\%)$	**Level 7**	**2,704 kg/ha**	**2,708 kg/ha**	**0.1%**	**0.880**	
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	WESM Input	4,507 kg/ha	4,514 kg/ha	0.1%	0.880	

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	*p-value*	
Seed percentage$_{it}$ (%)	WESM Input	60%	60%	0%		
Panel F3: Calculation of sales revenue (lint)						
Sales revenue$_{it}$(lint) $\left(\frac{\$}{ha}\right)$ $= \text{Lint yield}_{it} \left(\frac{kg}{ha}\right) \times \text{Lint price}_{it} \left(\frac{\$}{kg}\right)$	**Level 6**	**$3,765 /ha**	**$3,770 /ha**	**0.1%**	**0.880**	
Lint yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	1,803 kg/ha	1,806 kg/ha	0.1%	0.880	
Lint price$_{it}$ $\left(\frac{\$}{kg}\right)$	WESM Input	$2.09/ kg of lint	$2.09/ kg of lint	0%		
Panel F4: Calculation of sales revenue (cotton seed)						
Sales revenue$_{it}$(cotton seed) $\left(\frac{\$}{ha}\right)$ $= \text{Seed yield}_{it} \left(\frac{kg}{ha}\right) \times \text{Seed price}_{it} \left(\frac{\$}{kg}\right)$	**Level 6**	**$865/ha**	**$867/ha**	**0.1%**	**0.880**	
Seed yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	2,704 kg/ha	2,708 kg/ha	0.1%	0.880	

Seed price$_{it}$ $\left(\frac{\$}{kg}\right)$	WESM Input	\$0.32/kg of seed	\$0.32/kg of seed	0%		
Panel F5: Calculation of traded irrigation volume						
Traded irrigation volume$_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$ $=$ Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$ $\times$ Traded irrigation to Irrigation abstracted ratio$_{it}$ (%)	**Level 7**	**0 ML/ha**	**0 ML/ha**			
Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	7.59 ML/ha	5.51 ML/ha	–27%	0.000	***
Traded irrigation to Irrigation abstracted ratio$_{it}$ (%)	WESM Input	0%	0%			
Panel F6: Calculation of licensed irrigation volume						
Licensed irrigation volume$_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$ $=$ Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$ $\times$ Licensed irrigation to Irrigation abstracted ratio$_{it}$ (%)	**Level 7**	**7.59 ML/ha**	**5.51 ML/ha**	**–27%**	**0.000**	***
Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	7.59 ML/ha	5.51 ML/ha	–27%	0.000	***
Licensed irrigation to Irrigation abstracted ratio$_{it}$ (%)	WESM Input	100%	100%	0%		

Panel F7: Calculation of traded irrigation cost						
Traded irrigation cost$_{it}$ $\left(\frac{\$}{\mathbf{ha}}\right)$ $= \text{Traded irrigation volume}_{it} \left(\frac{\text{ML}}{\text{ha}}\right)$ $\times \text{ Unit traded irrigation cost}_{it} \left(\frac{\$}{\text{ML}}\right)$	**Level 6**	**$0 /ha**	**$0 /ha**			
Traded irrigation volume$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	0 ML/ha	0 ML/ha			
Unit traded irrigation cost$_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	WESM Input	N/A	N/A			
Panel F8: Calculation of licensed irrigation cost						
Licensed irrigation cost$_{it}$ $\left(\frac{\$}{\mathbf{ha}}\right)$ $= \text{Licensed irrigation volume}_{it} \left(\frac{\text{ML}}{\text{ha}}\right)$ $\times \text{ Unit traded irrigation cost}_{it} \left(\frac{\$}{\text{ML}}\right)$	**Level 6**	**$458/ha**	**$333/ha**	**–27%**	**0.000**	***
Licensed irrigation volume$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	7.59 ML/ha	5.51 ML/ha	–27%	0.000	***
Unit licensed irrigation cost$_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	WESM Input	$60.30/ML	$60.30/ML	0%		
Panel F9: Calculation of total water cost						

Total water cost$_{it}\left(\frac{\$}{ha}\right)$ $= \text{Licensed irrigation cost}_{it}\left(\frac{\$}{ha}\right) + \text{Traded irrigation cost}_{it}\left(\frac{\$}{ha}\right)$	**Level 6**	**\$458/ha**	**\$333/ha**	**–27%**	**0.000**	***
Licensed irrigation cost$_{it}\left(\frac{\$}{ha}\right)$	Level 6	\$458/ha	\$333/ha	–27%	0.000	***
Traded irrigation cost$_{it}\left(\frac{\$}{ha}\right)$	Level 6	\$0/ha	\$0/ha			
Panel F10: Calculation of other variable cost						
Other variable cost$_{it}\left(\frac{\$}{ha}\right)$ $= \text{Unit other variable cost}_{it}\left(\frac{\$}{\text{kg of lint}}\right) \times \text{Lint yield}_{it}\left(\frac{kg}{ha}\right)$	**Level 6**	**\$216/ha**	**\$217/ha**	**0.1%**	**0.880**	
Unit other variable cost$_{it}\left(\frac{\$}{\text{kg of lint}}\right)$	WESM Input	\$0.12/kg of lint	\$0.12/kg of lint	0%		
Lint yield$_{it}\left(\frac{kg}{ha}\right)$	Level 7	1,803 kg/ha	1,806 kg/ha	0.1%	0.880	

This Table reports univariate tests using the student **t-test.** Two-tailed test of significance: ***< 0.001, **< 0.01 and *< 0.05.

8.3.4 Statistical test – Level 5 of WESM

This section discusses the results of *t-test* for five WESM measures presented in Level 5 (see Table 8.3, Panel E).

8.3.4.1 Water input efficiency (%)

In Chapter 4, water input efficiency is defined as the degree to which crop water supply is used for carbon assimilation to generate lint product, measured as a ratio of transpiration to crop water supply. It is also evident in Section 8.3.2 that water input efficiency is mainly driven by crop water loss to crop water supply ratio.

Table 8.3, Panel E1, shows that there is a statistically significant ($p\text{-value} < 0.001$) difference in the means of water input efficiency between Scenario 1 and Scenario 2. While there is an increase by 6% in water input efficiency when switching from Scenario 1 water management conditions to Scenario 2 water management conditions, on average, the water input efficiency of 37% for Scenario 2 is still relatively low (e.g. compared to the theoretical value of 100%) as nearly half of the water (43%) that is applied to the cropping system is non-productive and lost from the system[116].

8.3.4.2 Transpiration index

Table 8.3, Panel E2, shows that there is no statistical difference in the means of transpiration index between Scenario 1 and Scenario 2. On average, the numerator of the index (biomass yield) slightly increases by 2.7% while its denominator (transpiration) only increases by 1.6%. As a result, the mean of transpiration index only slightly increases by 1.1% when moving from Scenario 1 to Scenario 2.

The results reported for changes in transpiration index are as expected since the simulation designed in DSSAT to enable crops to grow under non-limiting nitrogen conditions (a total of 300 kg of nitrogen is applied over a crop season) in both scenarios. As discussed in Chapter 3, nitrogen management is considered as a driving factor of the transpiration index. Given the same nitrogen applications, it is expected there should be no significant difference in transpiration index between the two scenarios.

[116] As discussed in Section 8.3.2, 20% of water supply is from recycled runoff.

8.3.4.3 Harvest index

Similar to the transpiration index, on average the harvest index only slightly decreases by 2.5% from 0.151 under Scenario 1 to 0.147 in Scenario 2. This is because the DSSAT software is designed in a way that crops grow under well controlled pest and disease management, which is considered as the key driver of harvest index. Therefore, as expected, there should be no significant difference in the means of the harvest index between the Scenario 1 and Scenario 2 samples

8.3.4.4 Total sales revenue

Since it is shown in the previous section (Section 8.3.3) that there is no significant difference in the means of both sales revenue generated from lint and cotton seed, it is expected that there should be no significant difference in the means of the sum of them – total sales revenue.

8.3.4.5 Total operating cost

Table 8.3, Panel E5, reveals that there is significant difference in the means of total operating cost (p-*value* < 0.001) between Scenario 1 and Scenario 2. By definition, fixed operating costs do not change while it is evident that there is no significant difference in the means of other variable costs (see Section 8.3.3) between the two scenarios. It is shown that a reduction of $125/ha in total operating cost is a result of the decrease of $125/ha in total water cost.

Though water cost only contributes a small portion to total operating cost, and a significant reduction in water cost (e.g. 27%) merely results in a 4% of reduction in total operating cost, when looking at the business level and the industry level, a reduction of $125/ha in total operating cost provides significant economic implications for crop businesses. Detailed analysis and discussion of economic significance of the Scenario 2 sample will be presented in Section 8.4.

The analysis of five measures in Level 5 of WESM reveals that by switching from Scenario 1 to Scenario 2 conditions, there is statistical and materially significant difference in the means of water input efficiency and total operating cost. This indicates that these two measures and their associated drivers (deep drainage and total water cost respectively) can be used to explain changes in higher level measures of WESM.

Table 8.3 Statistical Test: Univariate Mean Differences between Scenario 1 and Scenario 2 – Panel E (Level 5 of WESM)

Variable	WESM Level	Mean (Scenario 1)	Mean (Scenario 2)	Difference in means $\left(\frac{S2-S1}{S1}\right)\times 100\%$	*p-value*	
Panel E1: Analysis of water input efficiency						
Water input efficiency$_{it}$(%) $= 100\% - \text{Crop water loss to crop water supply ratio}\% - \text{Recycled runoff to crop water supply ratio (\%)}$	**Level 5**	**35%**	**37%**	**6%**	**0.000**	***
Crop water loss to crop water supply ratio (%)	Level 6	57%	43%	–23%	0.000	***
Recycled runoff to crop water supply ratio (%)	Level 6	8%	20%	151%	0.000	***
Panel E2: Analysis of transpiration index						
Transpiration index$_{it}$ $\left(\frac{\textbf{kg of biomass}}{\textbf{ML of tranpiration}}\right)$ $= \text{Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{\text{ha}}\right) \div \text{Transpiration}_{it}\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$	**Level 5**	**2,600 kg of biomass/ML**	**2,629 kg of biomass/ML**	**1.1%**	**0.200**	
Biomass yield$_{it}$ $\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	WESM Input	11,948 kg/ha	12,270 kg/ha	2.7%	0.004	*
Transpiration$_{it}$ $\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$	WESM Input	4.61 ML/ha	4.69 ML/ha	1.6%	0.259	
Panel E3: Analysis of harvest index						

Variable	**WESM Level**	**Mean (Scenario 1)**	**Mean (Scenario 2)**	**Difference in means** $\left(\frac{\mathbf{S2-S1}}{\mathbf{S1}}\right)\times\mathbf{100\%}$	***p-value***	
$\mathbf{Harvest\ index_{it}}\left(\frac{\mathbf{kg\ of\ lint}}{\mathbf{kg\ of\ biomass}}\right)$ $=\ \text{Lint yield}_{it}\left(\frac{\text{kg of lint}}{\text{ha}}\right)$ $\div\ \text{Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	**Level 5**	**0.151**	**0.147**	**–2.5%**	**0.000**	***
$\text{Lint yield}_{it}\left(\frac{\text{kg of lint}}{\text{ha}}\right)$	Level 7	1,803 kg/ha	1,806 kg/ha	0.1%	0.880	
$\text{Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	WESM Input	11,948 kg/ha	12,270 kg/ha	2.7%	0.004	*
Panel E4: Analysis of total sales revenue						
$\mathbf{Total\ sales\ revenue_{it}}\left(\frac{\mathbf{\$}}{\mathbf{ha}}\right)$ $=\ \text{Sales revenue}_{it}(\text{lint})\left(\frac{\$}{\text{ha}}\right)$ $+\ \text{Sales revenue}_{it}\ (\text{cotton seed})\left(\frac{\$}{\text{ha}}\right)$	**Level 5**	**$4,630 /ha**	**$4,637 /ha**	**0.1%**	**0.880**	
$\text{Sales revenue}_{it}(\text{lint})\left(\frac{\$}{\text{ha}}\right)$	Level 6	$3,765 /ha	$3,770 /ha	0.1%	0.880	
$\text{Sales revenue}_{it}(\text{cotton seed})\left(\frac{\$}{\text{ha}}\right)$	Level 6	$865/ha	$867/ha	0.1%	0.880	
Panel E5: Analysis of total operating cost						

Variable	**WESM Level**	**Mean (Scenario 1)**	**Mean (Scenario 2)**	**Difference in means** $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	***p-value***	
Total operating cost$_{it}\left(\frac{\$}{ha}\right)$ $= \text{Total water cost}_{it}\left(\frac{\$}{ha}\right) + \text{Other variable cost}_{it}\left(\frac{\$}{ha}\right) + \text{Fixed operating cost}_{it}\left(\frac{\$}{ha}\right)$	**Level 5**	**\$3,486/ha**	**\$3,361/ha**	**–4%**	***0.000***	***
Total water cost$_{it}\left(\frac{\$}{ha}\right)$	Level 6	\$458/ha	\$333/ha	–27%	*0.000*	***
Other variable cost$_{it}\left(\frac{\$}{ha}\right)$	Level 6	\$216/ha	\$217/ha	0.1%	*0.880*	
Fixed operating cost$_{it}\left(\frac{\$}{ha}\right)$	WESM Input	\$2,812/ha	\$2,812/ha	0%		

This Table reports univariate tests using the student t-**test.** Two-tailed test of significance: ***< 0.001, **< 0.01 and *< 0.05.

8.3.5 Statistical test – Level 3 and Level 4 of WESM

This section discusses the results of the *t-test* for the two middle-levels of WESM, Level 3 and Level 4, which are reported in Table 8.3, Panel D and Panel C respectively.

8.3.5.1 Level 4 of WESM

In the fourth level of WESM, three measures are presented, including operating profit, crop water use index, and weighted average cotton price. First, Table 8.3, Panel D1, shows that there is a significant difference (*p-value* < 0.01) in the means of operating profit between Scenario 1 and Scenario 2. The table also shows that, on average, while there is not much difference (e.g. $7/ha) in the value of total sales revenue between the two scenarios, total operating cost reduces by 4% or $125/ha when moving from Scenario 1 to Scenario 2. As a result, operating profit, which is total sales revenue after subtracting total operating cost, for Scenario 2 increases considerably by 12% or $132/ha compared to that of Scenario 1.

Similarly, Table 8.3, Panel D2, also shows that there is significant (*p-value* < 0.01) difference in the means of crop water use index – a measure of how productive a crop is in producing lint product from one unit of volume (e.g. ML) of water supplied to the cropping system – between Scenario 1 and Scenario 2. Inspections of the data show that a 5% increase in crop water use index, from 137 kg of lint/ML to 144 kg of lint/ML, is a result of a slight increase (e.g. 1.1%) in transpiration index, a relatively low decrease in harvest index (e.g. 2.5%), and a considerable increase (e.g. 6%) in water input efficiency. In contrast, there is no difference in weighted average cotton price between Scenario 1 and Scenario 2 (see Table 8.3, Panel D3). This is because it is assumed that the economic factors (lint price and seed price), as well as variety factors (lint percentage and seed percentage), remain constant across years and between the two scenarios.

The comparisons presented above indicate that of the three measures of Level 4 of WESM, on average, both operating profit – which represents profitability of a crop business – and crop water use index – which reflects productivity of the crop business in respect to water resource use – improve when switching from Scenario 1 conditions to Scenario 2 conditions. This provides empirical evidence for further discussions of causes of changes of Level 3 measures in Section 8.3.5.2.

Table 8.1 Statistical Test: Univariate Mean Differences between Scenario 1 and Scenario 2 – Panel D (Level 4 of WESM)

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	*p-value*	
Panel D1: Analysis of operating profit						
$\textbf{Operating profit}_{it}\left(\frac{\$}{ha}\right) = \text{Total sales revenue}_{it}\left(\frac{\$}{ha}\right) - \text{Total operating cost}_{it}\left(\frac{\$}{ha}\right)$	**Level 4**	**$1,144/ha**	**$1,276/ha**	**12%**	**0.000**	**
$\text{Total sales revenue}_{it}\left(\frac{\$}{ha}\right)$	Level 5	$4,630 /ha	$4,637 /ha	0.1%	0.880	
$\text{Total operating cost}_{it}\left(\frac{\$}{ha}\right)$	Level 5	$3,486/ha	$3,361/ha	-4%	0.000	***
Panel D2: Analysis of crop water use index						
$\textbf{Crop water use index}_{it}\left(\frac{\text{kg of lint}}{\text{ML}}\right) = \text{Transpiration index}_{it}\left(\frac{\text{kg of biomass}}{\text{ML of tranpiration}}\right) \times \text{Harvest index}_{it}\left(\frac{\text{kg of lint}}{\text{kg of biomass}}\right) \times \text{Water input efficiency}_{it}(\%)$	**Level 4**	**137 kg of lint/ML**	**144 kg of lint/ML**	**5%**	**0.000**	**

Variable	**WESM level**	**Mean (Scenario 1)**	**Mean (Scenario 2)**	**Mean difference** $\left(\frac{\mathbf{S2-S1}}{\mathbf{S1}}\right) \times \mathbf{100\%}$	***p-value***	
Transpiration $\text{index}_{it}\left(\frac{\text{kg of biomass}}{\text{ML of tranpiration}}\right)$	Level 5	2,600 kg of biomass/ML	2,629 kg of biomass/ML	1.1%	0.200	
Harvest $\text{index}_{it}\left(\frac{\text{kg of lint}}{\text{kg of biomass}}\right)$	Level 5	0.151	0.147	-2.5%	0.000	***
Water input $\text{efficiency}_{it}(\%)$	Level 5	35%	37%	6%	0.000	***
Panel D3: Analysis of weighted average cotton price						
Weighted average cotton $\mathbf{price}_{it}\left(\frac{\$}{\textbf{kg of total yield}}\right)$ $= \left[\text{Lint percentage}_{it}\ (\%) \times \text{Lint price}_{it}\left(\frac{\$}{\text{kg}}\right)\right] + \left[\text{Seed percentage}_{it}\ (\%) \times \text{Seed price}_{it}\left(\frac{\$}{\text{kg}}\right)\right]$	**Level 4**	**$ 1.03/kg**	**$ 1.03/kg**	**0%**	**0.085**	
Lint $\text{percentage}_{it}\ (\%)$	WESM Input	40%	40%	0%		
Seed $\text{percentage}_{it}\ (\%)$	WESM Input	60%	60%	0%		

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	*p-value*	
Lint price_{it} $\left(\frac{\$}{\text{kg}}\right)$	WESM Input	\$2.09/ kg of lint	\$2.09/ kg of lint	0%		
Seed price_{it} $\left(\frac{\$}{\text{kg}}\right)$	WESM Input	\$0.32/kg of seed	\$0.32/kg of seed	0%		

This Table reports univariate tests using the student t**-test.** Two-tailed test of significance: ***< 0.001, **< 0.01 and *< 0.05.

8.3.5.2. Level 3 of WESM

Level 3 of WESM consists of two drivers of return on water (which is presented in Level 2 of WESM) – profit margin and economic water use index – both of which show a significant difference in their means between Scenario 1 and Scenario 2 (see Table 8.3, Panel C). This is expected since operating profit, a driver of profit margin, and crop water use index, a driver of economic water use index, are significantly different when moving from Scenario 1 to Scenario 2.

More particularly, Table 8.3, Panel C1, shows that though total sales revenue is very much the same between the two scenarios, operating profit, as reported in Section 8.3.5.2, shows a 12% increase. As a result, profit margin increases by 12%, from 24% for Scenario 1 to 27% for Scenario 2.

Economic water use index – a ratio of sales revenue to crop water supply – is shown to increase by 5% or $17/ML of crop water supply (see Table 8.3, Panel C2). Since its other two drivers – lint percentage and weighted average cotton price – are assumed to remain constant within and between the two scenarios, crop water use index, with an increase of 5%, is the only driving factor to cause the change in economic water use index.

Table 8.3 Statistical Test: Univariate Mean Differences between Scenario 1 and Scenario 2 – Panel C (Level 3 of WESM)

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	*p-value*	
Panel C: Analysis of profit margin						
$\mathbf{Profit\ margin_{it}}(\%) = \left[\text{Opearating profit}_{it}\left(\frac{\$}{\text{ha}}\right) \div \text{Total sales revenue}_{it}\left(\frac{\$}{\text{ha}}\right)\right] \times 100\%$	**Level 3**	**24%**	**27%**	**12%**	**0.000**	***
$\text{Operating profit}_{it}\left(\frac{\$}{\text{ha}}\right)$	Level 4	$1,144/ha	$1,276/ha	12%	0.000	**
$\text{Total sales revenue}_{it}\left(\frac{\$}{\text{ha}}\right)$	Level 5	$4,630 /ha	$4,637 /ha	0.1%	0.880	
Panel C2: Analysis of economic water use index						
$\mathbf{Economic\ water\ use\ index_{it}}\left(\frac{\$}{\mathbf{ML}}\right) = \text{Crop water use index}_{it}\left(\frac{\text{kg of lint}}{\text{ML}}\right) \div \text{Lint percentage}_{it}(\%) \times \text{Weighted average cotton price}_{it}\left(\frac{\$}{\text{kg of total product}}\right)$	**Level 3**	**$352 /ML**	**$369 /ML**	**5%**	**0.000**	**
$\text{Crop water use index}_{it}\left(\frac{\text{kg of lint}}{\text{ML}}\right)$	Level 4	137 kg of lint/ML	144 kg of lint/ML	5%	0.000	**

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $\left(\frac{\mathbf{S2-S1}}{\mathbf{S1}}\right)\times\mathbf{100\%}$	*p-value*	
Lint percentage$_{\text{it}}$ (%)	WESM Input	40%	40%	0%		
Weighted average cotton price$_{it}$ $\left(\frac{\$}{\text{kg of total yield}}\right)$	Level 4	$ 1.03/kg	$ 1.03/kg	0%	0.085	

This Table reports univariate tests using the student **t-test.** Two-tailed test of significance: ***< 0.001, **< 0.01 and *< 0.05.

8.3.6 Statistical test – Level 1 and Level 2 of WESM

This section reports results of the *t-test* for the two high-levels of WESM – Level 2 and Level 1 – which are reported in Table 8.3, Panel B and Panel A, respectively.

8.3.6.1. Level 2 of WESM

In the second level of WESM, the three drivers of the overall economic and environmental sustainability measure – profit to water cost ratio – are discussed.

First, it is shown that there is a significant ($p\text{-}value < 0.001$) difference in the means of return on water – a measure of economic return on water resource use – between the two scenarios (see Table 8.3, Panel B1). The 17% increase in return on water, which is equivalent to an additional gain of $14/ML (= 101 – 87), is a result of a 12% increase in profit margin and 5% increase in economic water use index when switching from Scenario 1 to Scenario 2.

Second, Table 8.3, Panel B2, shows that there is a significant difference in the means of water use leverage between Scenario 1 and Scenario 2. Since rainfall to crop water supply, on average, is not significantly different between the two scenarios, it is the significant change in recycled runoff to crop water supply ratio driving the change in water use leverage. More particularly, water use leverage decreases by 24%, from 58% for Scenario 1 to 44% for Scenario 2, as a result of a substantial increase in recycled runoff to crop water supply ratio. The results reported in Table 8.3, Panel B2, emphasise the impact of runoff recycling decisions on both environmental and economic performance of the crop business. The higher recycled runoff to crop water supply ratio, the lower water use leverage, indicating that lower abstractions/withdrawals from the environment are required and lower irrigation water costs will be incurred (as a result of the reduction in the amount of abstracted water).

Table 8.3 Statistical Test: Univariate Mean Differences between Scenario 1 and Scenario 2 – Panel B (Level 2 of WESM)

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	*p-value*	
Panel B1: Analysis of return on water						
$\textbf{Return on water}_{it}\left(\frac{\$}{ML}\right) = \text{Profit margin}_{it}(\%) \times \text{Economic water use index}_{it}\left(\frac{\$}{ML}\right)$	**Level 2**	**$87/ML**	**$101/ML**	**17%**	**0.000**	***
$\text{Profit margin}_{it}(\%)$	Level 3	24%	27%	12%	0.000	***
$\text{Economic water use index}_{it}\left(\frac{\$}{ML}\right)$	Level 3	$352 /ML	$369 /ML	5%	0.000	**
Panel B2: Analysis of water use leverage						
$\textbf{Water use leverage}\ (\%) = 100\% - [\text{Rainfall to crop water supply ratio}\ (\%) + \text{Recycled runoff to crop water supply ratio}\ (\%)]$	**Level 2**	**58%**	**44%**	**–24%**	**0.000**	***
Rainfall to crop water supply ratio (%)	Level 6	34%	36%	5%	0.000	
Recycled runoff to crop water supply ratio (%)	Level 6	8%	20%	151%	0.000	***
Panel B3: Analysis of weighted average irrigation cost						

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $\left(\frac{S2 - S1}{S1}\right) \times 100\%$	*p-value*	
Weighted average irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$ $= \left[\text{Licensed irrigation to Irrigation abstracted ratio}_{it}\ (\%) \times \text{Unit licensed irrigation cost}_{it}\left(\frac{\$}{ML}\right)\right] + \left[\text{Traded irrigation to Irrigation abstracted ratio}_{it}\ (\%) \times \text{Unit traded irrigation cost}_{it}\left(\frac{\$}{ML}\right)\right]$	**Level 2**	**$60.30 /ML**	**$60.30 /ML**	**0%**		
Licensed irrigation to Irrigation abstracted ratio$_{it}$ (%)	WESM Input	100%	100%	0%		
Traded irrigation to Irrigation abstracted ratio$_{it}$ (%)	WESM Input	0%	0%			
Unit licensed irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$	WESM Input	$60.30 /ML	$60.30 /ML	0%		
Unit traded irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$	WESM Input	N/A	N/A			

This Table reports univariate tests using the student **t-test.** Two-tailed test of significance: ***< 0.001, **< 0.01 and *< 0.05.

8.3.6.2 Level 1 of WESM

In the top level of the WESM model, there is a significant (*p-value < 0.001*) difference in the means of profit to water cost ratio between Scenario 1 and Scenario 2 (see Table 8.3, Panel A). This can be explained by a significant increase in the numerator (return on water) accompanied by a significant decrease in the denominator (water use leverage) when moving from Scenario 1 to Scenario 2. More specifically, it is empirically evident that a substantial increase of 56% in profit to water cost ratio is a result of a considerable increase of 17% in return on water and a significant reduction of 24% in water use leverage.

The 17% change in return on water is driven by a 12% increase in profit margin and a 5% increase in economic water use index; this is driven by a reduction of 27% in water cost and increase in operating profit, and by an increase of 6% in water input efficiency, respectively. In addition, it is reported that the considerable decrease in total water cost is driven by a reduction of 27% in the amount of irrigation abstracted from the environment, while the improvement of water input efficiency is mainly driven by a substantial reduction of 96% in water loss from deep drainage. At the operational level, it is empirically evident that such a significant reduction (27%) in the amount of irrigation abstracted and the substantial reduction (96%) in deep drainage is a result of runoff recycling decisions and irrigation scheduling decisions, respectively.

On the other hand, the decrease of 24% in water use leverage is driven by a significant increase of 151% in recycled runoff to crop water supply ratio; this is driven by a substantial increase of 138% in the amount of recycle runoff. Similar to the change in return on water, it is empirically evident that such a considerable decrease (24%) in water use leverage is a result of runoff recycling decisions at the operational level.

Table 8.3 Statistical Test: Univariate Mean Differences between Scenario 1 and Scenario 2 – Panel A (Level 1 of WESM)

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $\left(\frac{\mathbf{S2-S1}}{\mathbf{S1}}\right)\times\mathbf{100\%}$	*p-value*	
Profit to water cost ratio$_{it}$ $= \text{Return on water}_{it}\left(\frac{\$}{\text{ML}}\right) \div \left[\text{Water use leverage}_{it}\ (\%) \times \text{Weighted average irrigation cost}_{it}\left(\frac{\$}{\text{ML}}\right)\right]$	Level 1	2.62	4.10	56%	0.000	***
Return on water$_{it}\left(\frac{\$}{\text{ML}}\right)$	Level 2	\$87/ML	\$101/ML	17%	0.000	***
Water use leverage$_{it}$ (%)	Level 2	58%	44%	–24%	0.000	***
Weighted average irrigation cost$_{it}\left(\frac{\$}{\text{ML}}\right)$	Level 2	\$60.30 /ML	\$60.30 /ML	0%	0.395	

This Table reports univariate tests using the student t**-test.** Two-tailed test of significance: ***< 0.001, **< 0.01 and *< 0.05.

8.4 Environmental and economic implications of moving from Scenario 1 to Scenario 2

In Section 8.3, results of the statistical test *(t-test)* for the significant difference in the means of all measures presented in WESM (from Level 7 to Level 1) between Scenario 1 and Scenario 2 are reported and discussed.

The key findings, based on 86 years for the period of 1924–2014 (excluding 1928, 1940, 1945 and 2002 since crops could not be grown due to drought conditions), show that there is a statistically significant difference in the means of a range of key economic and environmental sustainability measures between the two scenarios. They include:

i. Irrigation abstracted, crop water loss and total water cost (Level 6 and Level 7 of WESM)
ii. Water input efficiency and total operating cost (Level 5 of WESM)
iii. Crop water use index and operating profit (Level 4 of WESM)
iv. Profit margin and economic water use index (Level 3 of WESM)
v. Water use leverage and return on water (Level 2 of WESM) and
vi. Profit to water cost ratio (Level 1 of WESM).

It is empirically evident[117] that statistically, the choice of improved management practices in furrow irrigation systems results in better economic and environmental performance than that of current practices in furrow irrigation systems.

The comparison between the means of the two samples across seven levels of WESM are represented in Figure 8.2, which shows the top-down approach to how the overall organisational decisions, with regards to economic and water sustainability, made at the organisational level, link to the key management decisions made at an operational level.

[117] By 'empirically evident', I mean I apply simulation method to obtain data for testing theory relating to how crop water and economic sustainability performance can be improved by changing water management practices.

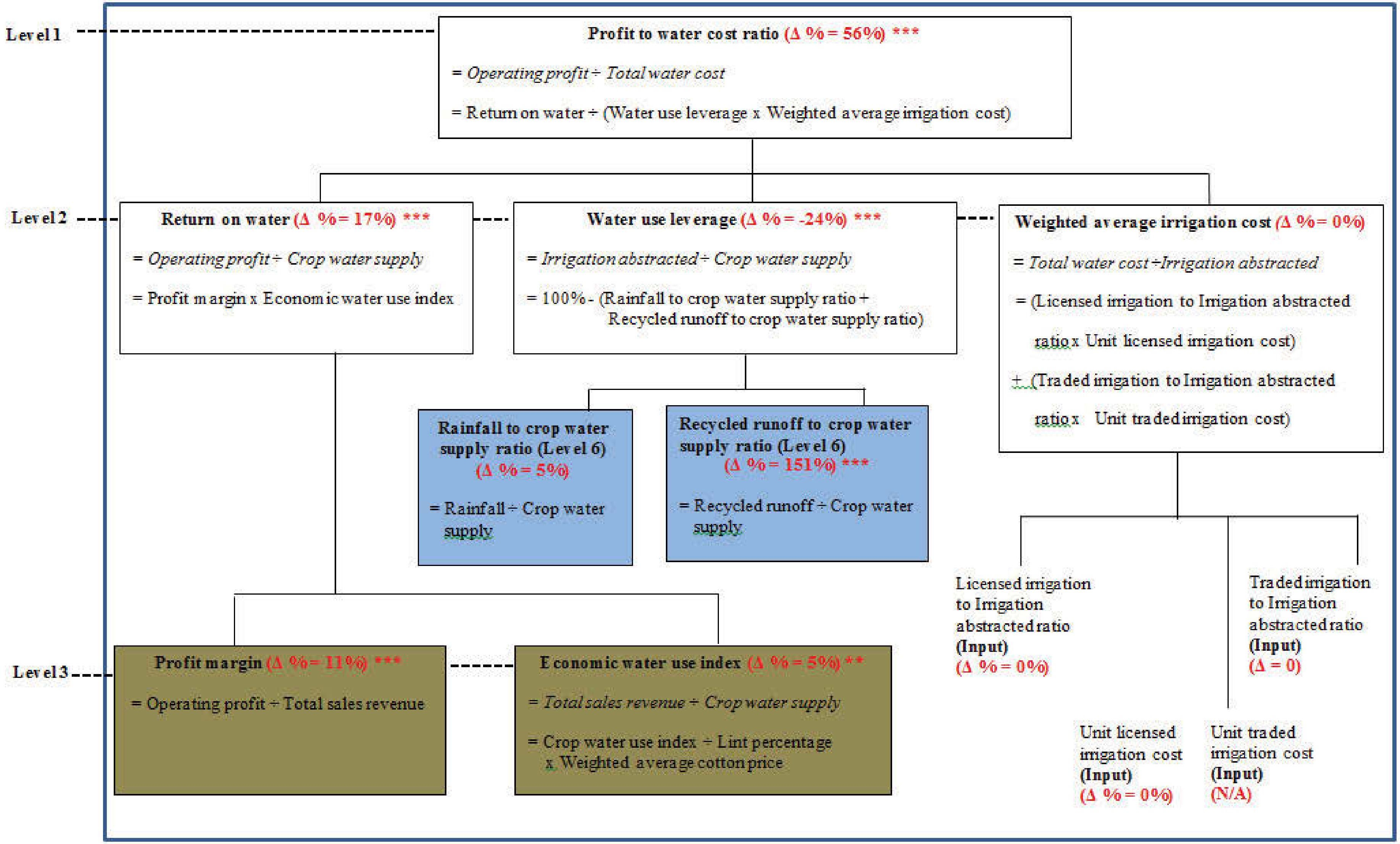

Figure 8.2 Levels 1 to 2 of the WESM model

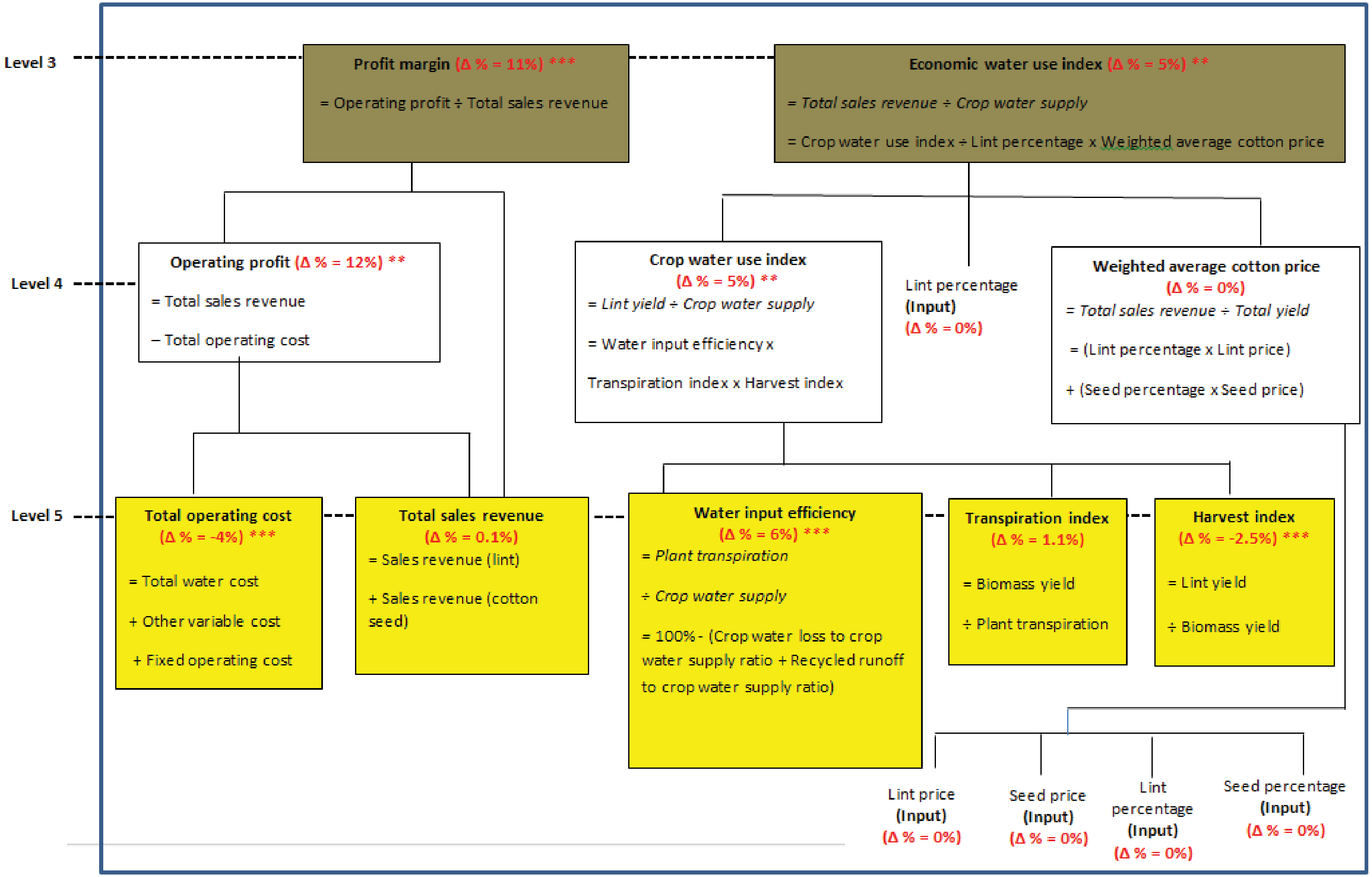

Figure 8.2 Levels 3 to 5 of the WESM model

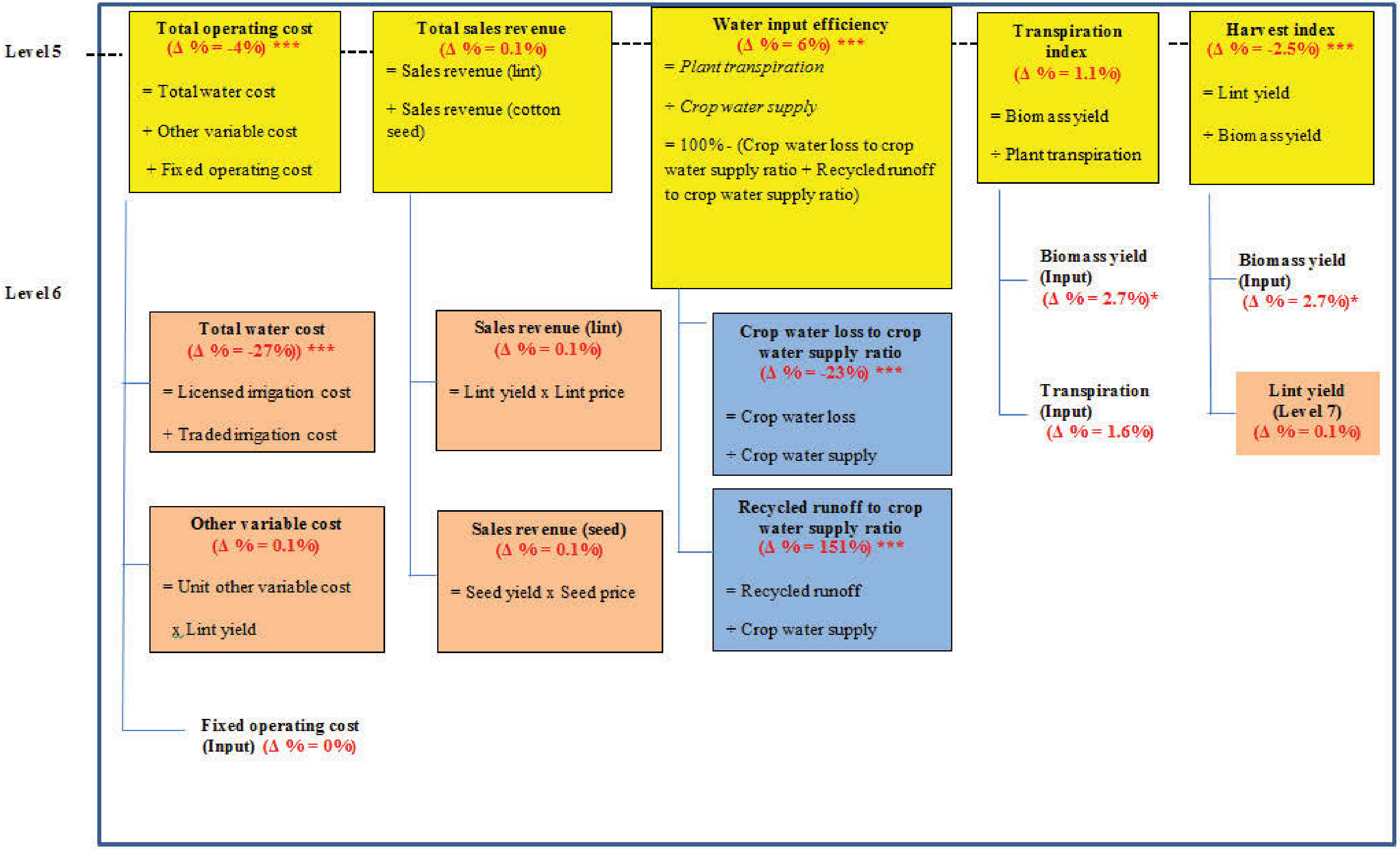

Figure 8.2 Levels 5 to 6 of the WESM model

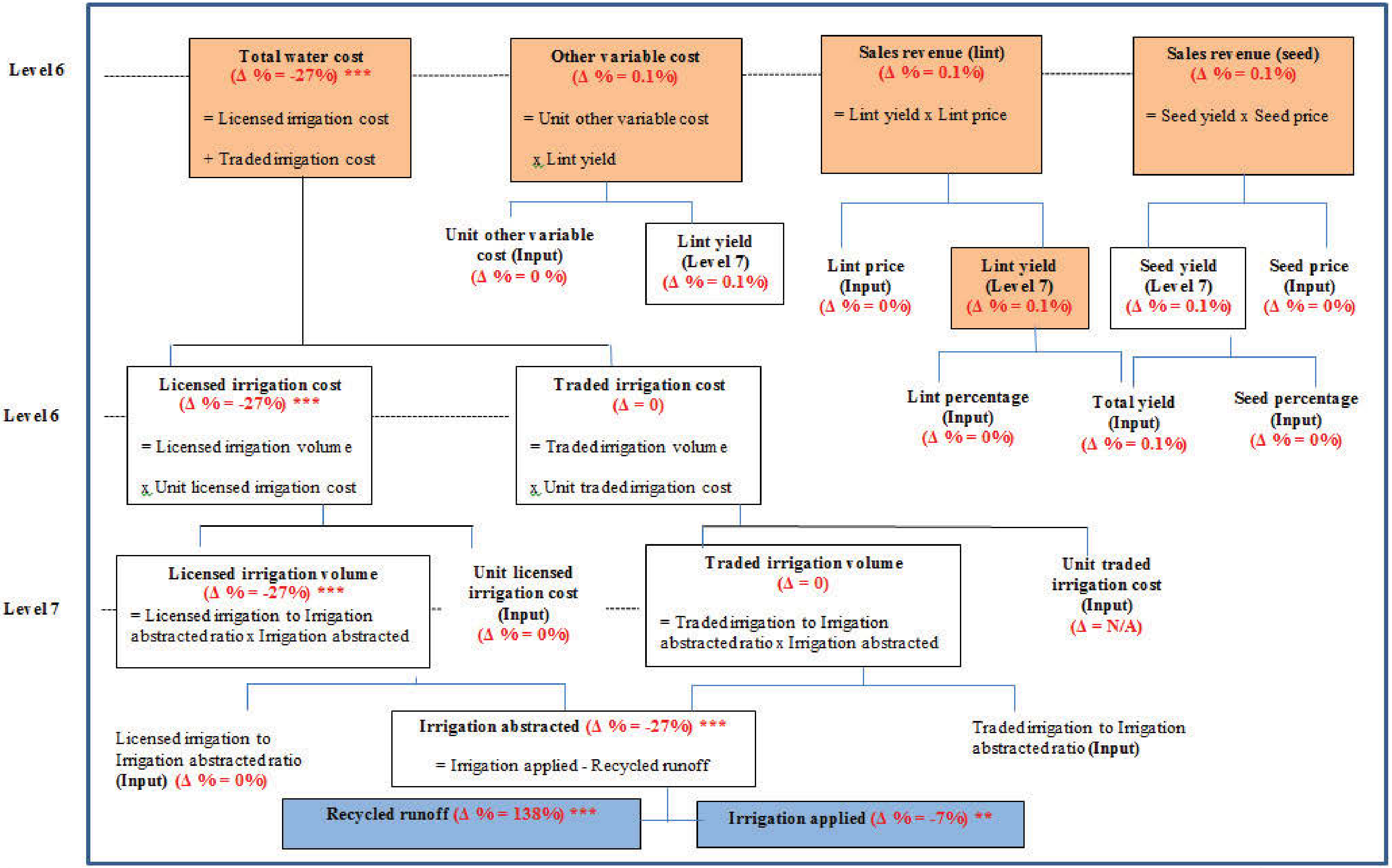

Figure 8.2 Levels 6 to 7 of the WESM model (economic low-level measures)

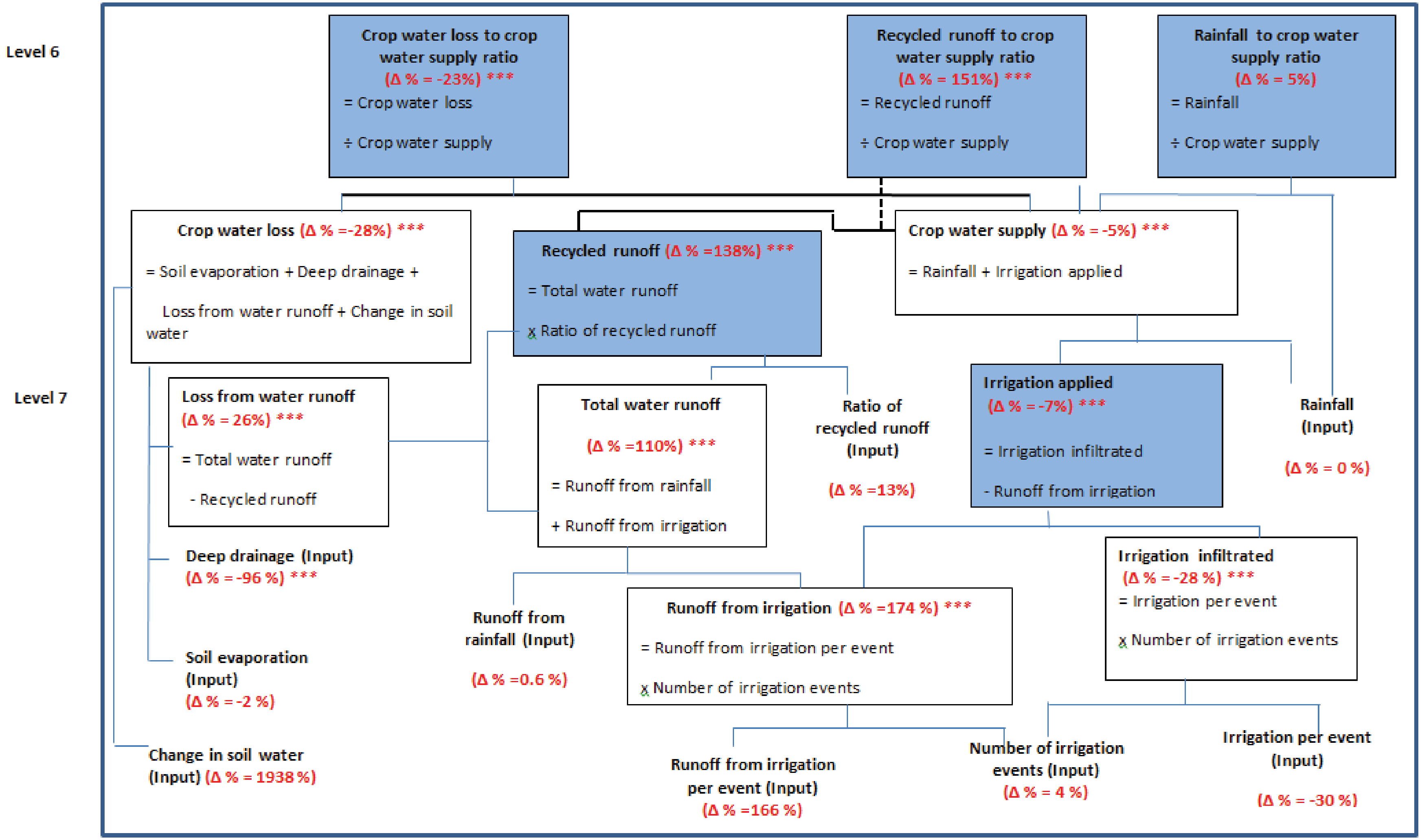

Figure 8.2 Levels 6 to 7 of the WESM model (environmental low-level measures)

8.4.1 Difference in environmental resource use and environmental sustainability performance between Scenario 1 and Scenario 2

As discussed in the previous sections, environmental and economic performance of the crop business will change significantly as a result of changes in irrigation scheduling decisions (e.g. increasing furrow inflow rate from 2.8 ML/ha to 6.0 ML/ha while reducing irrigation time from 745 minutes to 310 minutes) and runoff recycling management decisions (e.g. increasing the ratio of recycled runoff from 75% to 85%). This section focuses on discussions of changes in use of environmental resources, more specifically water resources, and water sustainability performance between Scenario 1 and Scenario 2 as a result of these two water management decisions.

8.4.1.1 Difference in recycled water runoff and loss from water runoff

Table 8.4, Panel A1, reports that runoff from irrigation increases considerably from 0.90 ML/ha in Scenario 1 to 2.47 ML/ha in Scenario 2. This is because furrow inflow rate increases rapidly from 2.8 l/s to 6.0 l/s (which can be observed via SIRMOD animation). Consequently, total water runoff increases substantially by 1.58 ML/ha.

However, water runoff can be recycled and stored in a dam belonging to the farm. Assuming that 75% of water runoff is recycled under Scenario 1 while 85% of water runoff can be recycled under Scenario 2 due to a better runoff recycling management practice, a considerable increase in the amount of runoff is recycled to the dam (e.g. 1.48 ML/ha) with relatively low increases in water loss from runoff (e.g. 0.10 ML/ha) observed when moving from Scenario 1 to Scenario 2. This means runoff recycling management implemented in Scenario 2 not only enables more water to be added to the dam to supplement irrigation that is required for a crop, but also reduces the gap in loss from water runoff between the two scenarios.

8.4.1.2 Difference in irrigation applied and irrigation abstracted

It is shown in Table 8.4, Panel A2, that there is not much difference (e.g. only a slight decrease of 0.60 ML/ha) in the amount of irrigation needs to be applied to the furrows to supplement seasonal rainfall when moving from the current furrow irrigation practices to the improved furrow irrigation practices. In this sense, Scenario 2 does not provide any better irrigation performance (e.g. the amount of withdrawals) than that of Scenario 1.

However, an increase of 1.48 ML/ha in recycled runoff results in an additional decrease of 1.48 ML/ha in irrigation water that needs to be abstracted from the environment. In total, a significant decrease in withdrawals (e.g. 2.08 ML/ha) is reported when moving from Scenario 1 to Scenario 2. This not only implies less water impost of cotton cultivation on the environment, but also a significant reduction in water cost (for example $125/ha, assuming irrigation cost of $60.30/ML).

8.4.1.3 Difference in crop water loss components

Table 8.4, Panel A3, shows that a reduction of 2.15 ML/ha is mainly driven by a decrease of deep drainage (e.g. 0.97 ML/ha) and a decrease in change in soil water (e.g., 1.13 ML/ha). A significant decrease in deep drainage indicates that Scenario 2 does provide better irrigation performance with regard to losses to deep drainage than that of Scenario 1. In addition, a substantial decrease in change in soil water under S2 indicates that better use of soil water is made by the crop.

On the one hand, changes in irrigation scheduling from Scenario 1 to Scenario 2 leads to significant increase in water runoff (but it can be managed via better recycling management practices). On the other hand, the improved irrigation management practices result in a substantial reduction in deep drainage and change in soil water. Water loss to deep drainage, which is unlike water loss to runoff, cannot be managed after it occurs, and therefore, provides significant economic and environmental consequences. For example, the amount of crop water saved from reductions in loss to deep drainage could be potentially used to grow more cotton given that farms are growing under capacity due to limitations on available water[118] and add more value to the crop business. In addition, deep drainage causes potential harm to ecosystems and the environment as a whole (Smith 2005).

Furthermore, the change in crop water loss reported in the section will translate to important economic and environmental outcomes for individual farms and the cotton industry as a whole. This will be discussed in detail in Chapter 9.

[118] However, this is a huge debate. Environmentalists argue that the water should be returned as environmental flows. The industry wants to grow more cotton. The government wants more taxes.

8.4.1.4 Difference in crop water supply components

Crop water supply can be viewed from two different perspectives, depending on the purpose for which the crop manager/farmer wants to know the information. Typically, he/she looks at two different questions: how dependent her/his crop is on the water abstracted from the environment, and how efficient the crop is at converting water resources into biomass. For the former question, it is useful to decompose crop water supply into rainfall, irrigation abstracted and recycled runoff components. For the latter question, it is useful to view crop water supply as a sum of a non-productive water component (e.g. crop water loss), recycled runoff, and a productive water component (e.g. transpiration).

Water use leverage

In order to gain insights into what drives water use leverage, crop water supply needs to be considered from the crop water inflow point of view. Among rainfall, irrigation abstracted and recycled runoff, irrigation abstracted is the only component that reflects the dependency of crop water use on withdrawals from the environment. Moreover, the degree to which crop water used is sourced by water abstracted from the environment (which is defined as water use leverage) depends on the proportion of rainfall and recycled water runoff in total crop water supply. The higher the ratios of rainfall and/or recycled runoff to crop water supply, the lower the proportion of crop water requirements that need to be abstracted from the environment.

Table 8.4, Panel A4, shows that given the same seasonal rainfall (cumulative rainfall from the planting date to the harvesting) and a slight decrease in crop water supply (0.6 ML/ha, see Section 8.3.2), the improvement of water use leverage from 58% under Scenario 1 conditions to 44% under Scenario 2 conditions is mainly driven by a significant increase in recycled runoff to crop water supply ratio (from 8% to 20%). This implies that water sustainability performance of a crop, represented by the water use leverage measure, can be improved as a result of better water recycling management practices.

Water input efficiency

Table 8.4, Panel A5, reports ratios of crop water supply components, from the crop water outflow point of perspective, to the total crop water supply, to gain a better understating of what drives water input efficiency. It is empirically evident that the improvement of water input efficiency, from 35% under Scenario 1 conditions to 37% under Scenario 2 conditions, is driven by a decrease in crop water loss to crop water supply ratio (from 57% to 43%) and an increase in recycled runoff to crop water supply ratio (from 8% to 20%).

Table 8.4 Economic and environmental differences between Scenario 1 and Scenario 2 – Panel A (Difference in environmental resource use)

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Difference in means $(\mathbf{S2} - \mathbf{S1})$
Panel A1: Difference in recycled runoff and loss from water runoff				
Runoff from irrigation $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	0.90	2.47	1.57
Runoff from rainfall $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	0.52	0.53	0.01
Total water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	1.42	3.00	1.58
Recycled runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	1.07	2.55	1.48
Loss from water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	0.35	0.45	0.10
Panel A2: Difference in irrigation abstracted				
Irrigation applied $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	8.66	8.06	–0.60
Recycled runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	1.07	2.55	1.48
Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	7.59	5.51	–2.08

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Difference in means $(\mathbf{S2}-\mathbf{S1})$
Panel A3: Difference in crop water loss				
Soil evaporation $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	6.24	6.10	–0.15
Loss from water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	0.36	0.45	0.09
Deep drainage$_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	1.01	0.04	–0.97
Change in soil water$_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	-0.06	-1.19	–1.13
Crop water loss$_{it}$ $\left(\frac{ML}{ha}\right)$	Level 6	7.55	5.40	–2.15
Panel A4: Difference in crop water supply components (from crop water inflow point of view) and water use leverage				
Crop water supply $\left(\frac{ML}{ha}\right)$	Level 6	13.23	12.63	-0.60
Rainfall to crop water supply ratio (%)	Level 6	34%	36%	5%
Recycled runoff to crop water supply ratio (%)	Level 6	8%	20%	151%

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Difference in means $(\mathbf{S2 - S1})$
Water use leverage$_{it}$ (%)	Level 2	58%	44%	–14%
Panel A5: Difference in crop water supply (from crop water outflow point of view) and water input efficiency				
Crop water loss to crop water supply ratio (%)	Level 6	57%	43%	-14%
Recycled runoff to crop water supply ratio (%)	Level 6	8%	20%	12%
Water input efficiency$_{it}$(%)	Level 5	35%	37%	2%

8.4.2 Difference in water cost and economic sustainability performance between Scenario 1 and Scenario 2 samples

Table 8.4, Panel B, summarises changes in total sales revenue, total operating costs, and operating profit, as a result of water management decisions under Scenario 2 conditions, outlined in Sections 8.3.2, 8.3.3 and 8.3.4, in order to provide better understanding of economic implications of moving from Scenario 1 to Scenario 2.

It is shown that the change of total water cost (e.g. $125/ha) is the key driver of change in profitability (e.g. $132/ha). Furthermore, a reduction of water cost from $458/ha to $333/ha is explained by a reduction of irrigation water abstracted (e.g. 2.08 ML/ha) – a result of better runoff recycling management practices.

The change in operating profit, a measure of the economic sustainability performance of a crop business, will translate into economic value created for the crop business by moving from the current water management practice to the more advanced water management practice, and provide economic implications for individual farms and the cotton industry as a whole. This will be discussed in details in Section 8.4.4.

Table 8.4 Economic and environmental differences between Scenario 1 and Scenario 2 – Panel B (Difference in economic performance)

Variable	WESM Level	Mean (Scenario 1)	Mean (Scenario 2)	Difference in the means $(\mathbf{S2} - \mathbf{S1})$
Difference in economic yield and total sales revenue				
$\text{Lint yield}_{\text{it}} \left(\frac{\text{kg}}{\text{ha}}\right)$	Level 7	1,803	1,806	2.6
$\text{Total yield}_{\text{it}} \left(\frac{\text{kg of total product}}{\text{ha}}\right)$	WESM Input	4,507	4,514	7
$\text{Total sales revenue}_{\text{it}} \left(\frac{\$}{\text{ha}}\right)$	Level 5	$4,630	$4,637	$7
Difference in irrigation cost and total operating cost				
$\text{Total water cost}_{\text{it}} \left(\frac{\$}{\text{ha}}\right)$	Level 6	$458	$333	–$125
$\text{Other variable cost}_{\text{it}} \left(\frac{\$}{\text{ha}}\right)$	Level 6	$216	$217	$1
$\text{Total operating cost}_{\text{it}} \left(\frac{\$}{\text{ha}}\right)$	Level 5	$3,486	$3,362	–$126
Difference in operating profit and profit margin				
$\text{Operating profit}_{\text{it}} \left(\frac{\$}{\text{ha}}\right)$	Level 4	$1,144	$1,276	$132/ha
$\text{Profit margin}_{\text{it}}(\%)$	Level 3	**24%**	**27%**	3%

8.4.3 Economic and environmental sustainability performance

This section reports changes in four key measures that imply both economic and environmental performance – crop water use index, economic water use index, return on water and profit to water cost ratio – when moving from Scenario 1 to Scenario 2 (see Table 8.4, Panel C).

First it is demonstrated that there are small increases in the crop water use index and economic water use index. This is because the irrigation rules chosen, on average, do not favour Scenario 2 more than Scenario 1, leading to a slight change in economic yield between Scenario 1 and Scenario 2. Given that total crop water supply for Scenario 2 is not much different from that of Scenario 1 and the economic factors (e.g. lint price and cotton seed price) are assumed constant within and between the two examined samples, the crop water use index and economic water use index do not shown significant improvements. We might expect that future crops, using a refined/optimal irrigation management, should result in higher economic yield, and therefore, higher a crop water use index and economic water use index.

On the other hand, it is reported that return on water increases by 17% from $87/ML to $101/ML. Since return on water measures the economic return on water resource use (in volume), the value of return on water for Scenario 2 is used to quantify the economic gain from water saving when moving from Scenario 1 to Scenario 2. This will be discussed in detail in Section 8.4.4.

Lastly, the profit to water cost ratio is shown to improve significantly by 56% or 1.48 (e.g. from 2.62 for Scenario 1 to 4.10 for Scenario 2). Since the numerator of this ratio – operating profit – is used as a proxy for economic sustainability, and its denominator – water cost or irrigation cost – is used as an indicator of the water impost of cotton cultivation on the environment, this result implies improvements to both economic and environmental sustainability. We have maintained economic sustainability while improving environmental sustainability, which is a move towards sustainability.

Table 8.4 Economic and environmental differences between Scenario 1 and Scenario 2 – Panel C (higher level measures)

Variable	WESM level	Mean (Scenario 1)	Mean (Scenario 2)	Mean difference $(\mathbf{S2} - \mathbf{S1})$
Crop water use index$_{it}$ $\left(\frac{\text{kg of lint}}{\text{ML}}\right)$	Level 4	137 kg	144 kg	7 kg
Economic water use index$_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	Level 3	\$352	\$369	\$17
Return on water$_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	Level 2	\$87	\$101	\$14
Profit to water cost ratio$_{it}$ $\left(\frac{\$\text{ operating profit}}{\$\text{ water cost}}\right)$	Level 1	2.62	4.10	1.48

8.5 Refining simulation experimental design

There are a number of ways in which simulation experimental design can be refined in future research. These are outlined below.

a. Improvement of irrigation applied

For the particular improved scenario examined in this thesis, as explained in Section 8.2, there is not much improvement/reduction in the amount of irrigation water applied to the cropping system compared to the current scenario.[119] As a result, on average, total crop water supply only reduces by 5% or 0.6 ML/ha. It is expected that future crops, using a refined/optimal furrow irrigation management practice, would result in more significant decreases in irrigation required and hence crop water supply for the crop business.

b. **Improvement of crop water loss**

Since under the improved water management practice, deep drainage decreases significantly to nearly zero, while loss to water runoff is reduced by 85% and only makes up 6% of total crop water loss (e.g. 0.45ML/ha of loss from water runoff in 6.59 ML/ha of total water lost, see Table 8.3, Panel G8), the only water loss component that needs to be reduced considerably in order to reduce total crop water loss is soil evaporation. However, under furrow irrigation systems, soil surface is still dramatically wet and water lost from soil evaporation is still a major cause of crop water loss.

Since the large residual soil evaporation cannot be reduced whenever the irrigation process results in a wet soil surface, the sprinkler irrigation method may not improve water input efficiency. Other irrigation methods need to be considered to resolve this issue. With current technology, subsurface irrigation may be the best irrigation management strategy to improve water input efficiency.

c. **Improvement of lint yield**

One way to improve crop production and hence total sales revenue for future crops is to refine irrigation scheduling under Scenario 2 conditions to increase potential yield for a crop. Associated with the improvement of yield production will be a greater transpiration and hence possibly greater crop water requirement. This then leads to some increase in total

[119] However, it is worth recalling that deep drainage reduces substantially and a greater amount of runoff is recycled under Scenario 2.

variable costs, including water cost and other variable cost. However, it is expected that the value of the increased lint exceeds the cost of the additional water and additional other variable costs. This can be tested in future research. Given that Scenario 2 examined in this thesis is considered as the improved, not optimal, management practice, the empirical results and implications provided in this thesis offer a step towards sustainability. In future research, further refinements in irrigation management can be examined in an optimisation process to identify the best management practice to maximise economic and water sustainability performance for a crop business.

d. **Weighted average irrigation cost**

There is no difference in the means of weighted average irrigation cost – the third driver of the profit to water cost ratio (see Table 8.3, Panel B3). This is because it is assumed that irrigation allocations are the same (e.g. 100% of irrigation abstracted is sourced by licensed irrigation) and licensed irrigation cost per ML remains unchanged (e.g. $60.30) across years and between the two scenarios. By doing that, the effects of irrigation scheduling decisions and runoff recycling decisions on profit to water cost ratio are isolated from irrigation allocation decisions. Future research can relax the assumption of irrigation allocation decisions that are described above to gain more insights into the impact of irrigation allocations on the overall economic and environmental performance of a crop business.

Future research can consider other scenarios of irrigation allocations, for example, irrigation is sourced from only traded irrigation or a mix of licensed irrigation and traded irrigation. This will enable gaining insights into the magnitude effect of various irrigation allocation decisions on the water cost incurred by a crop business and the economic implications of such decisions

e. **Improvement of profit to water cost ratio**

It can be argued that an increase of 56% in profit to water cost ratio is a result of **runoff recycling decisions** and **irrigation scheduling decisions** made at the operational level. Given that Scenario 2 still reflects suboptimal irrigation management decisions, further improvement in profit to water cost ratio is expected for future crops by using optimal conditions.

f. **Incorporation of energy cost**

These figures reported above are quantified without taking into consideration costs saved from reductions in energy use (for example, diesel fuel used for pumping irrigation water from rivers/bores/dams to the field). Furthermore, it is expected that irrigation performance under Scenario 2 conditions can be further improved through a process of optimization, leading to a further potential social, environmental and economic gain for a crop business and the industry as a whole.

8.6 Conclusion

In this chapter, in order to demonstrate the utility of the designed WESM, I apply and test theory around how irrigation practice can be improved (Scenario 2) and provide empirical evidence as to how and to what extent changing management practice at the operational level of a crop business has impacts on its overall water and economic sustainability performance.

The novel two-phased simulation modelling approach enables a comparison between two scenarios. Furthermore, the hierarchical WESM model allows me to analyse and identify what activities at the operational level are driving the change in the overall water and economic performance of a crop business when moving from Scenario 1 to Scenario 2.

It is empirically evident that there is a statistically, economically and environmentally significant difference when switching from the current water management practice to the improved water management practice described in this chapter. More specifically, the organisational level measure of profit to water cost ratio increases by 56%, operating profit increases by 30%, and 28% of water volume can be saved. In Chapter 9, detailed discussions on how individual cotton farms, as well as the industry as a whole, can improve their economic and environmental performance by moving from the current management practice to the improved management practice.

Finally, the output of Scenario 2 could provide the basis for setting better targets (compared to using Scenario 1). However, future crops, using a refined/optimal furrow irrigation management practice, should result in more significant improvement in the overall water and economic sustainability measure as well as other key sustainability measures contained in the designed WESM model. To do this, better targets can be set to enable crop managers to move towards sustainability.

Chapter 9. Conclusions and Implications

9.1 Research Summary

The central research question addressed in this thesis was how can Environmental Performance Measurement Systems (EPMS) be *designed* and *used* in an agricultural setting to support managers in water and economic sustainability-related decision making and control.

Water plays a crucial role in crop agriculture in enabling crop businesses to maintain profitability in the long-term. On the other hand, as a substantial user of water, agriculture has a significant impact on the sustainability of freshwater at both global and local levels. Therefore, improvement of water management in agriculture is vital for global economic and environmental sustainability. Despite this, extant research provides little guidance on how EPMS can be designed and used to support improved environmental (water) and economic sustainability in the crop production context.

Cotton production in Australia is selected as the empirical setting in this thesis for four main reasons: (i) cotton is a high value crop and is of economic significance; (ii) cotton production provides fibre, a primary cotton product to meet one of the most essential needs of human beings[120]; (iii) cotton production (both yield and quality) is sensitive to water availability; and (iv) cotton is perceived to be a high user of water, therefore, improvement of water sustainability of cotton production implies economic and environmental significance at the regional and global levels.

In the context of cotton businesses, extant research has not identified valid crop water performance measures which are informative about both water and economic sustainability performance. As outlined in Chapter 3, the literature surrounding efficiency of water used by plants is littered with either inconsistent or invalid terminology. Further, given such issues, standards and targets developed based on existing measures are unlikely to be useful for managers to support sustainability- related decision making and control at the organisational level.

[120] Another product from cotton production is cotton seed which can be used as cooking oil.

From a management accounting (MA) research perspective, there has been very little MA research conducted in an agricultural setting. In addition, extant EPMS research presents two underlying theoretical problems, which are also reflected at a more general level in broader performance measurement systems (PMS) research. The first relates to the validity issue of EPMS design. The second relates to the target setting issue of EPMS design.

9.1.1 Validity issue of EPMS (contribution 1)

In respect to the validity characteristics of EPMS, there is little work on how to design *valid* environmental performance measures to provide managers more precise information enabling better environmentally sustainable decision making and control. I argue that there are two key reasons for this. First, from the MA research to date, there is still little work on integration between PMS and natural science when researchers define the concept of environmental sustainability and/or develop environmental sustainability measures (Bebbington & Thomson 2013; Lamberton 2005). This means MA researchers do not always have a good scientific understanding of the underlying environmental issues of the phenomena they are studying, and hence they do not know what should be measured in regard to environmental sustainability performance (e.g. Figge & Hahn 2013). Second, while environmental management typically occurs at an operational level in organisations – the level at which environmental sustainability issues arise and need to be managed – there has been little recognition of the connection between this and the organisational level where EPMS typically reside.[121] This means there is still little understanding about how the environmental issues at the operational level can inform decision making and control at the organisational level (Kolk & Mauser 2002).

To address this, I apply an interdisciplinary approach – an integration of water and crop science and accounting – to develop a theoretical discussion of water sustainability at the global and regional levels and apply it to an examination of crop water sustainability in a cotton production setting. Based on this, I develop a number of key water sustainability measures that capture crop water sustainability at an operational level, the level at which water sustainability issues related to cotton production occur and need to be managed.

[121] While EPMS studies at the higher organizational levels provide aggregate information about environmental performance of an organization, for example resource use efficiency (Figge & Hahn 2013), such aggregate, high level information itself does not capture the underlying phenomenon being examined. In contrast, the examination of EPMS at the lower level, an operational level, will provide disaggregate and detailed information in relation to environmental sustainability and a better understanding of the actual drivers of the overall environmental performance of the organization.

Furthermore, I develop an organisational level summary measure (profit to water cost ratio), which incorporates information about both economic sustainability and environmental sustainability and can be used to assess the overall sustainability performance of a crop business.

Then, I take a decomposition ratio analysis approach to develop and articulate theoretical and logical links between measures at an operational level through to the organisational level and tie them together in a clear and structured way. By doing this, a theoretical connection between the organisational level summary measure and the operational level measures is established. This forms a new theoretical construction of EPMS – which I label the Water and Economic Sustainability Performance Measurement (WESM) model – comprising measures spanning across all levels of the organisation, providing guidance at an operational level, as well as informing and being informed by the organisational level.

The new designed WESM overcomes the two key problems with EPMS validity addressed in extant research. The first key problem is the missing link between science and MA research as identified by Bebbington & Thomson (2013) and Lamberton (2005), who call for more work addressing this issue. My study is one of the first to establish the theoretical links between crop and water science with PMS. The second key problem is the lack of connection between operational (low) and organisational (high) level measures (Kolk & Mauser 2002). In their review of existing environmental management research, Kolk and Mauser (2002) note that environmental management models are focused at a broad and conceptual level, and, despite the evidence of a close link between organisational activities at the operational level and an organisation's environmental performance, there is still lack of EPMS that can be operationalized at an organisation's operational level[122] (Kolk & Mauser 2002). My study is one of the first to establish the theoretical connection between organisational (high) level sustainability measures and operational (low) level sustainability measures in a hierarchical, logical and structured way. By addressing these two key problems in the context of crop production, I also contribute to the PMS literature by providing a new theoretical construct that overcomes the validity issue of PMS addressed by (Flamholtz, Das & Tsui 1985; Ittner & Larcker 2003; Nørreklit, Nørreklit & Israelsen 2006; Otley 1999).

[122] Kolk and Mauser (2002) also raised a concern that despite several calls from environmental management researchers for more attention in this field in order to improve the insights into organizations' environmental performance measurement and management, this area of research has still been understudied – which continues to be the case.

This study is the first to develop a scientifically and hierarchically valid EPMS model for decision making and control for water and economic sustainability in broad acre agriculture. By providing the theoretical development of a new, valid, science-based model, I make a theoretical contribution of overcoming the validity issue of EPMS, one of the key issues of EPMS design that has been raised in the literature.

Furthermore, the research makes a methodological contribution to sustainability- related MA research by demonstrating a new approach – the interdisciplinary approach, an integration of environmental science and accounting – to studying EPMS to overcome the validity issue of EPMS design. This study is the first to incorporate water and crop production science into accounting research to develop theoretical explanations as to what water sustainability means at the global and regional levels. From this, a theoretical development of water and economic sustainability for crop businesses is provided as a foundation for the design of WESM. Other MA researchers who are interested in studying issues related to environmental sustainability may find the interdisciplinary approach pioneered in this study a useful guide.

9.1.2 Target setting issue of EPMS (contribution 2)

The second issue of EPMS design addressed in this thesis is the target setting issue. Extant MA research has discussed the critical role of target setting in managing and directing organisational performance, and the problem of constructing valid targets (Ahmed & Rafiq 1998; Dekker, Groot & Schoute 2012; Elnathan, Lin & Young 1996; Figge & Hahn 2013; Ittner & Larcker 2001; Josée & Louis 2004). While there is a lot of discussion around target setting in the literature, there is little research around how to construct targets.

In the development of EPMS, issues related to appropriate target values for performance measures become an even greater challenge as decision makers have to deal with a more complex environment where economic and environmental performance aspects are simultaneously taken into consideration (Virtanen, Tuomaala & Pentti 2013). From the research to date, there is still lack of an all-encompassing and comprehensive approach to steer managerial decision making towards sustainability (Figge & Hahn 2013). Extant research provides little evidence how to develop environmental performance standards that can be used as *targets* to support managers in better sustainability-related decision making and control.

I find that simulation models, coupled with valid performance measures, enable the construction of standards, which may be used as the basis for targets. Specifically, I use the CROPGRO-Cotton embedded in the DSSAT system, a well-recognised and widely-used cotton production model (Thorp et al. 2014), to simulate a cotton cropping system to generate crop production and water data, which provides input data to the WESM model. Furthermore, I select furrow irrigation practice, the most common form of irrigation used in the cotton industry, as an irrigation method for the model, to examine the impact of irrigation management practice on sustainability performance of a crop business. In order to improve the quality of simulated information, I designed a new two-phased simulation modelling process to simulate furrow irrigation practice more accurately.

In addition, I implemented the designed simulation modelling process to simulate the current furrow irrigation practice. By doing this, I demonstrated that the theoretical WESM model works and was able to quantify a number of valid crop water and economic sustainability performance measures. In principle, these measures could be used for standard and target setting in decision making and control for researchers and farmers.

In order to demonstrate the utility of the designed WESM, I apply and test theory around how irrigation practice can be improved and what kind of impacts this has on environmental sustainability and economic performance. The novel two-phased simulation modelling approach enables a comparison between base line (current) furrow irrigation practice and alternative (improved) irrigation practice. I find statistically significant improvements in water use and economic outcomes. More specifically, the organisational level measure of profit to water cost ratio increases by 56%, operating profit increases by 30%, and 28% of water volume can be saved. The output of Scenario 2 could provide the basis for setting better targets (compared to using Scenario 1). Moreover, these results provide significant implications to the cotton industry (and potentially agriculture more broadly) with the potential to save hundreds of gigalitres of water and increase profitability by tens of millions of dollars per crop season for cotton farming in Australia.

By applying simulation modelling to quantify a range of valid crop water and economic sustainability performance measures presented in the designed WESM, I show how to overcome the challenge identified by Figge and Hahn (2013) and Virtanen, Tuomaala & Pentti (2013) of how targets can be set more rigorously in the context of EPMS. Furthermore, this is one of the first studies to specifically focus on how to design and construct performance targets, addressing the critisim by (Bol et al. 2010; Dekker, Groot & Schoute 2012; Ittner & Larcker 2001), that this is an underresearched topic in the PMS literature more broadly.

In addition, this study is the first to develop a novel two-phased simulation modelling process to examine the impact of water management practice on water and economic sustainability performance of a crop business. By doing this, the thesis also explains how the quality of information can be improved and how the designed WESM can be used to support managers in better water and economic sustainability-related decision making and control. Further to this, I demonstrate the usefulness of simulation modelling as a research method which has not had a great deal of application in research beyond a few costing studies (Balachandran, Balakrishnan & Sivaramakrishnan 1997; Balakrishnan & Sivaramakrishnan 2001, 2002; Christensen & Demski 1995; Dhavale 2005; Hansen & Banker 2002; Kaplan & Thompson 1971; Labro & Vanhoucke 2007; Noreen & Burgstahler 1997). In this respect, this thesis makes a method contribution to sustainability- related management accounting research by demonstrating a new way to model the effect of various decision choices on the economic and environmental sustainability performance of a business, even when those decision choices have not been use in practice.

This research also provides a theoretical contribution to the accounting literature through the development and application of theory from science which has the potential to contribute to overcoming validity and target setting problems in PMS design; this further increases the explanatory power of our theory. To the author's knowledge, this is the first study to provide empirical evidence on a statistically, economically and environmentally significant difference between the modelled scenarios. This demonstrates that the designed WESM can be used to help decision-makers make better water and economic decisions. My approach reflects the sentiment expressed by Davis, Eisenhardt & Bingham (2007) and Harrison et al. (2007), that simulation is a useful method for theory development and theory testing when the examined phenomena involve longitudinal, nonlinear and/or complex processes, or when empirical data are challenging to obtain elsewhere – which is the study examined in this thesis[123].

[123] Since my simulation approach enables my work to make contribution to the subset literature of EPMS, it also makes contribution to the broader sustainability accounting literature.

Finally, this is the first study which provides evidence that a comprehensive WESM can be empirically derived, and hence may be utilised by growers in decision making and control. Practically, the results also have implications for the cotton industry as to how changing water management practices can improve economic and environmental sustainability performance at the industry level.

9.1.3 Agriculture- related management accounting research (contribution 3)

While agriculture is economically and socially significant in meeting human needs for food and clothing, it is surprising that there has been very little management accounting research conducted within an agricultural setting and almost none on its role in environmental sustainability. This study addresses Jack's (2005, p. 60) contention that "*agricultural academics tend not to be interested in accounting and accounting researchers tend to stay clear of agriculture and related industries*". In addition, this study reflects the concern raised by Argilés and Slof (2001) that despite the important role of agriculture, accounting researchers have given it little attention, and hence there is little empirical research in the agricultural setting.

This thesis is the first study, to the author's knowledge in the management accounting literature, which incorporates water and crop science into accounting to develop EPMS model for the agricultural sector, specifically the cotton industry. The study has provided an insight into how management accounting has a key role to play in understanding how the sector may move towards water and economic sustainability. In doing so, a new avenue of investigation is opened up for studying EPMS in the agriculture sector more broadly, as discussed in Section 9.3.

9.1.4 Novel EPMS model for agriculture (contribution 4)

The contribution to the agriculture literature relates to the novel theoretical framework of EPMS – the WESM model – developed and provided to crop agriculture research.

While the water use efficiency concept has been used in crop science research to describe how efficiently water can be converted into crop output, the literature surrounding efficiency of water used by plants is influenced by inconsistent terminology (Blum 2009; Cossani, Slafer & Savin 2012; Hochman, Holzworth & Hunt 2009; Igbadun et al. 2006; Liu-Kang & Hsiao 2004; Moore, Robertson & Routley 2011; Passioura 2006; Pereira, Cordery &

Iacovides 2012; Tennakoon & Milroy 2003; van Halsema & Vincent 2012). More specifically, I find three issues related to crop water efficiency definitions in the literature: (i) different terminologies are used to express the concept of "water use efficiency" – the relationship between crop yield and crop water use – including WUE, CWP and CWUI; (ii) different water terms are used to define the denominator (e.g. water component) and/or the numerator (e.g. crop output) of water efficiency measures; (iii) the same WUE measure is used to express two different concepts of water efficiency. Accordingly, the concept of water use efficiency remains ambiguous and inconsistent.

Furthermore, since improving water use efficiency with regards to irrigation water has become an important issue in agricultural water management research and practice, new indicators have been developed in an attempt to capture the efficient use of irrigation (Cammarano et al. 2012; Pereira, Cordery & Iacovides 2012). While an irrigation measure (e.g. the WP_{Irrig} indicator in Pereira et al.'s 2012 study) is proposed as a measure of how efficient irrigation water is used to generate economic yield, this measure, expressed as the ratio between total economic yield obtained by the crop business and irrigation amount, suffers a validity issue since the economic value of irrigation use is over-represented.[124] In addition, by presenting the comparisons of lint yield (kg/ha) response to irrigation amount (mm) among three different cotton locations with different rainfall, Cammarano et al. (2012) provide an invalid comparison and hence an invalid evaluation of economic outcomes of cotton production with respect to irrigation application across regions.[125]

In order to overcome the ambiguity, inconsistency and, most importantly, the validity issue of water use efficiency measurement in the extant literature (Cammarano et al. 2012; Igbadun et al. 2006; Pereira, Cordery & Iacovides 2012), I develop, based on water and crop science, a set of key water sustainability measures that more precisely capture water sustainability-related activities and management practices occurring at the crop production level, the level at which water sustainability issues arise and need to be managed. By doing this, I not only overcome the validity issue of how to measure water use efficiency, but also establish a theoretical connection between water coming into a cropping system and crop production coming out the cropping system.

[124] Section 3.3.1.2 provides detailed discussion on this issue.
[125] Similar to Pereira et al.'s 2012 study, in Cammarano et al.'s study, the contribution of rainfall to the economic outcomes of the crop is not separated from that of irrigation.

In addition, I incorporate an accounting perspective in the discussion of crop water and economic sustainability to develop a summary measure of water and economic sustainability performance of a crop business (profit to water cost ratio) and its building block (the WESM model). This links the summary measure at the organisational level to its drivers across all levels of the organisation and in particular to the operational level. To the author's knowledge, this study is the first study to provide a theoretical development of a set of valid water sustainability measures at the operational level, and the designed WESM is the first EPMS to provide a comprehensive conceptual framework for crop water and economic sustainability performance. This can be used to support better sustainability- related decision making and control for crop agriculture.

Moreover, the new WESM model uses a novel two-phased crop simulation modelling process to enable the development of more valid and precise standards for crop businesses' economic and environmental performance measures. In this respect, I provide a new tool to allow crop businesses to evaluate their actual performance against a target and identify areas for improvement in water and economic sustainability performance. The model also has utility at the regional level where the value of the summary sustainability measure of individual crops will signal how profitable a crop is in respect to water resource use compared to other crops grown in the same region. This will support policy makers in relevant decisions related to water allocation under water constraint.

Finally, by designing the novel two-phased crop simulation modelling process, I provide the crop simulation modelling literature a new approach to improve the quality of simulated information and establish an end-to-end connection between irrigation strategies and their economic and environmental outcomes. Both issues have not been examined in the literature to date (Jones et al. 2003; Keating et al. 2003; Smith, Raine & Minkevich 2005; Wang et al. 2002)

9.2 Implications of the research

This section discusses the implications of the research findings. There are two key practical implications from this research. First, the novel WESM model developed is a new tool which practitioners can use for on-farm decision making and control for water and economic sustainability management. Second, it is empirically evident that moving from current to improved practice has industry-level environmental and economic significance.

9.2.1 Use of new tool

There are two key components of the novel WESM model developed. First, the WESM model provides a theoretical framework which practitioners may use in implementing improved EPMS. In addition, the developed crop water use index can enable crop managers and farmers to identify areas for improved sustainability performance.[126] The sustainability measures developed in this thesis can be translated into guidance for crop managers to enable them to improve their economic and environmental performance, including identifying areas for improved sustainability performance, and making appropriate/optimal operational decisions to achieve better economic and environmental performance.

Second, this thesis provides cotton growers and other industry's stakeholders (including crop agronomists, crop researchers, industry partners) a simulation tool to enable them:

a. Identify strategies to improve the environmental and economic performance under furrow irrigation systems, such as by forecasting and using 'what if' scenario analysis. For example, test and experiment with changes in furrow irrigation as demonstrated in Chapter 8.
b. Test and experiment changes in irrigation practice, such as sub-surface irrigation.
c. Estimate and select targets to work towards environmental sustainability.
d. Utilise diagnostic control through variance analysis, where simulated performance (budget) is compared with actual output.
e. Construct improved information to support capital investment decisions regarding irrigation systems.

In summary, the developed WESM incorporating the two-phased simulation modelling process provides crop managers a tool for risk management and the identification of new

[126] For example, when a farmer looks at the crop water use index, if the crop water use index in respect to water input efficiency turns out to be poor, irrigation management needs to be examined. On the other hand, if the harvest index is poor (i.e. very low compared to the theoretical value), it suggests that things such as pest control and disease control need to be better managed. Alternatively, if the transpiration index is poor, this means the farmer needs to improve nitrogen management practices. The detailed discussion of crop water use index with the constructed decision tree is provided in Section 3.3.3.

possibilities and potentials in farming, in particular improvements in water and economic sustainability.

9.2.2 Economic and environmental significance

In this section I demonstrate that moving from current to improved practice has industry level environmental and economic significance. To do this I provide a naive estimate of the potential effect if Scenario 2 was adopted by applying the results from Chapter 8 (calculated on a per ha basis) to a typical 400 ha farm, and also a conservative estimate of the industry size. For the purpose of this analysis, I use the average irrigated area for the Australian cotton industry from 2010–2011 crop season to the 2013–2014 season, based on data from the Australian Bureau of Statistics (2015) f 365,365 hectares (see Appendix E, Table E1) for further information of industry size from different sources). The environmental and economic gains from moving from Scenario 1 to Scenario 2 at both business level and industry level are summarised in Appendix E, Table E2.

Potential environmental gain:

At the farm level, it is evident in this thesis that by simply increasing furrow inflow from 2.80 L/s to 6.0 L/s and reducing irrigation time (time of cut-off) from 745 minutes to 310 minutes, individual cotton farms with a size of 400 irrigated hectares can save up to 860 ML of water, produce an additional 550 bales of lint, and gain an additional operating profit of nearly $139,600 per crop season (given a lint price of $474/bale, seed price of $0.32/kg, and licensed water cost of $60.3/ML).

At the industry level, it is reported that, in respect to environmentally significance, Scenario 1 results in a net water loss of 2.15 ML per ha, 860 ML per business, or nearly 786 GL in total at the industry level. This means by simply moving from the current water management practice (Scenario 1) to the improved water management practice (Scenario 2), the cotton industry as a whole can save up to 786 GL per crop season (i.e. every 6 months).

Potential crop production gain:

The amount of crop water saved could be potentially used to grow more cotton[127]. Given that the crop water use index for Scenario 2 is 144 kg of lint per ML, an additional of 310 kg of

[127] However, this is a huge debate. Environmentalists argue that the water should be returned as environmental flows. The industry wants to grow more cotton. The government wants more taxes.

lint is produced per ha as a result of 2.15 ML saved per ha (i.e. 2.15 ML/ha x 144 kg/ML = 310 kg/ha). This implies that when scaled up to business size and industry size, an additional 124,000 kg of lint (equivalent to 546 bales of lint) per business or an addition of 113,263,150 kg of lint across the industry (equivalent to 498,957 bales of lint), can be produced.

Furthermore, as a result of a slight increase in lint yield (e.g. 2.6 kg/ha), an additional 4.6 bales of lint can be produced at the business level, equivalent to 4,185 bales of lint at the industry level. In total, by simply moving from the current water management practice to the improved water management practice, a potential gain of 125,040 kg of lint (equivalent to 550 bales of lint) at the business level or 114,213,099 kg (equivalent to 503,141 bales of lint) at the industry level can be achieved.

Potential economic gain:
In terms of operating profit, by simply improving water management practices (e.g. from S1 to S2), a crop business can gain an additional profit of $217/ha from additional water saved of 2.15 ML//ha, giving a return on water for S2 of $101/ha (e.g. 2.15 ML/ha x $101/ML = $217/ha). This translates to additional profit of $86,800 at the business level or $79.3 million at the industry level can be achieved.

Moreover, as a result of the reduction in water costs when switching from Scenario 1 to Scenario 2, operating profit is reported to increase by $132/ha – equivalent to $52,800 (at the business level) and $48.2 million (at the industry level). In total, a potential gain of $94,000 operating profit at the business level or $85,860,775 operating profit at the industry level can be achieved.

In summary, by simply moving from current to improved water management practices an average cotton business, with 400 irrigated hectares, can save up to 860ML of water, produce an additional 550 bales of lint, and gain an additional operating profit of nearly $140,000 per crop season (given a lint price of $474/bale, seed price of $0.32/kg, and water licensed cost of $60.3/ML). For a crop business, these figures will be increased by the increase in size of irrigated land. At the industry level, these figures are aggregated to an additional 786 GL of water saved, an additional 503,141 bales of lint produced, and an additional operating profit of about $127.5 million gained per crop season.

9.3 Limitations, delineations and future research

Discussions of limitations and delineations of the research, and how the findings of the research are able to be extended in future research, are presented in this section.

9.3.1 Limitations and future research

One of the core contributions of this research is to provide empirical evidence on statistical, economic and environmental differences between the current management practice and the improved management practice with regard to water resource use in the cotton industry. However, these results have a set of limitations associated with it, which suggest avenues for future research.

First, it is assumed that economic factors such as lint price, cotton seed price, and unit licensed irrigation cost remain constant across 86 years of study and are based on the data of a sample budget for furrow irrigated cotton in 2014–2015 for the Central and Northern NSW area (NSW Government - Department of Primary Industries 2015). Since the analysis of economic and environmental implications of moving from Scenario 1 to Scenario 2 use the average crop water and production data over 86 years for each scenario, this assumption would impact the results of the economic significance from the analysis. Future research can explore the generalisability and sensitivity of the results to variations in economic factors.

Second, the irrigation scheduling set in DSSAT for both Scenario 1 and Scenario 2 do not favour Scenario 2 more than Scenario 1 since it is shown that, on average, the crops did not grow any better in Scenario 2. Furthermore, the way the irrigation scheduling is set is based on the assumption that in both cases crops grow under non-limiting irrigation supply. In practice, irrigation supply could be a challenge, particularly in low rainfall years; for example, in Scenario 1 27% more of irrigation needs to be abstracted compared to Scenario 2. Future research could refine irrigation scheduling to allow better economic yield produced under Scenario 2 conditions and place greater emphasis on irrigation-related risk management by moving to Scenario 2.

Third, it is noted that on average lint yield produced under both scenarios is around 8 bales/ha, which is lower than what can be obtained in practice (e.g. 10 bales/ha). Since the analysis conducted in the research is comparative analysis, this does not detract from the significance of the findings from the study. Since both SIRMOD and DSSAT software is calibrated and validated, and widely used internationally for water and crop production research (Gillies & Smith 2005; Hoogenboom et al. 2015; Jones et al. 2003; Smith, Raine & Minkevich 2005; Walker 2003), it is evident that these two software packages are reliable for undertaking simulation modelling studies. However, ongoing research is necessary to further calibrate these models in this respect.

Fourth, regarding irrigation allocation, it is assumed that the amount of irrigation abstracted in both scenarios is merely sourced by licensed irrigation. In practice, crop businesses usually need to source irrigation from both licensed and traded irrigation. In this respect, the impact of irrigation allocation on weighted irrigation cost particularly, and on the overall economic and environmental performance of a crop business generally, is not accounted for in this research. Future research could examine various alternatives of irrigation allocation to gain more insights into the impact of irrigation allocation of crop businesses' sustainability performance.

Fifth, when accounting for water cost, it is assumed that rain is a "free" water resource and recycling costs are equal to zero. In future research, costs related to capture and storage of rain and recycling costs need to be taken into consideration and be included in the denominator of profit to water cost ratio – total water cost.

Finally, while it is expected that fibre quality varies along the furrow in Scenario 1, and between Scenario 1 and Scenario 2, as a result of differences in irrigation distribution within and between the two scenarios, the lint price is assumed to be the same in the comparative analysis in Chapter 8. Future research could consider changes in lint price due to varied fibre quality.

While these limitations of the research are acknowledged, they do not devalue the significance of the findings from the study. In addition, this lays a basis to extend the research in future.

9.3.2 Delineations and future research

There are a number of choices I have made which delineate the scope of the research. First, I deal with water only, not energy or other sustainability issues. Second, I deal with agriculture, not other industry settings such as manufacturing. Third, cotton is examined, not other broad acre crops or other forms of agriculture. Fourth, the geographic location of the simulation model (i.e. Myall Vale), soil type (i.e. clay vertosol) and other choices (i.e. nitrogen application, plant density) were made in developing this model. Finally, I only consider furrow irrigation, and consider only two furrow irrigation strategies (two scenarios). While future research may explore these issues, in this section I will identify a number of potential avenues to expand the scope of the research.

First, while I use water as an environmental resource to be examined in this thesis, the research approach (i.e. interdisciplinary approach), the simulation method, and the hierarchical WESM model developed in this thesis can be expanded to incorporate other key resources; for example, energy and soil. In addition, further development of the WESM model designed in this thesis can be undertaken to enable soil sustainability and energy sustainability aspects to be included into the WESM, as well as linkages between soil, energy and water sustainability to be made, to provide an integrated and comprehensive decision tool that can be used to support crop businesses in making better sustainability- related decisions

Second, while the empirical setting considered in this thesis is agriculture, and the new EPMS – the WESM model – is designed specifically for crop agriculture, the application of simulation modelling for target setting and supporting decision making can be used as a research method in other settings where science related to production activity can be drawn upon. This includes studying energy sustainability- related PMS design and target construction in the manufacturing setting to expand the work of Virtanen, Tuomaala & Pentti (2013) .

Third, while cotton is selected as the empirical crop in this thesis, the findings have implications for other cropping systems. The scientifically and hierarchically valid WESM model, designed for cotton, could be expanded and the two-phased simulation modelling process developed in this thesis could be applied to other crops, for example wheat, soybean, and rice, in order to support other crop industries and crop agriculture as a whole to improve sustainability- related decision making and control.

Fourth, while only one Australian cotton area, Myall Vale, and one soil type, clay vertosol, is considered in this thesis, this study could be expanded to replicate the designed WESM model, coupled with the two-phased simulation modelling process, to examine other cotton regions and their associated soil type across Australia, in order to examine the effect of cotton locations and weather conditions on water and economic sustainability of crop businesses. Other forms of crop management, including nitrogen application, could also be examined to identify the optimal crop management conditions with respect to water use and crop yield.

Finally, in relation to furrow irrigation strategies and target setting, there are a number of ways the empirical work of this thesis can be extended. For example, refining the optimal furrow irrigation management under Scenario 2 conditions can be undertaken through a process of optimisation using simulation modelling (e.g. via SIRMOD and DSSAT) in order to improve/optimise furrow irrigation performance and irrigation scheduling so that crop yield can be further improved/maximised while irrigation applied can be further reduced/minimised. As a result, it is expected that higher profit to water cost ratio and further economic and environmental gains at both business and industry levels can be achieved, compared to the current management practice described in the Scenario 1.

However, even with a more refined/optimal furrow irrigation management, under furrow irrigation systems, the amount of water loss to soil evaporation is still substantial. The problem is that the large residual soil evaporation cannot be reduced while the irrigation process results in a wet soil surface. This means water input efficiency is still far from the target value of 1.0 when furrow irrigation systems are in use. In this respect, future research can consider other irrigation systems in order to reduce/minimise water loss from soil evaporation (while still maintaining the low level of deep drainage and further reducing runoff from irrigation described in Scenario 2) so that water input efficiency can be improved. This will provide both economic and environmental implications for crop businesses and the industry as a whole, since less water will be lost to the environment and more water can be saved to grow more cotton. With current technology, sprinkler irrigation systems and sub-surface drip irrigation systems can be considered as a replacement of furrow irrigation systems in the process of improving the sustainability performance with regard to water sustainability. However, it is expected that sprinkler irrigation systems may not improve water input efficiency since while there would be zero irrigation runoff to recycle and there would be equally small deep drainage (compared to Scenario 2), the soil surface will still be wet, and possibly more continuously. In contrast, it is hoped that sub-surface drip irrigation systems can provide water with no surface wetting from irrigation, and hence can improve water input efficiency and water sustainability for crop businesses and the whole industry. While it is recommended to explore the potential of sub-surface drip irrigation systems in improving water sustainability performance, capital investments as well as energy cost associated with system operation need to be taken into consideration. Though a sub-surface drip irrigation system could result in some increase in energy cost (and system depreciation), it is hoped that the value of the increase in economic yield and decrease in water cost exceeds the additional costs incurred when shifting from furrow irrigation systems to sub-surface drip irrigation system.

Another way to extend the target setting research, which also relates to the two points discussed above, is to develop staged sustainability targets which include reference to technology used in crop cultivation. Setting sustainability performance targets play an important role in providing guidance and goals to assist a manager in identifying what the business should aim for in the long-term, and directing organisational change to move towards sustainability. This research has laid out Stage 1 and Stage 2 sustainability targets which result from the application of the current furrow irrigation practice and the improved furrow irrigation practice, respectively. While this explicates how a crop business can move from the status quo to a more sustainable performance, it is shown that the improved management practice examined in this research is still sub-optimal and hence the question of how the crop business can move towards sustainability still remains open. Future research can undertake Stage 3 and Stage 4 sustainability targets which are based on the application of an optimal furrow irrigation practice and a sub-surface drip irrigation system, respectively.

9.4 Conclusion

This piece of research has been undertaken to answer the question: how can Environmental Performance Measurement Systems (EPMS) be *designed* and *used* in an agricultural setting to support managers in water and economic sustainability-related decision making and control.

This research is initially stimulated by the concept of sustainable development introduced by the Brundtland Commission as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (The Brundtland Commission 1987, p. 1). It is evidenced that some core activities at the organisation's operational level are roots of a number of environmental problems at the global and regional levels. Therefore, in order to enable future generations to meet their own needs, at present, organisations in many industries, such as agriculture, manufacturing or petroleum industries, need to operate in a more efficient and more sustainable manner so that the use of natural resources can be minimised and discharges to the natural environment can be mitigated.

The agricultural sector, a significant user of water, has a significant impact on the sustainability of freshwater at both global and local levels. On the other hand, agriculture is economically and socially significant in meeting human needs for food and clothing. Therefore, improvement of environmental (water) and economic sustainability of crop businesses is of crucial importance for society to become more sustainable. Management accounting researchers can contribute to crop agriculture and to broader society by applying PMS to sustainability issues to construct more valid and comprehensive models to support crop businesses in water and economic sustainability- related decision making and control.

Within these broad issues, this piece of research has taken initial and tentative steps to address more overtly than previous research the design of EPMS in an agricultural setting in two ways.

First, having undertaken an interdisciplinary approach – an integration of water and crop science and accounting, and a decomposition ration analysis approach, an accounting technique to enable the articulation of the theoretical and logical links between measures at the operational level through to the organisational level – I construct a theoretical EPMS model (WESM model) that has the potential to overcome validity issue in EPMS design. By doing this, the WESM model enables capture of water sustainability-related activities and management practices occurring at the operational level. This will provide the organisational level with more precise information to support economic and environmental sustainability decision making and control.

Second, the study examines the usefulness of the WESM model by designing a two-phase crop production simulation modelling approach, considering its application to the furrow irrigation practice (Scenario 1) and the improved furrow irrigation practice (Scenario 2). In doing so, I demonstrate that the theoretical model works and explains how targets can be set more rigorously in the context of EPMS. In this respect, the study lays the foundation for opening up the idea of consutructing targets based on simulation modelling and providing an approach to setting tagets to steer managerial decision making towards sustainability.

The study also provides economically and environmentally significant implications for the Australian cotton industry – the empirical setting considered in the thesis (and agriculture more broadly). By simply moving from the current to the improved water management practices, the industry can potentially save hundreds of gigalitres of water and increase profitability by tens of millions of dollars per crop season.

By developing a new theoretical model that potentially overcomes the validity and target setting issues of EPMS to support crop managers in water and economic sustainability-related decision making and control, the study lays the groundwork for future research in EPMS design and use in increasing depth and scope.

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Appendices

Appendix A: Supplementary information for Chapter 4

Appendix A1: An example of Cotton Gross Margins (Source: NSW Department of Primary Industries (2015))

NSW GOVERNMENT | Department of Primary Industries | CottonInfo | *Cotton Gross Margins*

Furrow Irrigated Cotton - (Roundup Ready Flex® Bollgard II®)

Central & Northern NSW ~ 2014-2015

GROSS MARGIN BUDGET

INCOME:

			Sample Budget $/ha	Your Budget $/ha
11.00 bales/ha at	Lint[1] $ 474	/bale (at gin)	$5,214	
	Seed[2] $ 80	/bale (at gin)	$880	
	(less discount) $ -	/bale (estimate)	$0	
	$ 554			
		A. TOTAL INCOME $/ha:	$6,094	

VARIABLE COSTS:

See Calendar of Operations for details

	Sample Budget	Your budget
Cultivation	$129	
Planting	$115	
Irrigation (9.79ML)	$573	
Fertiliser & application	$374	
Herbicide & application	$82	
Insecticide & application	$125	
Licence fees	$370	
Defoliation	$103	
Picking & cartage to gin	$334	
Ginning & levies	$756	
Refuge crop, pigeon pea, 5% of Bt cotton area	$31	
Crop insurance	$110	
Other (e.g. consultants)	$74	
B. TOTAL VARIABLE COSTS $/ha:	$3,177	
C. GROSS MARGIN (A-B) $/ha:	$2,917	
D. GROSS MARGIN (C/ML applied) $/ML:	$298	

EFFECT OF YIELD AND PRICE ON GROSS MARGIN PER HECTARE:

Approximate Breakeven Yield: 5.73 bales/ha (based on the lint, seed, discount prices above)

Approximate Breakeven Price: $ 289 /bale (based on 11 bales/ha. Overhead costs and permanent labour are NOT considered in the breakeven price)

SENSITIVITY TABLE

PRICE ($/bale incl. of seed & discounts)

Lint bales/ha YIELD	454	504	554	604	654
7.50	511	886	1,261	1,636	2,011
9.00	1,071	1,521	1,971	2,421	2,871
10.00	1,444	1,944	2,444	2,944	3,444
11.00	1,817	2,367	**2,917**	3,467	4,017
12.00	2,190	2,790	3,390	3,990	4,590
13.00	2,563	3,213	3,863	4,513	5,163
14.50	3,123	3,848	4,573	5,298	6,023

This budget should be used as a GUIDE ONLY and should be changed by the grower to take account of movements in crop and input prices, changes in seasonal conditions and individual farm characteristics. Estimated prices are GST exclusive.

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Central & Northern NSW ~ 2014-2015

Furrow Irrigated Cotton (Roundup Ready Flex® Bollgard II®)

Calendar of Operations			Machinery		Total $/ha	Inputs Rate /ha	Unit	Band Width	Cost $/unit	Cost $/ha	TOTAL Cost $/ha
Jul	Farming:	Discing	180kW PTO		11.43						11.43
Jul	Farming:	Hill up	180kW PTO		12.72						12.72
Jul	Fertiliser:	MAP	with above			120	kg	100%	0.72	86.64	86.64
Aug	Fertiliser:	Urea	135kW PTO	140kg N	4.27	304	kg	100%	0.50	152.41	156.67
Aug	Farming:	Rubber tyre roller	135kW PTO		11.07						11.07
Sep	Irrigation:	Pre Plant				1.60	ML	100%	60.30	96.48	96.48
Oct	Planting:	Precision planter	180kW PTO		11.13						11.13
Oct	Planting:	Seed[3]: Roundup Ready Flex Bollgard II	with above			13	kg	100%	8.00	104.00	104.00
Oct	Herbicide:	Fluometuron + prometryn (440g/L + 400g/L)	Self Propelled		3.67	2.00	kg	100%	17.56	35.12	38.79
Nov	Crop Insurance:			Premium depends on various factors							110.00
Nov	Irrigation:	In Crop				1.30	ML	100%	60.30	78.39	78.39
Nov	Fertiliser:	Urea (water run)	with above	120kg N		260	kg	100%	0.50	130.35	130.35
Nov	Herbicide:	Roundup Ready® Plantshield® (690g/kg Glyphosate)	Self Propelled		3.67	1.20	kg	100%	6.85	8.22	11.89
Dec	Insecticide:	Fipronil (200g/L), target: mirids	Self Propelled		3.67	0.10	L	100%	285.17	28.52	32.18
Dec	Irrigation:	In Crop				1.00	ML	100%	60.30	60.30	60.30
Dec	Farming:	Cultivation: Inter row	180kW PTO		11.85						11.85
Dec	Other:	Chipping or Spot Spray[4]			5.00						5.00
Dec	Irrigation:	In Crop				1.00	ML	100%	60.30	60.30	60.30
Jan	Irrigation:	In Crop				1.00	ML	100%	60.30	60.30	60.30
Jan	Insecticide:	Abamectin (18g/L), target: mites	Self Propelled		3.67	0.60	L	100%	19.11	11.47	15.13
Jan	Herbicide:	Roundup Ready® Plantshield® (690g/kg Glyphosate)	Self Propelled		3.67	1.20	kg	100%	6.85	8.22	11.89
Jan	Irrigation:	In Crop				1.00	ML	100%	60.30	60.30	60.30
Jan	Insecticide:	Dimethoate (400g/L), target: GVB, aphids	Aerial Spraying		14.00	0.40	L	100%	9.66	3.86	17.86
Jan	Irrigation:	In Crop				1.00	ML	100%	60.30	60.30	60.30
Feb	Insecticide:	Diafenthiuron (500g/L), target: SLW, aphids	Aerial Spraying		14.00	0.70	L	100%	65.32	45.72	59.72
Feb	Irrigation:	In Crop				0.80	ML	100%	60.30	48.24	48.24
Feb	Irrigation:	In Crop				0.80	ML	100%	60.30	48.24	48.24
Mar	Licence:	Bollgard II stacked RRF Licence Fee[5]									370.00
Mar	Defoliation:	Thidiazuron + Diuron (120g + 60g/L)	Aerial Spraying		14.00	0.25	L	100%	177.14	44.28	58.28
Mar	Defoliation:	Ethephon (720g/L)	with above			1.50	L	100%	6.42	9.63	9.63
Mar	Defoliation:	Crop oil	with above			2.00	L	100%	4.31	8.62	8.62
Mar	Defoliation:	Ethephon (720g/L)	Aerial Spraying		14.00	2.00	L	100%	6.42	12.85	26.85
Apr	Picking:	Own plant: round baler	Picker: JD7760		67.24	per ha					67.24
Apr	Picking:	plus fuel				28.00	L	100%	1.04	29.03	29.03
Apr	Picking:	plus wrap		40.00		/ round bale				9.41 / lint bale	103.53
May	Cartage:	Lift		7.00		/ round bale		12 round bales/truck		1.65 / lint bale	18.12
May	Cartage:	Freight[6]	costs related to yield	45.00		/ round bale		50 km from gin		10.59 / lint bale	116.47
May	Ginning:			65.00		/ lint bale				65.00 / lint bale	715.00
Jun	Levies:	Research Levy & Cotton Australia Levy		3.75		/ lint bale				3.75 / lint bale	41.25
Jun	Farming:	Mulcher with root cutter	135kW PTO		14.90						14.90
Jun	Other:	Consultant	Contractor		65.00						65.00
Jun	Other:	Soil moisture monitoring	Contractor		4.00						4.00
Jun	Farming:	Desilting & grading channels	Contractor		50.00						50.00
Jun	Herbicide:	Sterilising channels	135kW PTO		19.09						19.09
Jun	Farming:	Pupae busting	180kW PTO		17.39						17.39
Jun	Refuge:	Refuge Crop: Pigeon peas 5%, see page 4				0.29	ML				31.39
		B. TOTAL VARIABLE COSTS $/ha:									**3,177**
		Total Irrigation Water Use ML/ha:				9.79	ML[7]				

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FOOTNOTES: 2014-15 Central & Northern NSW, Furrow Irrigated Cotton Gross Margin Budget

1. $474/bale is the five-year average cotton lint price 2010-2015.

2. The cotton seed price is given indicatively as a per bale value. $80/bale for seed (prior to ginning costs being subtracted) is the equivalent of $320/t, assuming an average of 250kg of cotton seed per bale of lint.

3. Seed costs per kg will vary with the time of ordering and seed treatments chosen.

4. Chipping or spot spray can be used to control any surviving weeds.

5. The technology licence fee for Bollgard II® stacked with Roundup Ready® Flex for 2014-15 is $370 per green hectare (GST exclusive). This example uses Monsanto Cotton Choices™ Option 1, which provides a discount on the technology licence fees for 2014-15. However, you should choose the option which best suits your operation. See http://www.cottonchoices.com.au.

6. Assumptions made for module cartage are: property distance from the gin 50km, road train carting 12 round bales per trip, 4.25 lint bales per round bale.

7. Irrigation requirements typically range from 8-13ML/ha. The largest impact on water use is in-crop rainfall.

GENERAL INFORMATION

For a complete guide to cotton management, see the ***Australian Cotton Production Manual 2014.***

A gross margin represents the difference between gross income and the variable costs of producing a crop. Gross margin budgets do not take into account risk, overhead costs (including permanent labour) and do not calculate farm profit. This budget should be used as a GUIDE ONLY. It is designed to give an indication of operations and costs required to grow a cotton crop. A grower should alter this budget to take account of individual field management plans, movements in crop and input prices and changes in seasonal conditions. In all instances, operations should be tailored to the requirements of individual paddocks.

BALE: The industry term 'per bale' is in reference to a ginned lint bale of 227kg. New picking technology picks the cotton and packs it into round or rectangular bales on-farm.

Bt: A licence fee is paid to Monsanto for cotton seed that uses Bollgard technology.

CHEMICALS: Always read chemical labels and follow directions, as it is your legal responsibility to do so. Use of a particular brand name or active ingredient does NOT imply a recommendation by NSW DPI.

DEFOLIANT: Good conditions are required to get the best performance. The choice of defoliant and rate used depends on the moisture status of the plant and seasonal conditions.

FERTILISER REQUIREMENTS: All fertiliser strategies include comprehensive soil testing prior to sowing.

HERBICIDES: The cornerstone of weed management and managing herbicide resistance risks is controlling survivors and preventing new weed seeds from entering the seed bank. To reduce the likelihood of herbicide resistance, rotate herbicide groups and weed management techniques. Aim to plant into clean fields. See the Herbicide Resistance Management Strategy (found in the CottonInfo Cotton Pest Management Guide) and the Monsanto Roundup Ready Flex Cotton Weed Management Guide.

INSECTICIDES: Insecticides suggested in this budget and spray timing are examples only and strategies will vary with individual circumstances. Individual paddocks need careful monitoring to determine pest and beneficial insect populations. Use recommended thresholds for all pests. Avoid using broad spectrum sprays and continuously using chemicals from the same group. Follow the Insecticide Resistance Management Strategy (found in the CottonInfo Cotton Pest Management Guide) to protect the value of insecticide technologies for the future. Conserving and utilising beneficial insects is a key aspect of long-term effective pest management.

IRRIGATION: The cost of water varies considerably depending on the source, location and number of times water is pumped. A cost of $60.30/ML is used assuming pumping from the regulated Namoi River (fees $32.24/ML) with water 'lifted' twice using diesel pumps (pumping cost $28.06/ML). This pumping cost takes into consideration fuel and maintenance. Pumping costs can be in excess of $120/ML for bores.

LABOUR: Labour is assumed to be an overhead cost and not included in this budget. An estimate of labour costs is $250-$300/ha.

LEVIES: The Research Levy ($2.25/bale) is a compulsory levy that is invoiced by the ginning organisation following ginning. Funds collected through this levy are used to fund vital industry research by the Cotton Research and Development Corporation (CRDC). The Cotton Australia Levy ($1.50/bale) is a voluntary levy, which funds the peak industry body Cotton Australia that provides a valuable policy and advocacy role, farmer support and promotes the Australian cotton industry.

MACHINERY: The cost of each farming pass reflects variable costs only (fuel, repairs and maintenance), labour and depreciation are considered overhead costs, so are not included in this budget.

ROTATION: Whilst cotton can be grown in various rotations, this budget assumes a two-year rotation of cotton-wheat-long fallow.

YIELD: A yield of 11 bales/ha is achievable considering the long fallow, 'best practice' operations and a five-year average yield for the variety S74BRF in Cotton Seed Distributors (CSD) commercial trial results.

Appendix A2: WESM Analysis

Table A1 WESM model - Panel D (Level 4 of WESM)

Panel D1: Analysis of Crop water use index		
Variable	WESM Level	Formula
$\mathbf{Crop\ water\ use\ index_{it}}\left(\frac{\mathbf{kg\ of\ lint}}{\mathbf{ML}}\right)$	**Level 4**	$= \text{Lint yield}_{it}\left(\frac{\text{kg of lint}}{\text{ha}}\right) \div \text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$ $= \mathbf{Transp\ index_{it}}\left(\frac{\mathbf{kg\ of\ biomass}}{\mathbf{ML\ of\ tranpiration}}\right) \times \mathbf{Harvest\ index_{it}}\left(\frac{\mathbf{kg\ of\ lint}}{\mathbf{kg\ of\ biomass}}\right) \times \mathbf{Water\ input\ efficiency_{it}}(\%)$
$\text{Transpiration index}_{it}\left(\frac{\text{kg of biomass}}{\text{ML of tranpiration}}\right)$	Level 5	$= \text{Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{\text{ha}}\right) \div \text{Transpiration}_{it}\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$
$\text{Harvest index}_{it}\left(\frac{\text{kg of lint}}{\text{kg of biomass}}\right)$	Level 5	$= \text{Lint yield}_{it}\left(\frac{\text{kg of lint}}{\text{ha}}\right) \div \text{Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$

Water input efficiency$_{it}$(%)	Level 5	$= \left[\text{Transpiration}_{it}\left(\frac{\text{ML of transpiration}}{\text{ha}}\right) \div \text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)\right] \times 100\%$
Panel D2: Analysis of Weighted average cotton price		
Variable	WESM Level	Formula
Weighted average cotton price$_{it}$ $\left(\frac{\$}{\text{kg of total yield}}\right)$	**Level 4**	$= \text{Total sales revenue}_{it}\left(\frac{\$}{\text{ha}}\right) \div \text{Total yield}_{it}\left(\frac{\text{kg of total product}}{\text{ha}}\right)$ $= \left[\textbf{Lint percentage}_{it}\ (\%) \times \textbf{Lint price}_{it}\left(\frac{\$}{\textbf{kg}}\right)\right] + \left[\textbf{Seed percentage}_{it}\ (\%) \times \textbf{Seed price}_{it}\left(\frac{\$}{\textbf{kg}}\right)\right]$
Lint percentage$_{it}$ (%)	WESM Input	$= \left[\text{Lint yield}_{it}\left(\frac{\text{kg of lint}}{\text{ha}}\right) \div \text{Total yield}_{it}\left(\frac{\text{kg of total product}}{\text{ha}}\right)\right] \times 100\%$ Crop Data
Seed percentage$_{it}$ (%)	WESM Input	$= \left[\text{Seed yield}_{it}\left(\frac{\text{kg of seed}}{\text{ha}}\right) \div \text{Total yield}_{it}\left(\frac{\text{kg of total product}}{\text{ha}}\right)\right] \times 100\%$ $= 100\% - \text{Lint percentage}_{it}\ (\%)$ Crop Data
Lint price$_{it}$ $\left(\frac{\$}{\text{kg}}\right)$	WESM Input	Accounting Data

Seed price$_{it}$ $\left(\frac{\$}{kg}\right)$	WESM Input	Accounting Data

Table A1 WESM model - Panel E (Level 5 of WESM)

Panel E1: Water input efficiency		
Variable	WESM Level	Formula
Water input efficiency$_{it}$(%)	**Level 5**	$= \left[\text{Plant transpiration}_{it}\left(\frac{\text{ML of transpiration}}{\text{ha}}\right) \div \text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)\right] \times 100\%$ $= \mathbf{100\% - [Crop\ water\ loss\ \ to\ crop\ water\ supplied\ ratio}\ (\%) + \mathbf{Recycled\ runoff\ to\ crop\ water\ supplied\ ratio}\ (\%)$
Crop water loss to crop water supply ratio $_{it}$	Level 6	$= \text{Crop water loss}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \div \text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$
Recycled runoff to crop water supply ratio $_{it}$	Level 6	$= \text{Recyled runoff}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \div \text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$
Panel E2: Transpiration index		
Variable	WESM Level	Formula

Tra spiration index$_{it}$ $\left(\frac{\textbf{kg of biomass}}{\textbf{ML of tranpiration}}\right)$	**Level 5**	$= \textbf{Biomass yield}_{it} \left(\frac{\textbf{kg of biomass}}{\textbf{ha}}\right) \div \textbf{Transpiration}_{it} \left(\frac{\textbf{ML of transpiration}}{\textbf{ha}}\right)$
Biomass yield$_{it}$ $\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation)
Transpiration$_{it}$ $\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation)
Panel E3: Harvest index		
Variable	WESM Level	Formula
Harvest index$_{i}$ $\left(\frac{\textbf{kg of lint}}{\textbf{kg of biomass}}\right)$	**Level 5**	$= \textbf{Lint yield}_{it} \left(\frac{\textbf{kg of lint}}{\textbf{ha}}\right) \div \textbf{Biomass yield}_{it} \left(\frac{\textbf{kg of biomass}}{\textbf{ha}}\right)$
Lint yield$_{it}$ $\left(\frac{\text{kg of lint}}{\text{ha}}\right)$	Level 7	$= \text{Total yield}_{it} \left(\frac{\text{kg of total product}}{\text{ha}}\right) \times \text{Lint percentage}_{it}\ (\%)$
Biomass yield$_{it}$ $\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation)
Panel E4: Analysis of Operating profit		
Operating profit$_{it}$ $\left(\frac{\$}{\textbf{ha}}\right)$	**Level 4**	$= \textbf{Total sales re}\ \ {}_{it} \left(\frac{\$}{\textbf{ha}}\right) - \textbf{Total operating cost}_{it} \left(\frac{\$}{\textbf{ha}}\right)$

Total sales revenue$_{it}\left(\frac{\$}{ha}\right)$	Level 5	$= \text{Sales revenue}_{it}(\text{lint})\left(\frac{\$}{ha}\right) + \text{Sales revenue}_{it}\ (\text{cotton seed})\left(\frac{\$}{ha}\right)$
Total operating cost$_{it}\left(\frac{\$}{ha}\right)$	Level 5	$= \text{Total water cost}_{it}\left(\frac{\$}{ha}\right) + \text{Other variable cost}_{it}\left(\frac{\$}{ha}\right) + \text{Fixed operating cost}_{it}\left(\frac{\$}{ha}\right)$
Panel E5: Analysis of Total sales revenue		
Total sales revenue$_{\mathbf{it}}\left(\frac{\$}{\mathbf{ha}}\right)$	**Level 5**	$= \mathbf{Sales\ revenue}_{\mathbf{it}}(\mathbf{lint})\left(\frac{\$}{\mathbf{ha}}\right) + \mathbf{Sales\ revenue}_{\mathbf{it}}\ (\mathbf{cotton\ seed})\left(\frac{\$}{\mathbf{ha}}\right)$
Sales revenue$_{it}$(lint)$\left(\frac{\$}{ha}\right)$	Level 6	$= \text{Lint yield}_{it}\left(\frac{kg}{ha}\right) \times \text{Lint price}_{it}\left(\frac{\$}{kg}\right)$
Sales revenue$_{it}$(cotton seed)$\left(\frac{\$}{ha}\right)$	Level 6	$= \text{Seed yield}_{it}\left(\frac{kg}{ha}\right) \times \text{Seed price}_{it}\left(\frac{\$}{kg}\right)$
Panel E6: Analysis of Total operating cost		
Total operating cost$_{\mathbf{it}}\left(\frac{\$}{\mathbf{ha}}\right)$	**Level 5**	$= \mathbf{Total\ water\ cost}_{\mathbf{it}}\left(\frac{\$}{\mathbf{ha}}\right) + \mathbf{Other\ variable\ cost}_{\mathbf{it}}\left(\frac{\$}{\mathbf{ha}}\right) + \mathbf{Fixed\ operat\ \ \ cost}_{\mathbf{it}}\left(\frac{\$}{\mathbf{ha}}\right)$
Total water cost$_{it}\left(\frac{\$}{ha}\right)$	Level 6	$= \text{Licensed irrigation cost}_{it}\left(\frac{\$}{ha}\right) + \text{Traded irrigation cost}_{it}\left(\frac{\$}{ha}\right)$

Other variable $\text{cost}_{it}\left(\frac{\$}{ha}\right)$	Level 6	$= \text{Unit other variable cost}_{it}\left(\frac{\$}{\text{kg of lint}}\right) \times \text{Lint yield}_{it}\left(\frac{kg}{ha}\right)$
Fixed operating $\text{cost}_{it}\left(\frac{\$}{ha}\right)$	WESM Input	Accounting Data

Table A1 WESM model - Panel G - Level 6

Panel G1: Calculation of Crop water supply		
Variable	WESM Level	Formula
Crop water $\textbf{supply}_{it}\left(\frac{\textbf{ML}}{\textbf{ha}}\right)$	**Level 6**	$= \textbf{Rainfall}_{it}\left(\frac{\textbf{ML}}{\textbf{ha}}\right) + \textbf{Irrigation abstracted}_{it}\left(\frac{\textbf{ML}}{\textbf{ha}}\right) + \textbf{Recycled runoff}_{it}\left(\frac{\textbf{ML}}{\textbf{ha}}\right)$
$\text{Rainfall}_{it}\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (simulation)
Irrigation $\text{abstracted}_{it}\left(\frac{ML}{ha}\right)$	Level 7	$= \text{Irrigation applied}_{it}\left(\frac{ML}{ha}\right) - \text{Recycled runoff}_{it}\left(\frac{ML}{ha}\right)$
Recycled $\text{runoff}_{it}\left(\frac{ML}{ha}\right)$	Level 7	$= \text{Total water runoff}_{it}\left(\frac{ML}{ha}\right) \times \text{Ratio of recycled runoff}$
Panel F2: Calculation of Crop water loss		
Variable	WESM Level	Formula

Crop water loss$_{it}$ $\left(\frac{ML}{ha}\right)$	**Level 6**	$= \textbf{Soil evaporation}_{it} \left(\frac{ML}{ha}\right) + \textbf{Deep drainage}_{it} \left(\frac{ML}{ha}\right) + \textbf{Loss from water runoff}_{it} \left(\frac{ML}{ha}\right) + \textbf{Change in soil water}_{it} \left(\frac{ML}{ha}\right)$
Soil evaporation $_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (simulation)
Deep drainage$_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (simulation)
Change in soil water$_{it}$ $\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (simulation)
Loss from water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	$= \text{Total water runoff}_{it} \left(\frac{ML}{ha}\right) - \text{Recycled runoff}_{it} \left(\frac{ML}{ha}\right)$
Panel F3: Calculation of Sales revenue (lint)		
Variable	WESM Level	Formula
Sales revenue$_{it}$**(lint)** $\left(\frac{\$}{ha}\right)$	**Level 6**	$= \textbf{Lint yield}_{it} \left(\frac{kg}{ha}\right) \times \textbf{Lint price}_{it} \left(\frac{\$}{kg}\right)$
Lint yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	$= \text{Total yield}_{it} \left(\frac{\text{kg of total product}}{ha}\right) \times \text{Lint percentage}_{it} (\%)$
Lint price$_{it}$ $\left(\frac{\$}{kg}\right)$	WESM Input	Accounting Data
Panel F4: Calculation of Sales revenue (cotton seed)		

Variable	WESM Level	Formula
Sales revenue$_{it}$(cotton seed) $\left(\frac{\$}{ha}\right)$	**Level 6**	$= \textbf{Seed yield}_{it}\left(\frac{kg}{ha}\right) \times \textbf{Seed price}_{it}\left(\frac{\$}{kg}\right)$
Seed yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	$= \text{Total yield}_{it}\left(\frac{\text{kg of total product}}{ha}\right) - \text{Lint yield}_{it}\left(\frac{kg}{ha}\right)$
Seed price$_{it}$ $\left(\frac{\$}{kg}\right)$	WESM Input	Accounting Data
Panel F5: Calculation of Total water cost		
Variable	WESM Level	Formula
Total water cost$_{it}$ $\left(\frac{\$}{ha}\right)$	**Level 6**	$= \textbf{Licensed irrigation cost}_{it}\left(\frac{\$}{ha}\right) + \textbf{Traded irrigation cost}_{it}\left(\frac{\$}{ha}\right)$
Licensed irrigation cost$_{it}$ $\left(\frac{\$}{ha}\right)$	Level 6	Calculated in Panel G
Traded irrigation cost$_{it}$ $\left(\frac{\$}{ha}\right)$	Level 6	Calculated in Panel G
Panel F6: Calculation of Licensed irrigation cost		
Variable	WESM Level	Formula
Licensed irrigation cost$_{it}$ $\left(\frac{\$}{ha}\right)$	**Level 6**	$= \textbf{Licensed irrigation volume}_{it}\left(\frac{ML}{ha}\right)$ $\times$ **Unit l** **irrigation cost$_{it}$** $\left(\frac{\$}{ML}\right)$

Licensed irrigation $\text{volume}_{it} \left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	$= \text{Irrigation abstracted}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) \times \text{Licensed irrigation to Irrigation abstracted ratio}_{it}\ (\%)$
Unit licensed irrigation $\text{cost}_{it} \left(\frac{\$}{\text{ML}}\right)$	WESM Input	Accounting Data
Panel F7: Calculation of Traded irrigation cost		
Variable	WESM Level	Formula
Traded irrigation $\mathbf{cost}_{it} \left(\frac{\$}{\mathbf{ha}}\right)$	**Level 6**	$= \textbf{Traded irrigation volume}_{it} \left(\frac{\mathbf{ML}}{\mathbf{ha}}\right) \times \textbf{Unit traded irrigation cost}_{it} \left(\frac{\$}{\mathbf{ML}}\right)$
Traded irrigation $\text{volume}_{it} \left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	$= \text{Irrigation abstracted}_{it} \left(\frac{\text{ML}}{\text{ha}}\right) \times \text{Traded irrigation to Irrigation abstracted ratio}_{it}\ (\%)$
Unit traded irrigation $\text{cost}_{it} \left(\frac{\$}{\text{ML}}\right)$	WESM Input	Accounting Data
Panel F8: Calculation of Other variable cost		
Variable	WESM Level	Formula

Other variable cost$_{it}$ $\left(\frac{\$}{ha}\right)$	**Level 6**	$= \textbf{Unit other variable cost}_{it} \left(\frac{\$}{\textbf{kg of lint}}\right) \times \textbf{Lint y}_{it} \left(\frac{\textbf{kg}}{\textbf{ha}}\right)$
Unit other variable cost$_{it}$ $\left(\frac{\$}{kg\ of\ lint}\right)$	WESM Input	Accounting Data
Lint yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	$= \text{Total yield}_{it} \left(\frac{\text{kg of total product}}{\text{ha}}\right) \times \text{Lint percentage}_{it}\ (\%)$

Table A1 WESM model - Panel G - Level 7

Panel G1: Calculation of Seed yield		
Variable	WESM Level	Formula
Seed yield$_{it}$ $\left(\frac{\textbf{kg}}{\textbf{ha}}\right)$	**Level 7**	$= \textbf{Total yield}_{it} \left(\frac{\textbf{kg of total product}}{\textbf{ha}}\right) - \textbf{Lint yield}_{it} \left(\frac{\textbf{kg}}{\textbf{ha}}\right)$
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation)
Lint yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	Calculated in G2
Panel G2: Calculation of Lint yield		
Variable	WESM Level	Formula

Lint yield$_{it}$ $\left(\frac{\mathbf{kg}}{\mathbf{ha}}\right)$	**Level 7**	$=$ **Total yield**$_{it}$ $\left(\frac{\textbf{kg of total product}}{\textbf{ha}}\right)$ $\times$ **Lint pecentage**$_{it}$ (%)
Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	WESM Input	DSSAT Output (simulation)
Lint percentage$_{it}$ (%)	WESM Input	Crop Data
Panel G3: Calculation of Licensed irrigation volume		
Variable	WESM Level	Formula
Licensed irrigation volume$_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$=$ **Irrigation abstrated** $_{it}$ $\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$ $\times$ **Licensed irrigation to Irrigation abstracted ratio**$_{it}$ (%)
Irrigation abstracted $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	Calculated in Panel F
Licensed irrigation to Irrigation abstracted $_{it}$ ratio $_{it}$	WESM Input	Irrigation allocation data
Panel G4: Calculation of Traded irrigation volume		
Variable	WESM Level	Formula

$\mathbf{Traded\ irrigation\ volume_{it}}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \mathbf{Irrigation\ abstracted}_{\ it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right) \times \mathbf{Traded\ irrigation\ to\ Irrigation\ abstracted\ ratio_{it}}\ (\%)$
Irrigation abstracted $_{it}\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel F
Traded irrigation to Irrigation abstracted $_{it}$ ratio $_{it}$	WESM Input	Irrigation allocation data
Panel G5: Calculation of Loss from water runoff		
Variable	WESM Level	Formula
$\mathbf{Loss\ from\ water\ runoff}_{\ it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \mathbf{Total\ water\ runoff}_{\ it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right) - \mathbf{Recycled\ runoff}_{\ it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$
Total water runoff $_{it}\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel F
Recycled runoff $_{it}\left(\frac{ML}{ha}\right)$	Level 7	Calculated in Panel F
Panel G6: Calculation of Irrigation abstracted		
Variable	WESM Level	Formula
$\mathbf{Irrigation\ abstracted}_{\ it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \mathbf{Irrigatio\ \ \ applied}_{\ it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right) - \mathbf{Recycled\ runoff}_{\ it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$
Irrigation infiltrated $_{it}\left(\frac{ML}{ha}\right)$	Level 7	Calculated in G10

Recycled runoff $_{it}\left(\frac{ML}{ha}\right)$	Level 7	Calculated in G7
Panel G7: Calculation of Recycled runoff		
Variable	WESM Level	Formula
Recycled runoff $_{it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \textbf{Total water runoff}_{\textbf{it}}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right) \times \textbf{Ratio of recycled runoff}$
Total water runoff $_{it}\left(\frac{ML}{ha}\right)$	Level 7	Calculated in G8
Ratio of recycled runoff	WESM Input	Farming practice
Panel G8: Calculation of Total water runoff		
Variable	WESM Level	Formula
Total water runoff $_{it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \textbf{Runoff from rainfall}_{\textbf{it}}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right) + \textbf{Runoff from irrigation}_{\textbf{it}}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$
Runoff from rainfall $_{it}\left(\frac{ML}{ha}\right)$	WESM Input	DSSAT Output (simulation)
Runoff from irrigation $_{it}\left(\frac{ML}{ha}\right)$	WESM Input	SIRMOD Output (simulation)
Panel G9: Calculation of Runoff from irrigation		
Variable	WESM Level	Formula
Runoff from irrigation $_{it}\left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \textbf{Runoff from irrigation per event}_{\textbf{it}}\left(\frac{\textbf{ML per event}}{\mathbf{ha}}\right) \times \textbf{Number of irrigat} \quad \textbf{events}_{\textbf{it}}$
Runoff from irrigation per event $_{it}$	WESM Input	SIRMOD Output (simulation)

$\left(\frac{\text{ML per event}}{\text{ha}}\right)$		
Number of irrigation events	WESM Input	DSSAT Output (simulation)
Panel G10: Calculation of Irrigation infiltrated		
Variable	WESM Level	Formula
$\mathbf{Irrigation\ infiltrated}_{\mathbf{it}}\ \left(\frac{\mathbf{ML}}{\mathbf{ha}}\right)$	**Level 7**	$= \mathbf{Irrigation\ infiltrated\ per\ event}_{\mathbf{it}}\ \left(\frac{\mathbf{ML\ per\ event}}{\mathbf{ha}}\right) \times \mathbf{Number\ of\ irrigation\ events}_{\mathbf{it}}$
Irrigation infiltrated per event $_{it}$ $\left(\frac{\text{ML per event}}{\text{ha}}\right)$	WESM Input	SIRMOD Output (simulation)
Number of irrigation events	WESM Input	DSSAT Output (simulation)

Table A2 WESM Input Variables (DSSAT output parameters)

Panel A: Crop production data
Biomass yield_{it} $\left(\frac{\text{kg of biomass}}{\text{ha}}\right)$
Total yield_{it} $\left(\frac{\text{kg of total product}}{\text{ha}}\right)$
Panel B: Crop water data
Rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$
Irrigation amount $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$
Plant $\text{transpiration}_{it}$ $\left(\frac{\text{ML of transpiration}}{\text{ha}}\right)$
Soil evaporation $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$
Deep drainage_{it} $\left(\frac{\text{ML}}{\text{ha}}\right)$
Runoff from rainfall $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$
Change in soil water_{it} $\left(\frac{\text{ML}}{\text{ha}}\right)$

Table A3 WESM Input Variables (Non-DSSAT output parameters)

Panel A: Accounting Data
$\text{Lint price}_{it}\ \left(\frac{\$}{\text{kg}}\right)$
$\text{Seed price}_{it}\ \left(\frac{\$}{\text{kg}}\right)$
$\text{Fixed operating cost}_{it}\ \left(\frac{\$}{\text{ha}}\right)$
$\text{Unit other variable cost}_{it}\ \left(\frac{\$}{\text{kg of lint}}\right)$
$\text{Unit licensed irrigation cost}_{it}\ \left(\frac{\$}{\text{ML}}\right)$
$\text{Unit traded irrigation cost}_{it}\ \left(\frac{\$}{\text{ML}}\right)$
Panel B: Other input data
Recycled runoff ratio(%)
$\text{Licensed irrigation to Irrigation infiltrated ratio}_{it}$ (%)
$\text{Traded irrigation to Irrigation infiltrated ratio}_{it}$ (%)
$\text{Lint percentage}_{it}$ (%)
Panel C: Furrow irrigation data
Number of irrigation events
$\text{Runoff from irrigation per event}\ \left(\frac{\text{ML per event}}{\text{ha}}\right)$

Table A4 Summary of High-Level WESM measures

Variables	Level	Formula	Definition
Profit to water cost ratio$_{it}$ $\left(\frac{\text{\$ operating profit}}{\text{\$ water cost}}\right)$	Level 1	$= \text{Operating profit}_{it}\left(\frac{\$}{\text{ha}}\right) \div \text{Total water cost}_{it}\left(\frac{\$}{\text{ha}}\right)$	The amount of operating profit generated by each dollar spent on water resource.
Return on water$_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	Level 2	$= \text{Operating profit}_{it}\left(\frac{\$}{\text{ha}}\right) \div \text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$	The degree to which operating profit is generated by one unit of volume of all sources of water supplied to the crop business.
Water use leverage$_{it}$ (%)	Level 2	$= \left[\text{Irrigation abstracted}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \div \text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)\right] \times 100\%$	The degree to which Crop water supply to a cropping system is sourced by water withdrawn from the environment (i.e., irrigation water).
Weighted average irrigation cost $_{it}$ $\left(\frac{\$}{\text{ML}}\right)$	Level 2	$= \text{Total water cost}_{it}\left(\frac{\$}{\text{ha}}\right) \div \text{Irrigation abstracted}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$	The water rate (i.e., $ of water cost per ML of water) that a crop business has to pay on average to its two

			irrigation water sources.
$\text{Profit margin}_{\text{it}}(\%)$	Level 3	$= \left[\text{Operating profit}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) \div \text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right)\right] \times 100\%$	The extent to which economic return can be created from each dollar of sales.
$\text{Economic water use index}_{\text{it}}\left(\frac{\$}{\text{ML}}\right)$	Level 3	$= \text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) \div \text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)$	The ability of water resource used in crop production to generate sales.
$\text{Operating profit}_{\text{it}}\left(\frac{\$}{\text{ha}}\right)$	Level 4	$= \text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) - \text{Total opearing cost}_{\text{it}}\left(\frac{\$}{\text{ha}}\right)$	The amount of operating profit generated per unit of land.
$\text{Crop water use index}_{\text{it}}\left(\frac{\text{kg of lint}}{\text{ML}}\right)$	Level 4	$= \text{Lint yield}_{\text{it}}\left(\frac{\text{kg of lint}}{\text{ha}}\right) \div \text{Crop water supply}_{\text{it}}\left(\frac{\text{ML}}{\text{ha}}\right)$	The amount of primary crop product produced per unit of water volume supplied to the cropping system.
$\text{Weighted average cotton price}_{it}\left(\frac{\$}{\text{kg of total yie}}\right.$	Level 4	$= \text{Total sales revenue}_{\text{it}}\left(\frac{\$}{\text{ha}}\right) \div \text{Total yield}_{\text{it}}\left(\frac{\text{kg of total product}}{\text{ha}}\right)$	The average selling price of cotton products (i.e., \$/kg) that a crop business offers its customers.

Total sales revenue$_{it}\left(\frac{\$}{ha}\right)$	Level 5	$= \text{Sales revenue}_{it}(\text{lint})\left(\frac{\$}{ha}\right)$ $+ \text{ Sales revenue}_{it} \text{ (cotton seed)}\left(\frac{\$}{ha}\right)$	Consisting of sales revenues generated from the primary product (i.e., lint product) and sales revenue generated from the by-product (i.e., cotton seed product).
Total operating cost$_{it}\left(\frac{\$}{ha}\right)$	Level 5	$= \text{ Total water cost}_{it}\left(\frac{\$}{ha}\right)$ $+ \text{ Other variable cost}_{it}\left(\frac{\$}{ha}\right)$ $+ \text{ Fixed operating cost}_{it}\left(\frac{\$}{ha}\right)$	Consisting of cost components that are incurred as a result of operating activities undertaken for crop production.
Transpiration index$_{it}\left(\frac{\text{kg of biomass}}{\text{ML of tranpiration}}\right)$	Level 5	$= \text{ Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{ha}\right)$ $\div \text{ Transpiration}_{it}\left(\frac{\text{ML of transpiration}}{ha}\right)$	The amount of total dry mater (biomass) generated by each unit of volume of water actually used by a crop.
Harvest index$_{it}\left(\frac{\text{kg of lint}}{\text{kg of biomass}}\right)$	Level 5	$= \text{ Lint yield}_{it}\left(\frac{\text{kg of lint}}{ha}\right)$ $\div \text{ Biomass yield}_{it}\left(\frac{\text{kg of biomass}}{ha}\right)$	The extent to which biomass is converted into primary crop product.

Water input efficiency$_{it}$(%)	Level 5	$= \left[\text{Transpiration}_{it}\left(\frac{\text{ML of transpiration}}{\text{ha}}\right) \div \text{Crop water supply}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)\right] \times 100\%$	The degree to which Crop water supply is actually used for carbon assimilation to generate lint product.

Table A5 Summary of Low-Level WESM measures

Variables	Level	Formula
Crop water loss$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 6	$= \text{Soil evaporation}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Deep drainage}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Loss from water runoff}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Change in soil water}\left(\frac{\text{ML}}{\text{ha}}\right)$
Crop water supply$_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 6	$= \text{Rainfall}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Irrigation abstracted}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) + \text{Recycled runoff}_{it}\left(\frac{\text{ML}}{\text{ha}}\right)$
Sales revenue$_{it}$(lint) $\left(\frac{\$}{\text{ha}}\right)$	Level 6	$= \text{Lint yield}_{it}\left(\frac{\text{kg}}{\text{ha}}\right) \times \text{Lint price}_{it}\left(\frac{\$}{\text{kg}}\right)$
Sales revenue$_{it}$(cotton seed) $\left(\frac{\$}{\text{ha}}\right)$	Level 6	$= \text{Seed yield}_{it}\left(\frac{\text{kg}}{\text{ha}}\right) \times \text{Seed price}_{it}\left(\frac{\$}{\text{kg}}\right)$
Total water cost$_{it}$ $\left(\frac{\$}{\text{ha}}\right)$	Level 6	$= \text{Licensed irrigation cost}_{it}\left(\frac{\$}{\text{ha}}\right) + \text{Traded irrigation cost}_{it}\left(\frac{\$}{\text{ha}}\right)$
Licensed irrigation cost$_{it}$ $\left(\frac{\$}{\text{ha}}\right)$	Level 6	$= \text{Licensed irrigation volume}_{it}\left(\frac{\text{ML}}{\text{ha}}\right) \times \text{Unit licensed irrigation cost}_{it}\left(\frac{\$}{\text{ML}}\right)$

Traded irrigation cost$_{it}$ $\left(\frac{\$}{ha}\right)$	Level 6	$=$ Traded irrigation volume$_{it}$ $\left(\frac{ML}{ha}\right)$ $\times$ Unit traded irrigation cost$_{it}$ $\left(\frac{\$}{ML}\right)$
Other variable cost$_{it}$ $\left(\frac{\$}{ha}\right)$	Level 6	$=$ Unit other variable cost$_{it}$ $\left(\frac{\$}{\text{kg of lint}}\right)$ $\times$ Lint yield$_{it}$ $\left(\frac{kg}{ha}\right)$
Lint yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	$=$ Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{ha}\right)$ $\times$ Lint percentage$_{it}$ (%)
Seed yield$_{it}$ $\left(\frac{kg}{ha}\right)$	Level 7	$=$ Total yield$_{it}$ $\left(\frac{\text{kg of total product}}{ha}\right)$ $-$ Lint yield$_{it}$ $\left(\frac{kg}{ha}\right)$
Licensed irrigation volume$_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	$=$ Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$ $\times$ Licensed irrigation to Irrigation abstracted ratio$_{it}$ (%)
Traded irrigation volume$_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	$=$ Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$ $\times$ Traded irrigation to Irrigation abstracted ratio$_{it}$ (%)
Irrigation abstracted $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	$=$ Irrigation applied $_{it}$ $\left(\frac{ML}{ha}\right)$ $-$ Recycled runoff $_{it}$ $\left(\frac{ML}{ha}\right)$
Loss from water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	$=$ Total water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$ $-$ Recycled runoff $_{it}$ $\left(\frac{ML}{ha}\right)$
Recycled runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	$=$ Total water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$ $\times$ Ratio of recycled runoff
Total water runoff $_{it}$ $\left(\frac{ML}{ha}\right)$	Level 7	$=$ Runoff from rainfall $_{it}$ $\left(\frac{ML}{ha}\right)$ $+$ Runoff from irrigation $_{it}$ $\left(\frac{ML}{ha}\right)$

Runoff from irrigation $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	$= \text{Runoff from irrigation per event}_{it} \left(\frac{\text{ML per event}}{\text{ha}}\right) \times \text{Number of irrigation events}$
Irrigation infiltrated $_{it}$ $\left(\frac{\text{ML}}{\text{ha}}\right)$	Level 7	$= \text{Irrigation infiltrated per event}_{it} \left(\frac{\text{ML per event}}{\text{ha}}\right) \times \text{Number of irrigation events}_{it}$

Appendix B: Supplementary information for Chapter 5

Appendix B1: Description of cotton production operations

An Australian cotton farming system typically consists of six main cotton production processes, including field preparation (fallow), planting, in-crop, irrigation, harvest and post-harvest (Chen & Baillie 2009; Khabbaz 2010).

In addition, each cotton process comprises of a range of operations (activities) which can be further classified into different types of practices. For example, a field preparation process (a pre-planting process to create a suitable seedbed for germination) may consist of three different operations; tillage, fertilising and spraying. Tillage can involve discing, soil regrading and deep ripping practices (Chen & Baillie 2009; Khabbaz 2010).

Decisions on which operations are required and/or which type of practice needs to be carried out in a particular cotton production process is contingent on a wide range of factors, such as climatic conditions (i.e., rainfall amount and frequency, ambient temperature), soil types, irrigation availability, choices of different tillage methods, irrigation systems and cotton varieties (Chen & Baillie 2009; Khabbaz 2010). For example, as opposed to a tradition tillage method, a reduced tillage approach does not involve discing and soil regrading in an attempt to reducing adverse effects on soil conditions (such as soil compacting) and energy use. Furthermore, the irrigation process may or may not be included in a cotton farming system, depending on management decisions as to whether irrigated cotton or dry land cotton is grown (which is based on rainfall conditions and irrigation availability). While dry land cotton reduces the risk of irrigation shortage and saves water supply costs, this kind of approach may reduce fibre quality (such as fibre length and strength) and cotton production yield. In addition, most cotton operations and practices are machine-intensive activities, and involve the use of energy (mainly diesel fuel and electricity) for tractors and/or pumps (Chen & Baillie 2009; Khabbaz 2010).

1. Fallow

A fallow operation, which is conducted before planting, involves tillage and other soil preparation activities, such as fertilizing, pesticide and herbicide spraying. The purpose of a fallow operation is to create a suitable seedbed with warm soil for germination. This requires the use of heavy machinery (choices of tractors are depending on load and soil conditions) and a significant level of diesel fuel consumption (Chen & Baillie 2009; Khabbaz 2010).

Tillage

A tillage operation involves mechanical modification of soil structure to prepare a favorable seed bed. In recent years the trend in tillage operations has been towards a zero till practice. The advantage of reduced tillage operations is not only fuel cost savings but also a retention of soil organic matter and soil moisture, and reduced soil erosion application (The Cotton Industry Development and Delivery Team 2012). A comparison of farm operations by Baillie (2009) shows about 12% fuel savings with reduced tillage and a further 13% in the case of zero till practice.

2. Planting

A planting operation involves decisions on sowing density (i.e., number of cotton seeds per m) and row configurations. There are a range of row configurations that are used by cotton growers across the Australian cotton industry, such as single skip, double skip, and super single (The Cotton Industry Development and Delivery Team 2012).

In general, wider row spacing configurations result in less water use for growing a crop (per hectare) and more water use efficiency, and hence reducing the variable cost of water inputs. However, it may also limit yield potential. While a trade-off between water costs and cotton yield is a key consideration of cotton growers when making a row configuration choice, there are a number of other factors also need to be taken into account, such as soil type and environment (i.e., rainfall availability, temperature, weather). Wider row spacing configurations can be applied to help cotton growers manage water risk in dry land cotton production, but as mentioned above, this may lead to a reduction in cotton yield and fibre quality (The Cotton Industry Development and Delivery Team 2012) .

Row configurations and sowing density also drive energy use in irrigation activities, such as pumping and sowing. By using dry land cotton production, cotton growers can achieve energy savings as irrigation is not required. However, there is a trade-off between these energy costs and cotton yield and fibre quality that needs to be taken into consideration (Chen & Baillie 2009; Khabbaz 2010).

3. In-crop

Once the plant has become established, various operations to maintain the crop are undertaken. Fertilizers and pesticides are applied with a tractor via boom spraying, and inter-row cultivation is used to help weed control. Some chemicals such as herbicides and insecticides may also be applied via aircraft. Controlled traffic farming, which uses a global positioning system (GPS) to establish fixed tractor passages and precision drilling, can save 50% to 70% of fuel costs over the season.

Fertilization

Fertigation, an application of liquid fertilizer through the irrigation system, which can be applied using the aerial spraying method. This practice can be used to replace traditional fertilizer applied via tillage to reduce energy consumption while increasing efficiency of fertilization (Chen & Baillie 2009; Khabbaz 2010).

Pesticide Treatment

The use of biotechnology and the introduction of genetically modified crops such as Bollgard II, Roundup Ready and Liberty Link, has led to a significant reduction in insecticide and herbicide use, resulting not only in reduced costs but also in reduced energy usage in the application (The Cotton Industry Development and Delivery Team 2012). However, these genetically modified crops require adherence to strict insecticide resistance management strategies, including pupae busting after harvesting. Pupae busting is required as the cotton season normally ends in March or April (the autumn season), when shorter days and cooler temperatures can enable Helicoverpa pupae[128] to develop. As a result, the moths that emerge at the start of the next cotton season in September (the spring season) may be resistant to the limited pesticide applications at the end of the previous season. Cultivation to control the pupae under cotton stubble is therefore of critical importance to ensure that any moths emerging from pupation will become trapped and die. This practice, however, requires the use of machinery and diesel fuels.

4. Irrigation

Determining the timing and amount of irrigation can be a challenge due to unpredictable weather and difference in soil structure for each field (Roth 2010). Each soil type has a

[128] A pupa is an insect in the stage of development between a larva and an adult insect such as a moth.

different soil moisture capacity that is available to the plant (like a sponge holding water). The goal of irrigation is to make enough moisture available for the plant's daily use so that the plant does not become stressed. Stressed plants can result in yield reductions of up to 1.9 bales per hectare (The Cotton Industry Development and Delivery Team 2012).

Compensating for estimated rainfall with water applied through irrigation can be a difficult balancing act. Too much water causes deep drainage (where water below the root line is wasted), or even water logging (where excess water on the field causes low soil oxygen levels). This is especially the case when water is over applied through surface irrigation to ensure the water reaches the end of the furrow or if it rains shortly after an irrigation cycle (Chen & Baillie 2009).

5. Harvesting

A harvest process usually involves two main operations, cotton picking and module building, and requires two types of heavy machinery, cotton pickers and module builders. The use of such large machines means that energy consumption for a harvest process can make up 20-25% of on-farm direct energy use.

Cotton picking

While cotton grown in Africa is still mainly harvested by hand, cotton in Australia and other countries such as the USA and Brazil is harvested with large machines. Though it takes less time to harvest cotton using machine pickers as opposed to human pickers, this contemporary farming practice requires a considerable amount of energy and releases GHG emissions in the natural environment. In addition, the machine may take not only the mature fibre bolls but also unopened bolls, plant sticks, and other foreign matter (such as soil, leaves, and twigs),

Module building

After a cotton picker takes the seed cotton off the bolls via a spindle, the harvested cotton is transported to module builders at the edge of the field. Module builders press the cotton into square long modules, which are covered with a tarpaulin until transported to the ginning plant. Modern cotton pickers have built in module builders that can help reduce labour, machine and energy requirements.

6. Post-harvest

The process of pulling out the plant stubbles and burning them is no longer custom (The Cotton Industry Development and Delivery Team 2012). Instead, practices such as root cutting (residual cotton stalks are cut from the roots), mulching the stalk (shredding of cotton stalks) and pupae busting (pupae of insects in soil are destroyed by tillage) are promoted. After root cutting and mulching practices, the residues are incorporated into the soil, improving soil fertility and nitrogen content. As mentioned above, where Bollgard II cotton is grown, pupae destruction through tillage operation must be implemented to avoid over-wintering of the pest, which could lead to increasing resistance.

Appendix B2: The validity issue of the OZCOT model

As this research aims to examine cotton production simulation in an agricultural setting, the APSIM-OZCOT model would seem to be the first choice for the thesis given its roots in Australian research. As discussed in the Section 5.3, good crop production models allows generation of valid (reliable) estimate of crop parameters that can be used to support better decision making and control. Therefore, it is crucial importance to examine whether the selected crop production simulation model can produce scientifically defensible estimate of interested crop variables.

In this Appendix the APSIM-OZCOT model was tested by simulating cotton crops grown on black vertosol soil at Myall Vale, NSW for a 100-year run of weather data obtained from SILO[129]. Furthermore, furrow irrigation was used as the irrigation method for simulating water and economic performance of irrigated crops. The cotton crops were also simulated under the assumptions that there were no nutrient or pest limitations.

The models for crop water process and water economic sustainability performance presented in Chapters 3 and 4 place emphasis on transpiration, the productive flux of water out of the farming system. Usually, this is confounded with soil evaporation to estimate evapotranspiration. While this latter, an aggregated parameter, can be relatively easily be measured or estimated from the sort of crop water balance that astute farmers should be maintaining, it conceals the real value of transpiration.

In crop simulation modelling, transpiration can be easily calculated as a function of environmental evaporative demand, energy interception by the crop and stomatal closure due to water stress. The theory has been well developed and, while it is rare to have experimental data measuring transpiration directly, it is an appropriate test of model validity to see that its results are consistent with the theory.

The common calculating sequence follows three steps:

(i) Calculation of environmental demand, with potential evapotranspiration as the output parameter.

[129] SILO is an online database of more than 100 years of continuous daily weather records. https://www.longpaddock.qld.gov.au/silo/

(ii) Partitioning potential evapotranspiration into potential transpiration and potential soil evaporation on the basis of radiation interception by the crop canopy. The partition is generally represented by the relationship between normalized transpiration - the ratio between potential transpiration and potential evapotranspiration- and leaf area index - a measure of the leaf area displayed by the crop.

(iii) Adjusting potential transpiration for the effects of water stress, to estimate actual transpiration. This is generally represented as the relationship between normalized transpiration - the ratio between actual transpiration and potential evapotranspiration - and percentage of available soil water remaining.

The initial model that was used was the APSIM version of OZCOT, which was a porting of the OZCOT code (Hearn 1994) into the APSIM simulation environment.

(i) Potential evapotranspiration was based on the Priestly-Taylor method rather than the more modern Penman-Monteith equation. However, this is unlikely to introduce significant errors.

(ii) The radiation partitioning process was modelled using unpublished data from Mateos (Hearn 1994)

(iii) The effect of soil moisture deficit on transpiration is not described in Hearn (1994), but the source code of the OZCOT moiety was available and the following relationships are based on the parameter values used in that code.

Ritchie (1973) proposed a single model for this effect, where stomatal function and hence the ratio of actual transpiration and potential evapotranspiration would remain maximal at or near 1.0 until a threshold value of plant available water, in his case, 80%, had been withdrawn from the root zone. As soil water declined past this point, this ratio reduced to zero, irrespective of atmospheric conditions. In contrast, Denmead and Shaw (1962) proposed that the threshold would depend on atmospheric conditions represented by potential evapotranspiration and the threshold value for plant available water would decline as potential evapotranspiration declined. This more nuanced model has been supported by Sadras and Milroy (1996).

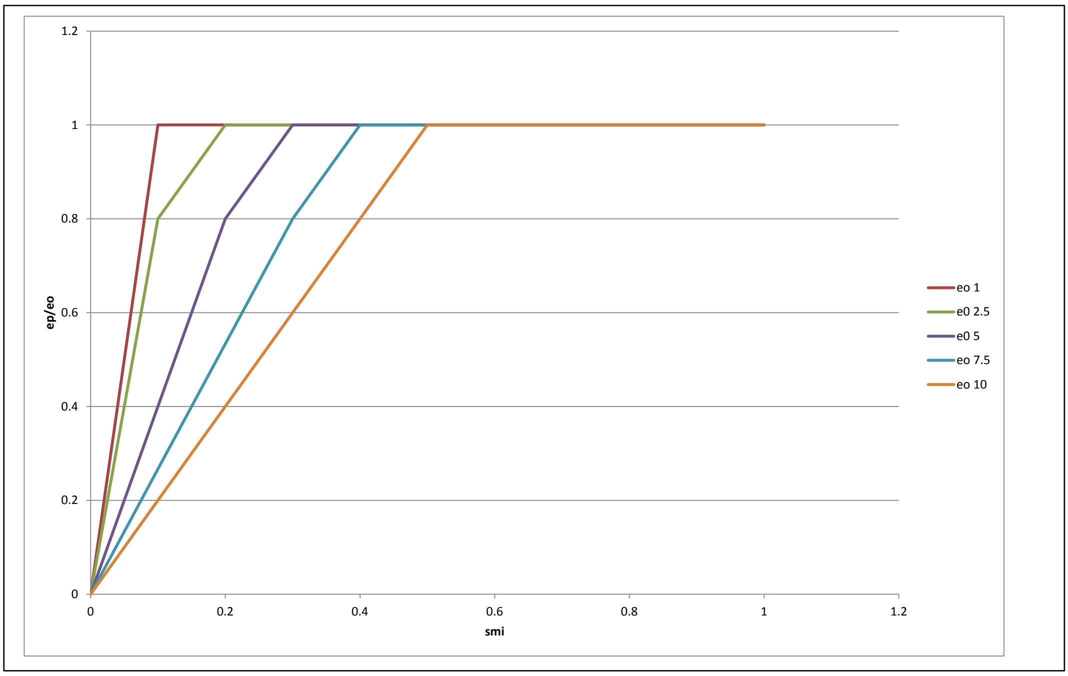

Figure B1 Ratio of potential transpiration to potential evapotranspiration as a function of both soil moisture index and evaporative demand (potential evapotranspiration)

Figure B.1 shows that the OZCOT parameter soil moisture index (smi) is functionally similar to plant available water. The ratio of potential transpiration to potential evapotranspiration was plotted against smi for all values of "plant status=alive", that is, a crop was actually growing.

The analytical description above shows three steps. The first is accommodated by normalising the simulated transpiration data against daily potential evaporative demand. The next two stages are separated by filtering the data into, initially, useful ranges of LAI. The data in Fig. B1 are for the range of LAI 1.0-1.5, which should give a maximal ratio of potential transpiration to potential evapotranspiration (horizontal maximum in Fig. B1) of 0.4-0.54. The range of potential evapotranspiration for this subset of data was 0.5-12mm/day and this was filtered to 2.5-10mm/day to allow comparison with Fig. B2, which implies a tail of data descending towards the origin for plant available water, represented here as smi in the range of 0.2-0.5, depending on potential evapotranspiration.

The filtered data are depicted in figure B2. The characteristics described above are present a maximal zone with values of ratio of potential transpiration to potential evapotranspiration ranging from 0.4 to 0.54 and a plant available water greater than approximately 0.2-0.4.

However, there are many simulated data in the region for smi greater than 0.2 and ratio of potential transpiration to potential evapotranspiration less than 0.4 for which there is no theoretical or coding reason. These represent days of grossly underestimated transpiration and, given the primary interest in transpiration as a pivotal parameter in our WESM, this result undermines the reliability and validity of APSIM-OZCOT as the crop model of choice.

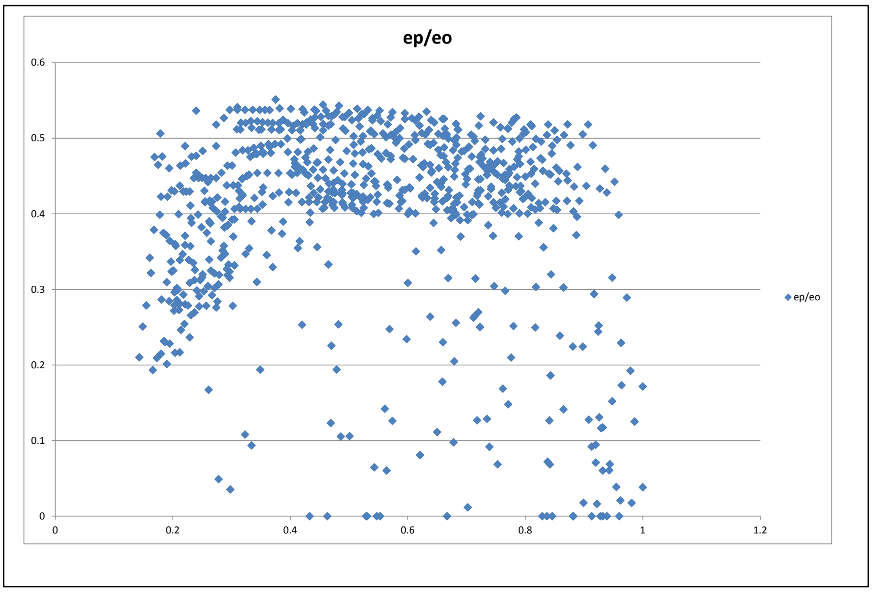

Figure B2 Simulated ratio of potential transpiration to potential evapotranspiration as a function of smi when leaf area index was restricted to 1.0-1.5 and potential evapotranspiration to 2.5-10 mm/day

Appendix B3: The validity of the DSSAT model

Simulation of the growth and water use of cotton crops grown on black vertosols at Myall Vale, NSW, using the same 100-year run of weather was conducted using the CROPGRO-Cotton model in the DSSAT system. The crop management rules are also set under furrow irrigation approach and with the assumptions of no nutrient or pest limitations.

Similar filtering of the data was performed, with one difference. DSSAT does not use smi to describe soil water status, instead using fraction of plant available water remaining. This is used on the x-axis in figure B3.

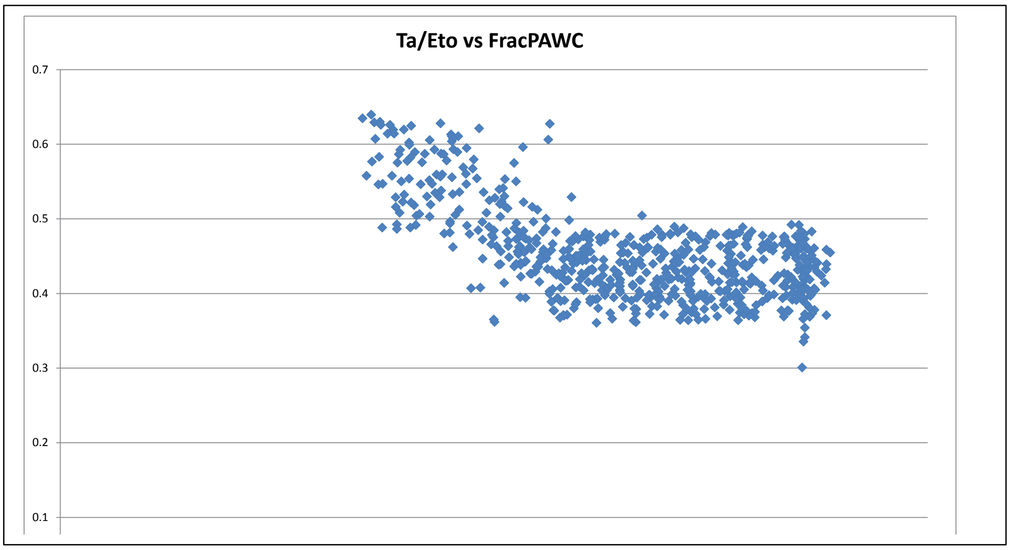

Figure B3 Ratio of **potential transpiration to potential evapotranspiration calculated from DSSAT simulation for leaf area index of 1-1.5 and potential evapotranspiration of 2.5-10 mm/day**

The relationship shows no data points in the region forbidden by theory. The simulation is, to that extent, more valid than the APSIM-OZCOT model. The simulation conditions maintained the crop in a well-, possibly excessively-watered condition, as shown by plant available water values > 100%. The irrigation frequency also meant that dry conditions were not experienced, so that portion of the transpiration response cannot be shown.

Appendix C: Supplementary information for Chapter 6

Appendix C1: Overview of subsurface (drip) irrigation systems

In subsurface (drip) irrigation, water is carried by pipes. Figure C1 provides an example of subsurface (drip) irrigation systems in a cotton farm.

These pipes are typically light weight flexible plastic tubing, so that water is released directly to the soil in the root zone. The release is via emitters attached to, or built into, the pipe and spaced to provide one emitter for each or a few plants in the care of row crops. The emitters are engineered to have reasonably uniform water release rates from a low (1-2 bar) water pressure in the lateral line along each row. The purpose is to provide an intentionally heterogeneous wetting pattern with the water applied only to the zone of active roots. Ideally, irrigation scheduling should allow the average application rate to match the average transpiration rate, with little or no excess to go to deep drainage. In the case of sub-surface drip irrigation, the lateral is buried beneath the row of crop plants at 30+ centimetres, typically, to avoid surface wetting and hence eliminate soil evaporation and runoff from irrigation (Bucks, Nakayama & Warrick 1982).

Figure C1 An example of subsurface (drip) irrigation systems in a cotton farm (Source: Khabbaz 2010)

Of the three irrigation systems, the subsurface drip irrigation system consumes the most energy as it involves pressurised irrigation and requires increased head pressure. In contrast, surface irrigation system requires less energy as it works by simply applying water from a head ditch, which is filled with water from a bore, river or catchment with a pump, into the furrows where water spreads due to gravity and the slope of the field. Research on the impact of farming systems on energy use and associated GHG emissions reports that energy usage for irrigation using a furrow (or border check) irrigation system is about two-thirds of that used in lateral move (or centre pivot) irrigation and less than half of the energy used in subsurface drip irrigation (Khabbaz 2010).

Appendix C2: Overview of lateral-move and centre pivot irrigation systems

Lateral-move and centre pivot irrigation systems are self-propelled irrigation systems. A centre pivot irrigation system rotates around a fixed central point and moves at a constant speed up and down a paddock (Khabbaz 2010). Figure C2 provides an example of a lateral-move system on a cotton farm. While about 80% of Australian cotton farms use surface irrigation systems, there is growing use of lateral-move and centre pivot irrigation systems due to their improved water use efficiency compared to surface irrigation systems (Roth et al. 2013).

Compared to modern irrigation systems like subsurface irrigation systems and lateral move irrigation systems, the traditional furrow irrigation systems are considered the least efficient systems with respect to water use (Jackson, Khan & Hafeez 2010). However, while deep drainage is reported nearly zero under lateral-move and centre pivot irrigation system (Roth et al. 2013), the soil surface is still wet, and hence water loss to soil evaporation is unavoidable. Accordingly, lateral-move and centre pivot irrigation systems are less water use efficient but more energy use efficient than subsurface (drip) irrigation systems. In contrast, lateral-move and centre pivot irrigation systems are more water use efficient but less energy use efficient than surface/furrow irrigation systems.

Farm managers need to consider the trade-offs between energy use efficiency and water use efficiency between irrigation systems when making decisions on which type of irrigation systems are applied in their cotton farms. Other factors that also need to be taken into account include climatic factors, soil structure, and local irrigation policy.

Figure C2 An example of lateral move irrigation systems in a cotton farm (Source: Khabbaz 2010)

Table C1 Soil properties of the Myall Valve soil (clay vertosol)

Soil Layer (cm)	Water Content[130]			Soil components			Other soil properties				
	LL15 (cm^3/cm^3)	DUL (cm^3/cm^3)	SAT (cm^3/cm^3)	Clay %	Silt %	Stone %	pH 1:5	Root Factor	Saturated hydraulic conductivities (Ks, cm/hr)	Bulk density (g/cm^3)	Organic content (%)
40	0.29	0.43	0.47	61.6	27.6	10.8	8.0	1	94.00	1.22	0.71
80	0.38	0.46	0.48	65.6	23.5	10.9	8.5	0.301	6.00	1.50	0.46
125	0.38	0.44	0.46	66.1	23.7	10.2	8.7	0.129	6.00	1.46	0.45
145	0.37	0.46	0.49	65.8	25.8	8.4	8.9	0.067	6.00	1.44	0.40
180	0.37	0.46	0.49	63.4	27.7	8.8	8.9	0.039	6.00	1.44	0.24

Table C2 Simulated infiltration – Scenario 1 versus Scenario 2

Furrow Points	Furrow Distance (m)	Infiltration(mm)_Scenario 1	Infiltration(mm)_Scenario 2
1	0	91	57
2	10	91	58
3	20	91	58
4	30	91	58
5	40	91	58
6	50	91	58
7	60	91	58
8	70	91	58
9	80	90	58
10	90	90	58
11	100	90	58
12	110	90	58
13	120	90	58
14	130	89	58
15	140	89	58
16	150	89	58
17	160	89	57
18	170	88	57
19	180	88	57
20	190	88	57
21	200	88	57
22	210	88	57
23	220	87	57
24	230	87	57
25	240	87	57
26	250	86	57
27	260	86	56
28	270	85	57
29	280	85	57
30	290	85	56
31	300	84	56
32	310	84	56
33	320	83	56
34	330	83	56
35	340	83	56
36	350	82	56
37	360	82	56
38	370	81	55
39	380	81	55
40	390	80	55
41	400	80	55
42	410	79	54

Furrow Points	Furrow Distance (m)	Infiltration(mm)_Scenario 1	Infiltration(mm)_Scenario 2
43	420	79	54
44	430	78	54
45	440	78	54
46	450	77	54
47	460	76	54
48	470	76	54
49	480	75	53
50	490	74	53
51	500	74	53
52	510	73	53
53	520	72	53
54	530	72	53
55	540	71	52
56	550	71	52
57	560	70	52
58	570	69	52
59	580	68	51
60	590	67	51
61	600	67	51
62	610	65	51
63	620	64	50
64	630	63	50
65	640	62	50
66	650	62	50
67	660	61	49
68	670	60	49
69	680	58	49
70	690	57	48
71	700	56	48
72	710	55	48

Appendix D: Supplementary information for Chapter 7

Appendix D1: Calculations of fixed operating cost per ha and unit other variable cost

In this appendix I explain how fixed operating cost per ha and unit variable cost ($/bale) is calculated based on economic data obtained from a cotton gross margin budget for furrow irrigated cotton in 2014 -2015(NSW Department of Primary Industries 2015).

An accounting technique (Cost-Volume-Profit (CVP) modelling) is coupled with a statistical technique (regression), is applied to undertake the analysis.

First, the CVP model is expressed as follow:

Gross margin ($/ha) = Total sales revenue ($/ha) – Total operating cost ($/ha) *[D.1]*

Or

Gross margin ($/ha) = Selling price*[131] *($/bale) x Lint yield (bales/ha) – Fixed operating cost ($/ha) + Unit variable cost ($/bale) x Lint yield (bales/ha) *[D.2]*

Or

Gross margin ($/ha) = Unit contribution margin ($/bale) x Lint yield (bales/ha) – Fixed operating cost ($/ha) *[D.3]*

I assume that contribution margin (the difference between selling price and unit variable cost) and fixed operating cost are constant in the short-term - therefore equation (D.3) shows that gross margin is a function of lint yield.

A data set of gross margin and associated lint yield is collected to establish the gross margin function. I assume a selling price of $554.00/bale. This set of data is shown in Table D1.

[131] The selling price provided by NSW Department of Primary Industries (2015) is already included cotton seed.

Table D1 The effect of lint yield on gross margin

(Source: NSW Department of Primary Industries (2015)

Lint yield (bales/ha)	Gross Margin ($/ha)
7.50	736.00
9.00	1445.00
10.00	1918.00
11.00	2391.00
12.00	2864.00
13.00	3337.00
14.50	4047.00

Based on the data set in Table D1, the gross margin function is determined using the regression technique (see Figure D1) as follow:

Gross margin ($/ha) = 473($/bale) x Lint yield (bales/ha) – 2812 ($/ha) *[D.4]*

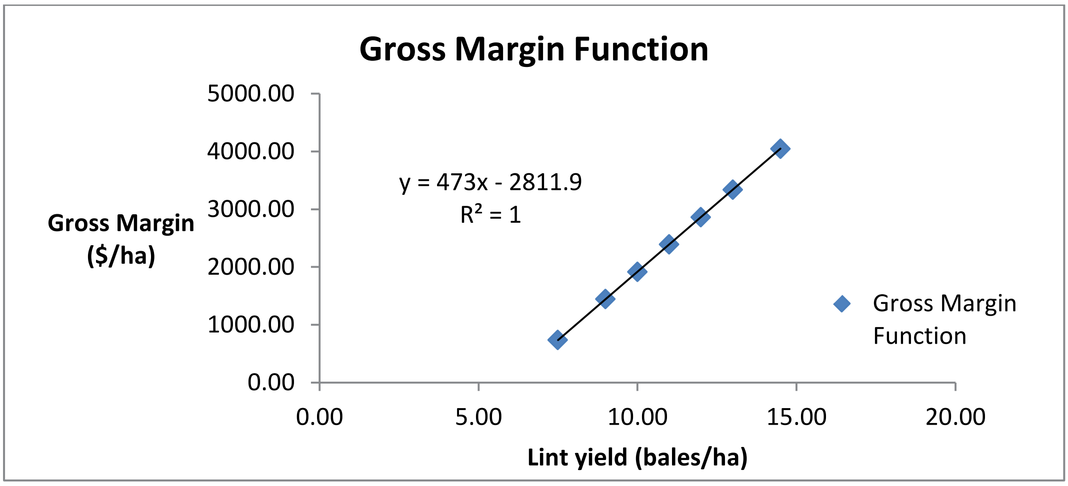

Figure D1 Cotton gross margin function

The equation (D.4) shows that fixed operating cost is $2812 per ha and unit contribution margin is $473 per bale.

In addition, given the selling price of $554 per bale, unit variable cost is equal to $81 per bale (= $554 -$473).

Furthermore, given licensed irrigation cost of $60.30 per ML(including licence fees of $32.24/ML and pumping cost of $28.06/ML),[132] or $53.67 per bale[133](=$60.30 x 0.89), unit variable cost, excluding irrigation cost is equal to $27.33 per bale (= $81 - $53.67). This figure is equivalent to $0.12 per kg of lint.

[132] (NSW Department of Primary Industries (2015).

[133] As shown in the example of cotton gross margin (NSW Department of Primary Industries, 2015), 9.79ML of irrigation required to produce 11 bales or 0.89 ML of irrigation per bale.

Appendix E: Supplementary information for Chapter 9

Table E1 Cotton irrigated area

Information Source	Cotton area	2010-11	2011-12	2012-13	2013-14	Average (2010-2014)
Cotton Australia	Total ha	599,630	566,000	425,786	414,000	501,354
ABS	Total ha	588,294	596,497	437,818	390,031	503,160
ABS	Irrigated ha	359,280	397,221	365,268	339,692	**365,365**
ABS	Dryland ha	229,015	199,276	72,549	50,340	137,795

Source: **(Australian Bureau of Statistics 2015; Cotton Australia (2015)**

Table E2 Environmental and economic gain by moving from Scenario 1 to Scenario 2

Size of analysis			**Per ha**	**Business Level**	**Industry Level**
Cotton irrigated area (ha)			1	400	365,365
Potential environmental gain	Water volume saving	= Decrease in crop water lost (from S1 to S2) = **2.15 ML/ha**	**2.15 ML**	**860 ML**	**785,535 ML** (785.5 GL)
Potential crop production gain	Gain in lint production (from additional available water resource)	= Crop water saved (ML/ha) (from S1 to S2) x Crop water use index (kg/ML) (S2) = 2.15 ML/ha x 144 kg/ML = **310 kg/ha**	310 kg (1.36 bale)	124,000 kg (546 bale)	113,263,150 kg (498,957 bale)
	Gain in lint production (based on improved practice)	= Increase in lint yield (from S1 to S2) = **2.6 kg/ha**	2.6 kg (0.01 bale)	1,040 kg (4.6 bale)	949,949 kg (4,185 bale)
	Total gain in lint production		**312.6 kg** (1.37 bale)	**125,040 kg** (550 bale)	**114,213,099 kg** (503,141 bale)
Potential economic gain	Gain in operating profit (from additional available water resource)	= Crop water saved (ML/ha) (from S1 to S2) x Return on water ($/ML) (S2) = 2.15 ML/ha x $101/ha = **$217/ha**	$217	$86,800	$79,284,205
	Gain in operating profit ($) (based on improved practice)	= Increase in operating profit (from S1 to S2) = **$132/ha**	$132	$52,800	$48,228,180
	Total gain in operating profit ($)		**$349**	**$139,600**	**$127,512,385**