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REVIEW OF WATER USE IN THE PRODUCTION OF COTTON AND OTHER FIBRES USING LIFE CYCLE ASSESSMENT

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EXECUTIVE SUMMARY

The Australian cotton industry is a world leader in the production of quality cotton with high levels of water efficiency. Australian cotton yields have increased steadily over the past 20 years, and are now two and a half times the global average with higher levels of water use efficiency than other key production regions in the world. In recent years, the industry has proactively improved the management of its water resources. It has invested substantial resources in research and extension programs to improve the cotton produced per unit of water input. However, the industry has never investigated water use using a supply chain assessment methodology such as life cycle assessment or water footprinting. These methods have grown in popularity and importance as tools to investigate and communicate the impacts of producing a product such as cotton throughout the supply chain. Ideally, such analyses provide results for a retail product and the use of that product by consumers. Recently, such studies have been commissioned for iconic cotton product manufacturers such as Levi Strauss.

A review of supply chain water use assessment methods identified two main methodological approaches; water footprinting or WF (which supersedes the term 'virtual water' or VW) and life cycle assessment (LCA). A third method, water balancing, is not strictly a supply chain assessment tool, though it could be applied that way. However, because it is the most commonly used way to quantify water use for cotton production at the farm level it is reviewed in detail here also. Results from water balance studies (at the farm level, for example) can be readily used as *inventory data* for either a WF or LCA study.

Differences between the LCA and WF methods are numerous. Water footprinting/virtual water was developed as a method of assisting countries to reduce water use by importing products that require a high amount of irrigation water to grow locally. Hence, water stressed regions such as the Middle East could reduce production of wheat and livestock that was grown locally using irrigation, and import these products from other countries. This would amount to water savings for the importing country. The key feature of the method was that it is based on the *theoretical water requirement for production regardless of the source of that water*. Initial WF/VF studies reported, for example, that Australian wheat 'used' 1588 L / kg of wheat produced, without identifying the fraction of water sourced from 'soil stored moisture derived from rainfall' (or green water) compared to the fraction sourced from irrigation. For a nation such as Australia that grows much of our cereal product from dryland areas, this approach was easily misinterpreted and equated to the volume of *irrigation* water required. Later studies clarified that only 25% of the water used for Australian wheat was derived from irrigation (still thought to be an over-estimate compared to other Australian research). Even for a predominantly irrigated crop such as cotton, inclusion of green water in the assessment would lead to a considerably higher level of reported water use. The WF method also includes 'grey water' or dilution water, which is the estimated volume of water required to assimilate pollutants released from a production system to ensure these are below threshold levels. Hence, releases of chemicals and nutrients would require an estimated volume of 'dilution' water to ensure these were below environmental and health thresholds, and this water 'use' would be attributed to the production system. This could also be quite significant for cotton production in some situations.

In the field of LCA there have been a number of advances aimed at accurately quantifying and interpreting water use data. Most of this work has been done in the past three years, and studies done prior (or even during) this time are quite variable in quality and rigour. LCA research is divided into two important stages relevant to this discussion; the inventory stage (data collection) and the impact assessment stage, when the inventory results are interrogated and interpreted. Different methods apply to each stage. At the inventory stage, an LCA study may use data collected for other purposes (i.e. irrigation water balance research or WF research), but at the impact assessment stage, these data are used to provide insight into the impacts of using water on competitive users or the environment using a number of methods. It is this impact assessment method that is more advanced than a simple 'inventory' of water use (which could be done with a series of water balances) or a WF study, which doesn't extend beyond the inventory stage either. This helps address the problem that we can understand intuitively, that the impact of water use will differ greatly depending on where it is used and particularly, if it is being drawn from a depleted, over-allocated (or stressed) source. Interestingly, while Australia may deem some catchments (notably the Murray Darling) as being over allocated or stressed, on a global scale the stress weighting is not comparable to severely stressed regions such as North Africa or India.

State-of-the-art LCA methods for water use specify the use of detailed inventory methods such as water balancing, specification of water quality inputs and outputs, and methods to quantify the impact of using water. However, WF methods provide no insight to these differences. Recent LCA methods have proposed ways to define water use in terms of the stress created on a catchment by using the water. 'Water stress' has been defined globally in order to allow comparisons with different production regions of the world. These methods are operational and have been applied to Australian beef production (by CSIRO and the authors) and for pork production (by the authors). To date, no study of an irrigated crop has been made to the Author's knowledge.

The major differences between WF and LCA can be summarised as follows:

i) The inclusion / exclusion of green water. This is included in the WF method and generally **excluded from LCA methods at the impact assessment level.**

ii) The inclusion / exclusion of grey water. This is included in the WF method and **excluded from LCA methods at the impact assessment level**.

iii) Inclusion of methods to assess the *impact* of using water (on competitive users and the environment) rather than simply the total volume used. This is excluded from the WF method and **included in LCA methods**.

On review and comparison of these methods, the authors felt LCA to be the most robust and useful method for conducting supply chain water use assessments in the Australian cotton industry. The reasons for this were:

i) State-of-the-art LCA research specifies the use of a detailed water balance to identify flows of water at each stage in the supply chain. This is a robust approach for quantifying water use in cotton production. Data are readily available and results can be communicated easily with the industry and the consumer.

ii) LCA has a robust methodology and framework for handling water 'uses' such as green water and grey water. This may be done excluding these from the impact assessment and including additional impact assessment methods that deal directly with the issue of concern (such as contaminant release). This results in a more readily understandable and meaningful result.

iii) Taking point ii) into account, LCA is able to include green and grey water use at the inventory level in order to provide a comparable result with a WF method *if this is desired*.

iv) Impact assessment methods are available in LCA that can quantify not only the total water used, but also the impact of using this water on either the environment or on other competitive users. This is an important advance on the water footprint method.

v) LCA is able to incorporate additional impact assessment areas such as energy use and GHG emissions to provide a broader assessment.

Considering most of the advances in LCA water methodology have been made recently, the cotton industry is in a good position to provide a robust study based on well-grounded methods that can be used as a benchmark for future research in the cotton supply chain and in the textiles industry more broadly. A number of recommendations are provided for future research in this area.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. BACKGROUND

Water scarcity is an issue of growing concern worldwide, largely because it is estimated that some 1.1 billion people do not have access to improved water supply sources (WHO 2009). With a growing human population, it follows that stress on water reserves will increase dramatically in the next 30-40 years (Rockström et al. 2007). While water scarcity is a relatively difficult term to define, there is little doubt that water resources are under considerable pressure worldwide (Falkenmark et al. 1989, Glieck et al. 2009, Shiklomanov 1998). An excellent review of these issues has been compiled by Rijsberman (2006).

At the simplest level, water scarcity is defined as the per capita per year water requirements for household, agricultural, industrial and energy supply sectors, and the needs of the environment. Falkenmark et al. (1989) developed a simple '*water stress index*' based on the above requirements and identified that 1700 m^3 of renewable water resources were required per person per year. Where supply falls below 1000 m^3 a country experiences *water scarcity*. It is of great importance to understand that the majority of this water requirement is used by agriculture. Hence, most assessments of water scarcity do not relate directly to the supply of water available for domestic purposes (which are as low as 20 m^3/person/year – Rijsberman 2006) but rather provide an indication of the availability of water resources for food and fibre production worldwide. This is reasonable, as agriculture uses more water than any other activity in the world (Qadir et al. 2003).

Traditionally, water 'use' has been defined by water engineering terms and principles, and water use has only considered 'stored' water. However, as researchers have sought new approaches to considering water scarcity, these traditional approaches have been broadened to include assessments of virtual water or the more recently used term, water footprint, which incorporates embedded water derived from multiple sources. In addition to this, the number of life cycle assessment studies reporting water use has grown considerably in the past number of years. These alternative approaches have introduced complexity and ambiguity to the term 'water use' and have created the need for new methodological approaches and clear documentation to avoid confusion.

In Australia, competition for water resources is one of the great challenges facing the most populated regions of the country. It has become increasingly apparent that water resources have been stretched beyond the sustainable limits for the Murray Darling Basin (MDB) where the majority of the population reside. As competition for water use grows, agricultural water use faces increasing scrutiny. This is not surprising, as agriculture accounts for 65-70% of water use nation-wide (ABS 2006). For these reasons water management is the subject of major state and federal political attention and funding, and has received increasing attention from the media and the community.

As with all agricultural commodities, there is a need for the cotton industry to examine the environmental sustainability of its production systems. There are many parameters by which environmental sustainability can be measured. These include, but are not limited to, greenhouse gas (GHG) emissions, water use, land degradation and impact on biodiversity. In Australia, water is a precious and limited resource and cotton production is a significant user of freshwater supplies. Hence, the cotton industry needs factual information on water use by cotton and its impact on the environment.

Water use is highly relevant to the cotton industry for a number of reasons. In the future, the cotton industry may need to justify their water requirements and compete for secured entitlement of this resource. Australia's cotton industry is a key user of water from the Murray Darling Basin. Access and sustainable use of this resource is essential for ongoing production.

In 1991, the Australian Cotton Foundation commissioned a ground-breaking independent environmental audit of the industry (1991). This audit focused largely on pesticide use, which was the main issue at the time. In 2003, a follow-up audit was commissioned by CRDC (GHD 2003). The later audit showed improvements in environmental performance. This audit again focussed primarily on pest and pesticide management, along with the management of chemicals. In addition, it discussed water use and management in greater detail than the 1991 audit. It determined that there had been ongoing increases in water use efficiency in the years following the earlier audit. It also discussed the extensive increase in water use efficiency research and implementation. The 2003 audit stated that most cotton growers involved in the survey had not quantitatively measured on-farm water use. It also stated that there were requirements for the industry to participate in water use efficiency trials and water use benchmarking schemes in order to improve water use efficiency data. Industry wide audits may be an important source of information regarding water use efficiency in the future and the increased focus is important for building the knowledge base in this area. Such knowledge is invaluable for conducting supply chain analyses such as LCA.

The Australian cotton industry has recently investigated the impacts of GHG emissions and energy use from cotton production, processing and consumer use by using life cycle assessment (LCA) (ISR 2009). LCA is now a reasonably well-established research methodology that is defined by a number of international and Australian standards. The assessment of water use using LCA (or more broadly, supply-chain water use assessment methods) has rapidly evolved in the past five years. A number of methodologies have been used to quantify water use for Australian plant products (including cotton) and livestock. Importantly, some of this research has been conducted by European researchers without local knowledge of farming practices or water management. Additionally, some methods have been proposed by Australian and international researchers for other agricultural products that are yet to be applied to an irrigation industry such as cotton. The development and progress of such methodologies, and their application of this type of research, is highly relevant to the cotton industry. This is particularly important as many companies and industries are investigating supply chain water use assessment. Companies that have completed studies on the water use of their products include Levi Strauss & Co., Coca-Cola, Volkswagen and AirDye Solutions. Australian industries that have carried out water supply chain assessments include Australian Pork Limited (APL), Meat & Livestock Australia (MLA), Australian Egg Corporation Limited (AECL) and Rural Industries Research and Development Corporation (RIRDC). International organisations that have commissioned research in this area include UNESCO-IHE, Waterwise, and the International Water Management Institute.

At this stage, it is not clear to what extent the Australian cotton industry may be called on to provide such information. Hence, this review of the current status of the methodologies and the uptake of supply-chain water use assessment will provide valuable and timely information for the industry.

1.2. PROJECT OBJECTIVES AND METHODOLOGY

To undertake this review, the following steps have been undertaken.

1.2.1. REVIEW OF THE LCA METHOD AND APPLICATION IN AUSTRALIAN AGRICULTURAL PRODUCTS

LCA is a tool that has been applied to many agricultural commodities in Australia and overseas. However, LCA methodology is still under development in specific areas such as water assessments. Different studies have used different methodologies particularly for agricultural systems.

Life cycle studies are generally not comparable without careful scrutiny of the methodology used. This review aims to cover all studies that reported results for cotton regardless of the quality of the work, in order to provide a comprehensive summary of the research to date. This component of the review will determine which LCA methods would be most suitable for the Australian cotton industry as a whole, and for individual producers (i.e. technical and data requirements), both for research and for market-driven data supply requirements for producers.

1.2.2. REVIEW OF METHODS FOR ASSESSING SUPPLY-CHAIN WATER USE

In this section of the review, the different approaches used for assessing supply-chain water use will be identified and critically compared, including a summary of the strengths and weaknesses of these methods when considered in the context of the Australian cotton industry. LCA is not the only methodology that has been used to assess water use. It is important to understand the different methodologies used because results determined using different methodologies are often misquoted and invalid water use comparisons are made.

1.2.3. REVIEW OF WATER USE ASSESSMENT METHODS IN LCA

Even within LCA studies, different approaches to the treatment of water use have been applied. One approach is a water inventory approach where resource use is quantified and expressed on a unit of output basis. More recent and advanced methods have included an impact assessment stage.

1.2.4. REVIEW WATER USE IN AUSTRALIAN COTTON PRODUCTION

A brief review of water use in the Australian cotton industry is provided including a review of improvements in water use over time and a description of the difference between water applied to the crop and water extracted from the natural environment.

1.2.5. REVIEW OF WATER USE IN COTTON USING LCA

This section reviews all available LCA studies that cover cotton production and its full supply chain. Where water is considered in the LCA studies, the data is reviewed critically.

A screening process will be used to assess the quality of literature, with preference being given to peer reviewed articles and government reports. However, some information regarding market uptake will be sourced from less formal publications as required. Studies extending to the full life cycle of the product along with 'farm gate' studies will be investigated.

1.2.6. REVIEW OF WATER USE OF OTHER FIBRES USING LCA

This section reviews available LCA studies covering other major fibre products (synthetics and wool).

1.3. THE COTTON PRODUCTION, SUPPLY AND USE CHAIN

Cotton is one the world's most important crops. According to Chapagain et al. (2006) cotton uses 2.4% of the earth's arable land area. It is cultivated in warm climates and needs large volumes of water to yield well. From a full LCA perspective, the cotton supply and use chain has six major stages. These stages are:

1. **Production** – cotton planting, crop care, irrigation, harvesting and ginning
2. **Fabric production** – spinning, dyeing, weaving and finishing
3. **Garment manufacturing** – garment make-up and finishing
4. **Transportation and distribution** – the entire life cycle of a cotton garment has many different transportation stages. For example, cotton may be cultivated in India but made into yarn in the USA. This will lead to environmental impacts in this stage of the life cycle of the product.
5. **Consumer use** – the amount of water used in this stage will be directly dependent on the lifetime of the product and the amount of washings it receives in its lifetime.
6. **End of life** – recycling or disposal.

Figure 1 shows a typical pathway (supply chain) for cotton from production to the consumer. This pathway does not include the use and end-of-life phases and, as such, is not a complete cradle-to-grave supply chain. The importance of defining supply chains (system boundaries) will be discussed in later sections. Clear system-boundary definitions are required to ensure that water use studies are comparable.

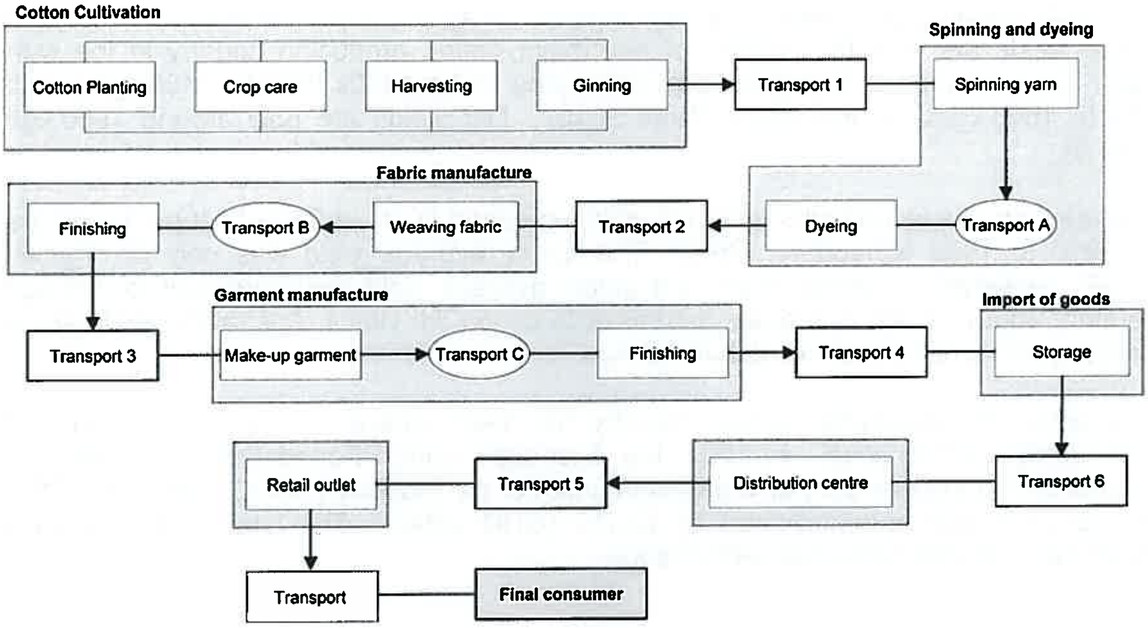


FIGURE 1 – TYPICAL SUPPLY CHAIN FOR COTTON TO CONSUMER (CAMP ET AL. 2010)

About 70% of Australia's cotton is grown in NSW with the remainder grown in Queensland. Although minor amounts of cotton have been grown since the 1860s, the most significant industry growth happened after the construction of Keepit Dam on the Namoi River. This was followed by a rapid expansion in the 1980s. By 2010, there were about 800 cotton farmers in Australia from Hillston in the south up to Emerald in the north (Figure 2). About 80% of farms are irrigated and they often produce cereal crops like wheat and sorghum and beef cattle as part of the enterprise mix (Roth 2010). Up to some 400 000 ha of irrigated cotton are grown in Australia depending on water availability.

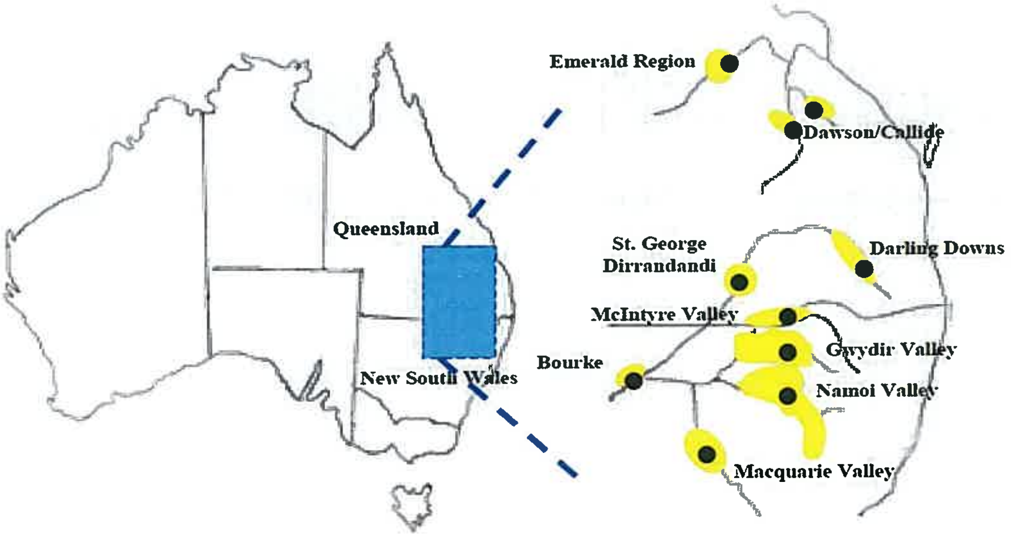


FIGURE 2 – COTTON GROWING AREAS OF AUSTRALIA (TENNAKOON & MILROY 2003)

Since 1960, cotton yields have increased at about 30 kg of lint per ha per year. Australian average yields are now the highest of any major cotton producing country in the world. Yields have continued to increase from 1200 kg/ha in the 1970s through 1400 kg/ha in the 1980s to 1600 kg/ha in the 1990s (Roth 2010). Lint yields are now around 1900 kg/ha (Figure 3).

By comparison, the world cotton average yield increased at about 8 kg of lint per ha per year from 1950 to 1990 (Chaudhry 1998). The global average yield was only 551 kg/ha in 1998/99. However in recent years, the global average yield has increased to 773 kg/ha (Chaudhry 2007). Even with these increases in cotton lint yields, Australian yields are still almost two and a half times the global average.

For decades, the Australian cotton industry has been aware of the need for improved environmental performance. In 1991, the Australian Cotton Foundation commissioned a ground-breaking independent environmental audit of the industry (CRDC 1991). In 2003, a follow-up audit was commissioned by CRDC (GHD 2003). The later audit has shown improvements in environmental performance.

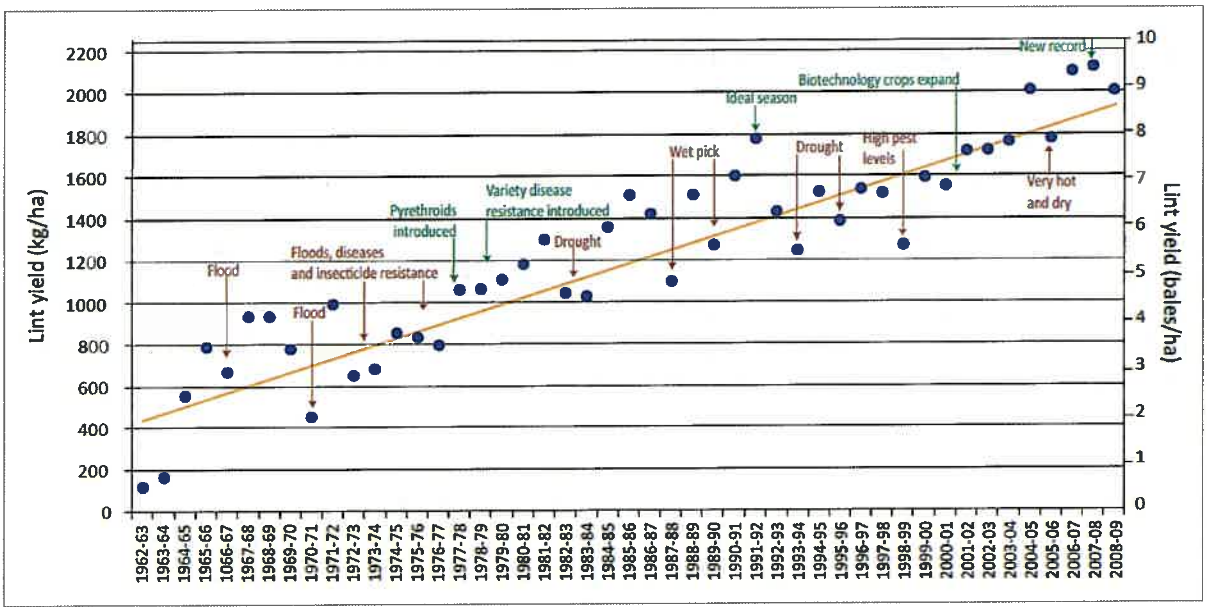


FIGURE 3 – INCREASE IN AUSTRALIAN COTTON YIELDS (1962 – 2009) (ROTH 2010)

2. LIFE CYCLE ASSESSMENT

LCA is a well established research method now defined by a number of international standards (ISO 2006a, b) . Initially, the tool was developed for industrial applications in the late 1960's, though in the past 10 years, increased interest and research activity has been directed to agricultural systems. This is evidenced by the repeat increase in the number of published agricultural LCAs in the period 2000-2010 compared with the previous 10 years.

LCA is a multi-impact tool used to investigate resource use and environmental impacts over the entire life cycle of a product or service. Studies are conducted in four stages (see Figure 4):

i. goal and scope establishment
ii. data collection (life cycle inventory, LCI)
iii. life cycle impact assessment (LCIA)
iv. interpretation.

The degree of flexibility within the research framework and the specific data collection processes employed allow a considerable degree of variance between studies. Consequently, LCA results should not be compared without careful review of critical methodological elements and standardisation of results. These elements primarily relate to the goal and scope of the study and the data collection (inventory) approach used.

Agricultural systems have some unique properties that require careful treatment within LCA. In particular, the long production cycles and open systems complicate collection of production data and environmental impact data. While these issues are not new to researchers in the agricultural sciences, the interdisciplinary nature of LCA research means careful attention must be directed to the methods and assumptions used during these research stages.

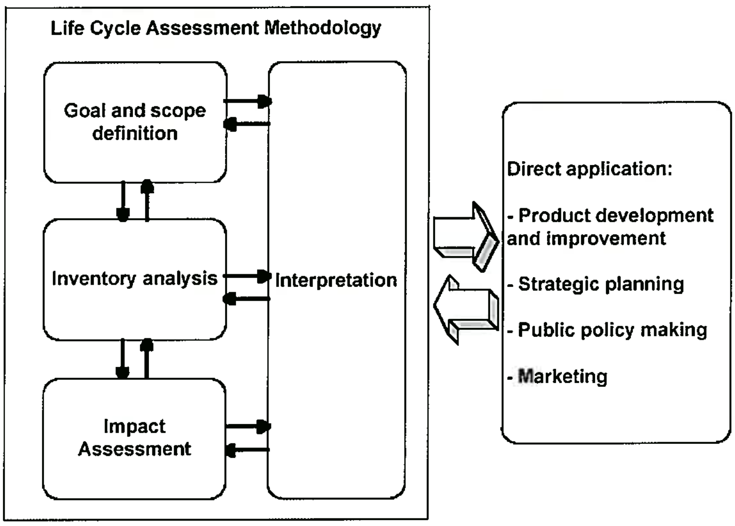


FIGURE 4 – GENERAL FRAMEWORK FOR LCA AND ITS APPLICATION (ISO 2006A: 14040)

2.1. GOAL AND SCOPE

The goal and scope stage of the project identifies the main aims and parameters for the study. Critical elements include determination of impact categories to be investigated, the functional unit (FU) for the system, system boundary definition and allocation processes. Common impact categories include total GHG, energy use, water use, human toxicity, eutrophication and land use.

Impacts assessed using LCA are reported relative to the primary output of the system, termed **the functional unit (FU)** of the system. The FU reflects not only the most common output, but also the purpose of that output. Hence, a full supply chain analysis for cotton could investigate the service cotton provides, e.g. the number of years over which a cotton shirt was used (worn) prior to disposal.

Determination of the **system boundary** defines what is included within the LCA study. In general, LCA includes the full supply chain for a product through to final product disposal (cradle-to-grave). However, many studies investigate the primary production stage only. For agricultural products, this is described as "cradle-to-farm-gate". A farm-gate study implies that all impacts for the production of the product through to that point are included in the study. This includes both on-farm processes (crop production, irrigation, general farm activities) and pre-farm processes (defined as upstream processes, such as fuel production, fertiliser and pesticide production, and transport processes).

Figure 5 shows a cradle-to-grave supply-chain system boundary for a cotton product (in this case, a pair of jeans). In Figure 5, the highlighted red box indicates the cradle-to-farm-gate component of the supply chain. As can be seen, the on-farm component is only a small proportion of the whole supply chain, although it may contribute a large amount to some resource use and environmental impact categories.

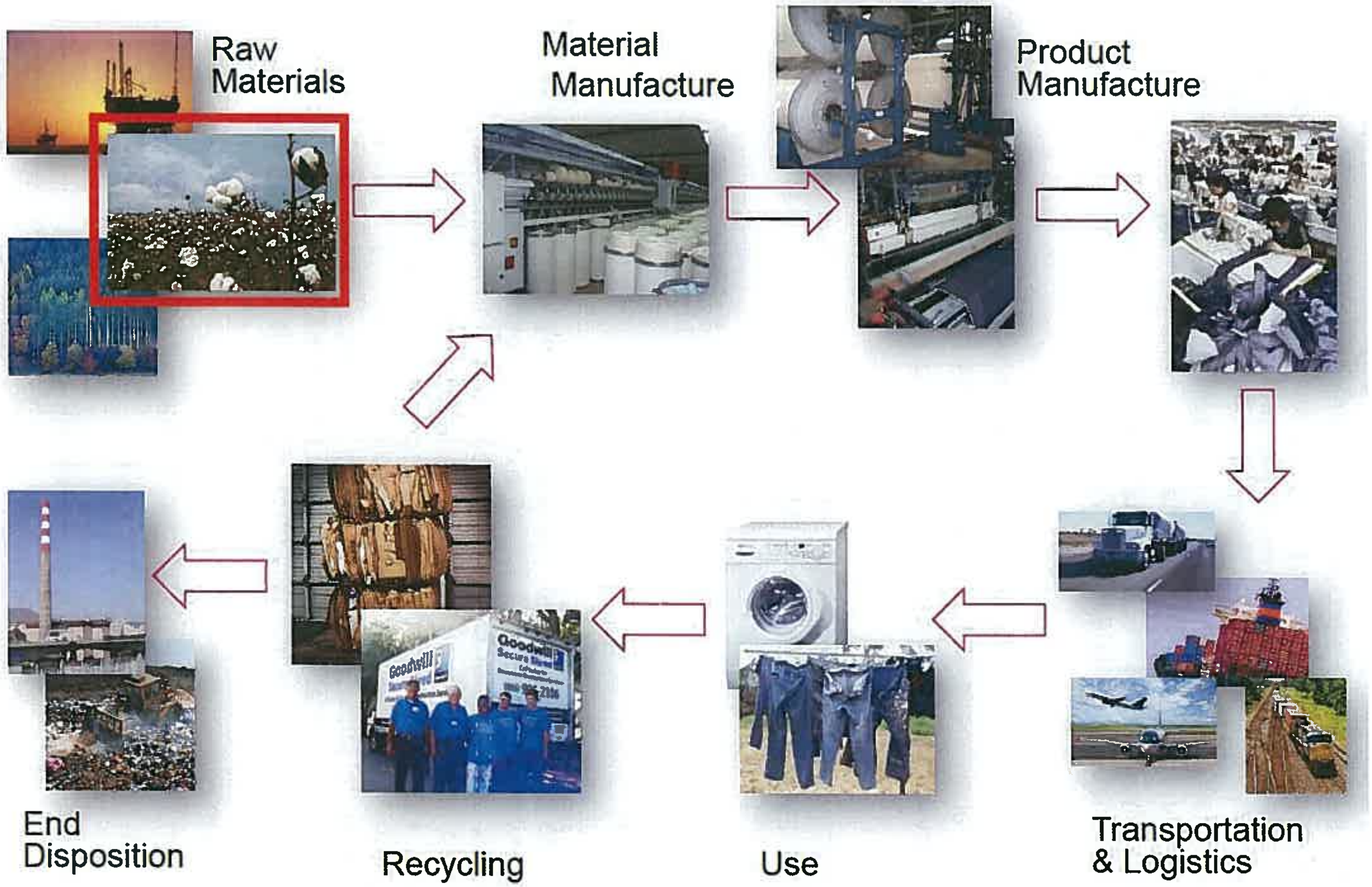


FIGURE 5 – CRADLE-TO-GRAVE COTTON SUPPLY CHAIN (WOLF 2011)

2.2. DATA REQUIREMENTS

Data collection for the life cycle inventory (LCI) is a complex process for agricultural systems. It requires a number of data sources to be aggregated over a given data collection time period. Because LCA uses a production efficiency measure, e.g. total water use *per kg of cotton lint produced*, all data must be accurately attributed to total production. Agricultural systems are variable, open systems with long and variable production cycles, making determination of total production difficult, particularly in regions with a high degree of climate variability. Additionally the water used in an agricultural system can be difficult and expensive to directly measure. By comparison, manufacturing industries (where LCA research originated) typically have rapid throughput and measurable inputs and outputs, with a lower degree of variability. In adapting LCA for use with agricultural industries, two issues are apparent:

i. the representativeness of the production system and data collected
ii. the comprehensiveness of the estimation process used for parameters that cannot be directly measured (such as GHG and water use).

The collection of accurate and representative production and resource use data is important both for the determination of overall productivity of the system and as an input to GHG and water use estimation models.

2.3. ALLOCATION

Allocation relates to the partitioning of impacts to multiple products that may arise from a single production system. Allocation issues exist for cotton production. About 300 kg of fuzzy cotton seed is produced for every 227 kg bale of cotton (Roth 2010). Cotton seed is a valuable by-product of cotton fibre production and makes up about 15% of the total financial returns to farmers. Hence, of the water use of cotton production needs to be allocated to the production of cotton seed. Standard LCA practice recommends (where possible) drawing the system boundary to avoid multiple products. However, where multiple products arise from the one system an allocation process must be undertaken. Three ways of addressing allocation issues are provided by the ISO (ISO 2006a: 14040), in order of preference:

- System expansion
- Allocation on the basis of physical or biological causality
- Allocation on the basis of economic value.

The impact of different allocation methods are significant.

2.4. LCA IMPACT CATEGORIES

A major strength of LCA is its ability to assess the resource use and environmental impact of a wide range of different parameters. Impact categories can include:

- Human toxicity
- Global warming
- Energy use
- Water use
- Eutrophication (nutrient loss to waterways)
- Land Use.

The focus on multiple impact categories in LCA is important to avoid 'burden shifting' between impact areas. It is also quite pragmatic, because there are many interrelated impact areas that 'share' the same inventory data. For example, it is necessary to investigate fertiliser and energy use to conduct a water use assessment, because both energy (electricity in particular) and fertiliser require water to produce. To accurately develop the water inventory, these data must be collected. Consequently, it may be little extra work to investigate these additional impact areas from the beginning.

2.5. CONSEQUENTIAL AND ATTRIBUTIONAL LCA

There are two basic perspectives that an LCA study can use. Most LCAs are done retrospectively. This is termed an attributional study because the impacts are attributed to the product being investigated. The main question for an attributional LCA is "*what impacts were created by producing and/or using this product?*" If a study is investigating production for a whole state or nation, every type of system that is currently being used needs to be included to get an accurate and representative result.

An alternative approach is to consider a dynamic system, and investigate the *consequences* of a *change* in production. In this case, the question might be "*what impacts on water systems would be created if one <u>more</u> bale of cotton was produced?*"

This report takes an attributional approach, which is a good starting point for LCA research. However, more challenging questions are asked in consequential LCA studies and these usually rapidly become a global investigation. For example, a consequential question is: "*if less cotton is produced in Australia due to water restrictions, what is the environmental impact on water resources globally?*"

2.6. LCA AS APPLIED RESEARCH

LCA may be classified as an applied research tool. This means LCA research does not generally involve conducting individual research studies into each impact area associated with the system. Instead, LCA draws from other studies that have been completed in the area, and relates the results to the system being investigated. Where knowledge gaps exist, the LCA practitioner can either conduct a very brief investigation with the aim of determining how significant the contribution may be from the unknown process, or exclude the process until further research has been undertaken. There are strengths and weaknesses with this type of applied research. One strength is that an LCA can provide broad answers long before the detailed research is completed. A second strength is that the broad scope allows impacts to be 'classified' in terms of their overall impact. Likewise, efficiency strategies can be evaluated in a holistic manner. This is something that many scientific research programs find difficult to achieve.

The weakness of an applied research tool such as LCA is that it relies on results from external research and modelling, which is less precise than if a full measurement campaign was undertaken. Modelling, or the extrapolation of other research findings, can introduce a source of error if there is a significant difference between the conditions of the research and the conditions investigated in the LCA.

It is common for a single production system to include over 2000 processes within the LCA model. Consequently, the process data used for common purchased products (such as diesel, pesticides or urea for example) are drawn from databases rather than from independent investigation of each sub-process. A distinction in LCA is made between **foreground data** (or data collected as part of the project from the industry involved), and **background data** (which is drawn from databases or literature sources).

LCA is a complementary tool that can be used in conjunction with detailed scientific R&D. For example, LCA can be used at the beginning of an R&D program to identify the most effective research directions and the potential trade-offs involved with mitigation techniques. Likewise, LCA may be used to evaluate the effectiveness of current research results by bringing them into the context of production systems.

This is important if real gains are to be made without 'burden shifting', which is an activity where one environmental impact is reduced in one sector of the supply chain only to be consequentially increased in another section of the supply chain.

2.7. AUSTRALIAN AGRICULTURAL LCA RESEARCH

Most major agricultural industries in Australia have (or are in the process of) conducting LCA research. Completed studies in the last 10 years include:

i. Dairy
ii. Red meat (Peters et al. 2009, Peters et al. 2010a, Peters et al. 2010b)
iii. Grains (wheat, barley, canola - Narayanaswamy et al. 2004), (maize - Beer et al. 2005)
iv. Pork (Wiedemann et al. 2010)
v. Eggs (Wiedemann & McGahan 2011)
vi. Chicken meat (Wiedemann et al. 2012)

In general, these studies have focused on GHG, energy and water use as this has been the major area of interest to producers and consumers. Few studies have considered the full suite of LCA impact categories.

Other private work has been carried out for some industries but these are not available in the public literature.

2.7.1. LCA METHODOLOGY DEVELOPMENT

The Rural Industries Research and Development Corporation (RIRDC) (with funding from MLA, APL, CRDC and others) developed a methodology for agricultural LCA in Australia (Harris & Narayanaswamy 2009). The methodology is particularly focussed on GHG, energy and water use, and represents an adaptation of the ISO Standards (ISO 14040-14044) to LCA in agriculture.

In respect to water, while providing some useful, broad-scale guidance, the methodology failed to provide guidance and did not resolve many critical issues, mainly because the fundamental research had not been done at the time. The methodology did specify the need for detailed estimation of on-farm water loss pathways such as evaporation, seepage and drainage.

The methodology proposes presenting water use under two definitions:

i. The ABS water use definition (which is roughly equivalent to blue water)
ii. Two definitions provided by the National Land and Water Resources Audit (NLWRA), namely:
    - Surface water sustainable flow regimes: the volume and pattern of water diversions from a river that include social, economic and environmental needs; and
    - Groundwater sustainable yield: the volume of water extracted over a specific time frame that should not be exceeded to protect the higher social, environmental and economic uses associated with the aquifer.

The methodology states that the sustainable use of water shall be reported as a percentage, namely:

- Water removed from rivers as a percentage of sustainable flow regimes; and
- Groundwater abstraction as a percentage of sustainable yields.

This may have some merit for its national relevance. However, no studies are currently available that follow the proposed Harris & Narayanaswamy (2009) water assessment approach.

Since development of the Australian methodology, a number of important methodological papers and case studies have been released. Hence, the recommendations presented by Harris & Narayanaswamy (2009) could not be considered definitive.

2.8. ASSESSMENT OF AGRICULTURAL SUPPLY-CHAIN WATER USE

Although this review aims to focus on LCA studies, several other water use methodologies have been reviewed to provide a clear understanding of the strengths and limitations of each. The methodologies can be broadly grouped into three categories. These are:

1. Water Footprinting – WF (and virtual water - VW)
2. Water Balances
3. Life Cycle Assessment (LCA).

Whilst these methodologies have been developed for different purposes and may relate at some levels, they rarely produce comparable results and are often used to draw conclusions that cannot be substantiated from the methodology used.

There are two issues with the assessment of water use for an agricultural commodity. They are **resource use**, which is an inventory of the quantity of water used and **environmental impact** or **impacts to humans and the environment**. Most methods focus on developing a water inventory. However, these do not include any assessment of the impact of using water. The implication is often made that '*the more you use, the worse you are*', which is a very simplistic assessment of the impact of using water. These issues will be discussed in detail in the following sections.

3. WATER FOOTPRINTING AND VIRTUAL WATER

3.1. METHODOLOGY

The virtual water (VW) concept was first proposed by Allan (1998) to describe the water required to produce tradable commodities (particularly food) in water stressed economies. The water footprint (WF) of a product is equal to the sum of all of the water that is consumed at the different stages of production and is equivalent to the virtual water content. The VW method makes a useful contribution to the global understanding of water transferability by showing that irrigation water in one region can be saved by importing food, thereby reducing water stress. Moreover, stress on irrigation water because of agriculture can be alleviated by growing products in regions where water requirements can be met by soil stored moisture.

To further improve the understanding of VW, Falkenmark (2003) describes water in terms of '**blue**' water (which represents our general understanding of water that may be sourced from surface or groundwater supplies) and '**green**' water, which may be classed as soil stored moisture from rainfall (i.e. Falkenmark 2003, Falkenmark & Rockstrom 2006). Additionally, the term '**grey**' water use has been developed to identify water 'required' to dilute contaminants released from a production system to acceptable concentrations for the given water system the contaminants are released into.

All three of these terms are now used in the field of water footprinting (Hoekstra et al. 2009a, Hoekstra et al. 2009b) and Hoekstra et al. (2011) .

Early methods for assessing VW or the WF of a product have been outlined by Chapagain & Hoekstra (2003), Hoekstra & Hung (2002), Hoekstra & Hung (2005) and Chapagain et al. (2006). These authors base their research on retrospective analyses of crop evapotranspiration requirements (using CROPWAT - FAO 1998). Hence, water use is modelled, not measured.

Prior to the distinction of blue/green/grey water sources, there was a substantial degree of confusion surrounding VW/WF results. In some instances, use of VW/WF data led to erroneous conclusions, particularly where the WF was considered synonymous with water extracted from a river or ground water source. According to Peters et al. (2010b), 98% of the VW associated with Australian beef production systems was sourced from green water, which has very different opportunity costs and impacts when compared to blue water.

Several authors have proposed using a modified WF/LCA approach for estimating water use for agricultural products, including Ridoutt et al. (2009a, b), Pfister et al. (2009), Milà i Canals et al. (2009) and Ridoutt and Pfister (2010). These authors identify the need for more detailed inventory methods (particularly differentiation between blue and green water), and recommend excluding green water from the impact assessment. Ridoutt & Pfister (2010) and Pfister & Hellweg (2009) propose introducing a weighting factor into water footprinting as a means to indicate the environmental impact of water use.

In 2011, Hoekstra et al. (2011) brought out "The Water Footprint Assessment Manual". This book contains the global standard for water footprint assessment as determined by the Water Footprint Network (WFN). This manual builds on the work carried out by (Hoekstra et al. 2009a) and as such provides a standard on definitions and calculation methods for water footprint accounting. This is essential, as the interest in water footprinting shown by governments and major companies is growing, and a shared standard for this process is necessary to formulate sustainable water strategies and policies. The Water Footprint manual presents the argument that green water must be considered when accounting for the water footprint. Hoekstra et al. (2011) argue that, although blue water resources are typically scarcer and have greater opportunity costs than green water, green water resources are also scarce. In addition to this, green water can be substituted with blue water processes, or vice versa in agricultural systems. Therefore, if the historical focus on just blue water is taken, the full picture of the water footprint will not be found. However, this view is not shared by many water use specialists. The draft International Standard for water footprinting (as yet unreleased) does *not* include green water use as part of the water footprint of a product (B. Ridoutt pers. comm.). The inclusion or otherwise of green water will depend on the focus of the study being undertaken. Clearly, with the focus in LCA being the impact of water use, LCA practitioners are less likely to consider green or grey water use. Further discussion regarding LCA approaches to water use are provided in Section 5.

Blue water – Surface water or groundwater that is consumed (evaporated) as a result of the production of a product.

Green water – Soil stored moisture from rainfall consumed as a result of the production of a product.

Grey water – Freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards as a result of the production of a product.

3.2. COTTON WATER FOOTPRINT STUDIES

Two studies of the water footprint of cotton were reviewed. Chapagain et al. (2006) conducted a water footprint study of global cotton production and consumption for the period 1997-2001. The study defined the contribution from green, blue and grey water use, and investigated the supply chain from the “cradle-to-consumer”, including all stages through to the point of retail (i.e. excluding the use and end-of-life phases). The study built on the work from previous water footprint studies (Chapagain & Hoekstra 2003) and (Hoekstra & Hung 2002) to include the impacts of pollution along with groundwater use, surface water and soil water.

This report listed the water footprint of five different products: 1 pair of jeans, 1 single bed sheet, 1 T-shirt, 1 diaper and 1 Johnson’s cotton bud. The blue, green and grey water content of each of these products is scalable by mass. The water footprint consisted of 4900 L (blue water), 4450 L (green water) and 1500 L (grey water), which gives a total water footprint of 10 850 L/kg processed cotton product.

Hoekstra and Mekonnen (2011) quantified the blue, green and grey water footprint of worldwide crop production for the period 1996-2005. The study used the Water Footprint Assessment Manual (Hoekstra et al. 2011) and included all supply chain stages up to and including the finished cotton fabric. The study determined that the blue water use was 5384 L/kg cotton fabric, green water was 3253 L/kg and grey water was 1344 L/kg, giving a total water footprint of 9981 L/kg fabric.

The differences in the water footprints between the two studies are due to the fact that the study by Chapagain et al. (2006) included the garment manufacturing stage and the data for both studies were from different time periods. It should also be noted that the reported water footprint data for both of these studies are a global average. Therefore, it is not representative of Australian water footprints for cotton products. Table 1 presents the results from two global water footprint studies of cotton.

TABLE 1 – WATER FOOTPRINT OF WHOLE SUPPLY CHAIN

Water footprint	Measured Unit and Scope	Water measurement methodology	Research location	Reference
4900 (blue) 4450 (green) 1500 (grey) **10 850 (total)**	L/kg of jeans (several other cotton products assessed and results were comparable when differences in mass are accounted for). All stages including production of cotton garment products (no use or end-of life phases considered)	Water footprint	The Netherlands but data is global average	Chapagain et al. 2006
5384 (blue) 3253 (green) 1344 (grey) **9981 (total)**	L/kg cotton fabric, finished textile. All stages including production of cotton textile (no garment production, use or end-of life phases considered)	Water footprint	The Netherlands but data is global average	Hoekstra and Mekonnen 2011

4. WATER USE ASSESSMENT USING WATER BALANCES

A water balance is a simple tool used to assess the total flows of water throughout a system. Essentially a water balance relies on the assumption that total inputs must equal total outputs (i.e. that water is neither created or destroyed from the given system). Water balances must be geographically defined, and are generally not focussed on assessing a supply chain, but rather a discrete sub-system within a supply chain, such as a farm. This said, they can be applied at a much larger scale, such as a whole catchment. For example, the Australian Bureau of Statistics (ABS) reports a water balance for the whole Murray Darling Catchment. In Australia, the main aggregator and reporter of water use data are the ABS. Hence, this is an important source of data and definitions in the assessment of Australian water use.

4.1. WATER BALANCE DEFINITIONS

The engineering approach to system water accounting describes water movements associated with system in the contexts of inputs and outputs. In its simplest sense, water use is defined as the sum of the water outputs from a system, or the sum of the water inputs minus water captured in storage within the system.

Within the definition of a water use, delineation can be made between *beneficial* uses of water and *non-beneficial* uses, or losses. This is consistent with the approach used by the ABS in differentiating *consumption* from *use,* where 'beneficial' uses effectively correspond to consumptive activities.

With this clarification made, a more representative working definition of water use is the sum of beneficial uses. However, it is also understood that there are non-beneficial uses (losses) associated with beneficial uses, and these should also be included in the total water use value.

4.2. WATER BALANCE METHODOLOGY

The water engineering approach quantifies water use for a physical system through construction of a water balance. The technique is based on accounting for system inputs and outputs, with imbalances resulting in changes to system storage under the assumption that there are no net gains or losses (i.e. no water is generated or destroyed).

The strength of this approach – when used for water accounting – is that it provides a full assessment of water movements attributable to a system, identifying where improvements can be made by reducing or eliminating losses. Water balances can be applied at any scale depending on the resolution of input data and the required resolution of output data. At a farm level, typical water balance components are provided in Figure 6.

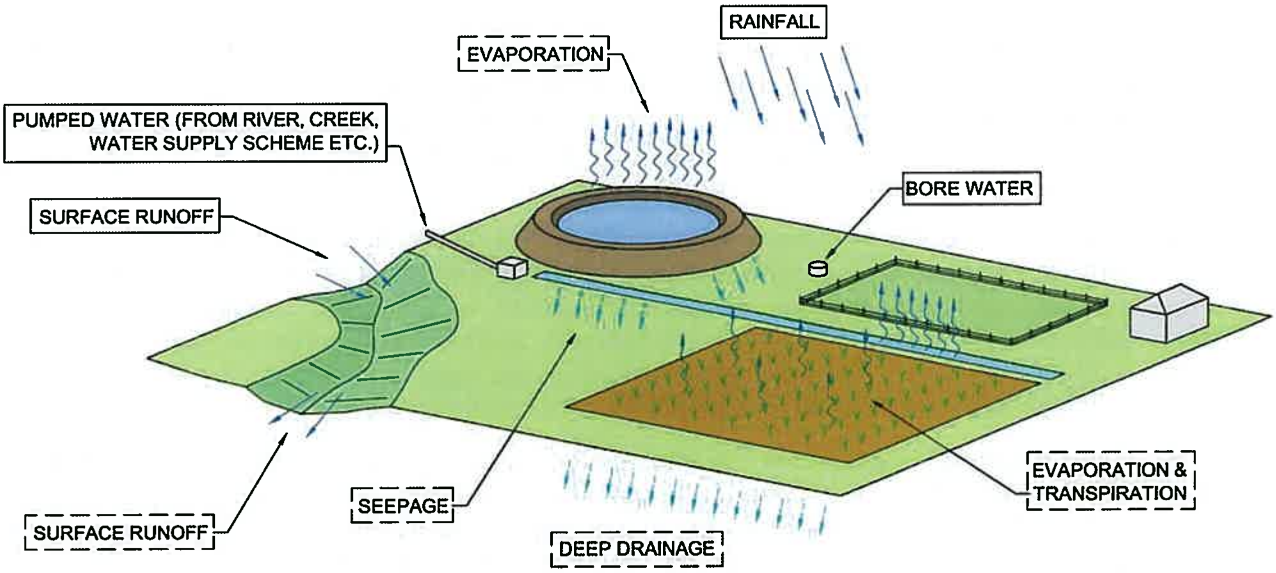


FIGURE 6 – TYPICAL FARM WATER BALANCE COMPONENTS

The factors involved in this balance are a mix of physical processes and farm operations. The major components of a farm water balance are as follows:

Inflows – water may enter the system from many sources, which include:

- **Rainfall** – describes water entering the system through rainfall. This can be accounted for as direct input to storages or cropping areas, but can also indirectly account for the generation of surface runoff.
- **Pumped water** – describes water brought into the system via some form of pumping. Common water sources are rivers, creeks and bores. This can also account for water delivered to the property by some form of distribution network or water supply scheme. Measurements of these inputs are generally quite simple with the use of flow meters in pipelines and channels.
- **Surface runoff** – describes water entering the system while flowing over the ground surface. Surface runoff inputs are usually very difficult to quantify, except where they are transferred into storages or for direct use by pumps, pipes or channels.

Outflows – depending on the level of detail, the water balance will define outputs by measurement and deduction. Outputs include:

- **Transpiration** – describes the process of plants removing water from the ground to support life and growth, and the eventual release of that water as vapour to the atmosphere. Transpiration rates vary considerably between plants of different types and species, and also vary according to climate and environmental conditions.
- **Evaporation** – describes the loss of water from open water surfaces through vaporisation. The driving factors of the evaporation process are solar radiation, temperature, wind speed and humidity. Evaporation can be inferred from measured rates using a standardised pan, or calculated from measures of climatic conditions. Evaporation losses can be reduced by a number of approaches from engineering

solutions (such as designing storages to minimise open water surface areas for the volume of water stored, covers for open water surfaces etc.) to management strategies (such as minimising time of storage, consolidating water into fewer storages etc.). In many locations across Australia, annual potential evaporation losses exceed annual rainfall inputs. It follows that evaporation is a major loss component for many farm water balances.

- **Seepage** – describes outflow from storages and distribution channels by percolation through the base and/or walls. In engineered earthen storages or channels, seepage can be minimised through careful compaction of the lining material. The target minimum seepage rate from compacted earthen structures is approximately 0.000001 mm/day. Alternatively, seepage losses can be eliminated by the provision of a physical barrier, such as a plastic or concrete lining layer.
- **Deep drainage** – describes the infiltration of water into the ground beyond the root zone of plants. In the case of irrigation, deep drainage is usually triggered by applications of water in excess of what is required to fill the root zone of the planted crop to it maximum water holding capacity. Deep drainage can also be induced through rainfall onto a recently irrigated field.
- **Surface runoff** – describes water draining off the farm on the ground surface, usually triggered by rainfall. Surface runoff may be captured in storages, and can also include excess irrigation water draining off irrigated fields.

Water balances must also be applied to the individual components of a system to represent the behaviour of the components and describe the interactions between components. The generation of surface runoff requires analysis of a soil moisture balance, while water storages are also subject to a separate balance analysis to quantify fluctuations in storage volume.

If water use is to be attributed to production (i.e. L per kg of cotton) the general approach would be to account for all 'system' water inputs (from watercourses, storages, groundwater etc) which are directly related to production. In this manner, rainfall is included in the balance, but is *generally excluded* from the calculations of 'water use' since it does not exist because of the production operation.

In the case of an irrigated crop, water use may be calculated as the water applied to the field without any further considerations of the water movements on the field after application. Depending on the level of available data, these water movements may be quantified to provide a better picture of the destination of the water if required (i.e. quantifying how much water ends up as deep drainage, evapotranspiration or runoff).

4.3. AUSTRALIAN BUREAU OF STATISTICS (ABS) DEFINITIONS AND METHODOLOGY

4.3.1. ABS DEFINITIONS

The ABS defines water use as *"the sum of distributed water use, self-extracted water use and reuse water use"*. This is compatible with data available to most water users (i.e. water bills for reticulated supply, meter readings for bores). Hence, water use is defined by the *inputs* to the system. "Distributed" and "self-extracted" water uses are defined as water supplied from engineered delivery systems. Delivery systems vary greatly in size and degree of infrastructure, incorporating a range of systems, from sub-artesian groundwater extraction to water supply from rivers or state-owned dams.

Water is classified as "distributed" if the water is purchased, or "self-extracted" if not. Essentially, this definition corresponds to "blue" water (water that may be sourced from surface or groundwater supplies) and does not include rain falling on properties. For water to be considered "used", it has either been transferred from its natural watercourse or extracted from groundwater. Hence, ring tanks that collect overland flow from local catchments or floodplain harvesting are not considered.

"Reuse water" refers to any drainage, wastewater or stormwater that has been used more than once without being first discharged to the environment. It can refer to both treated and untreated water.

Delineation is also made between the terms *consumption* and *use*. Water consumption differs from water use in the sense that it represents the net water balance for an activity *less* the amount of water passed on for other uses. For example; a hydroelectric power station has a high water use - accounting for all of the water which enters the facility - but a very low water consumption, since almost all of the water 'used' is discharged downstream for other uses.

The ABS definition of water use includes the volume of water lost through supply systems. The attribution of this loss volume to suppliers and consumers depends on the origin of the loss. For example, distribution system losses are considered to be a form of use by the *supplier* and metering losses are considered to be a form of use by the *consumer*.

4.3.2. ABS METHODOLOGY

The Water Account publications released by the ABS represent a collation of data from a wide range of sources. Water use statistics are derived from government agencies at all levels, water authorities, industry organisations, and a range of ABS surveys. It is reasonable to assume that organisations involved in the large-scale supply and transmission of water would base their information supplied to the ABS on metered data but this is not always so.

In cases where data has not been collected or where records are incomplete, values may be calculated or inferred from other related measures. An example relevant to agriculture is the volume of self-extracted water, where specific data does not exist due to monitoring impracticalities, and so the volume is inferred by subtracting the distributed water use from the total water use.

A similar water-use accounting approach could be applied at scales right down to a farm level. Required data could be sourced from transaction records supplied by water suppliers, reports from government water authorities, and inferred calculations (such as calculating volumes from pumping rates and time spent pumping). The collation and analysis of data from these sources would allow a reasonably accurate assessment of water movements and use on the farm.

More specific to agricultural production, the "Water Use on Australian Farms" publications present a higher resolution snapshot of water uses and sources. This includes a breakdown of irrigation activities by crop and method, as well as a breakdown of the sources of agricultural water (surface water, scheme supply, groundwater, reticulated mains etc.). The data presented in the "Water Use of Australian Farms" publications are derived principally through ABS surveys. Surveys generally ask respondents to provide areas of irrigation land and the volume applied to these areas. If the volume is unknown or unmetered, respondents are asked to estimate the applied volume, which in many cases would be inferred from an average crop water requirement value. Clearly, inaccuracies exist with this data.

"Water use" from a water balance can be defined from the inputs or the outputs.

Water use as defined by outputs is the sum of transpiration, evaporation, seepage, deep drainage and surface runoff etc.

Water use can also be based on inputs. The ABS define water use based on the total inputs to the system from various sources.

4.4. WATER BALANCE APPLICATION TO COTTON PRODUCTION

Water balances are commonly used to design irrigation systems and define water use efficiency on Australian cotton farms. Typically, a water balance will include both irrigation water and rainfall. Recent research by FSA Consulting and Aquatech – FSA/ATC (2011) included a detailed water balance study of six irrigation farms in the northern Murray-Darling Basin over a three-year period. The objective of the study was to develop methods for measuring the various components of land surface diversions (overland flow). The methodology used to achieve this objective included eleven steps. These were:

Step 1 – Site Selection. Select six representative sites (farms) across the northern MDB - three in NSW and three in QLD. Obtain co-operation from each participating grower and sign a confidentiality agreement.

Step 2 – Site Data and Water Movement Schematics. For each site, collect basic site data and prepare a water movement schematic to identify LSD and non-LSD water movements. Identify the most appropriate locations to measure the components of LSD.

Step 3 – Design the Monitoring System for each Site. Determine which water movement parameters would be directly **measured** over the whole period of the project and which parameters would be **estimated** from short-term measurements, scientific literature or modelling.

Step 4 – Monitoring System Installation. Procure and install appropriate monitoring equipment at each site.

Step 5 – On-going Data Collection. Conduct periodic visits to each site to inspect the irrigation areas, inspect/maintain installed equipment, collect monitoring data and liaise with site management to discuss water movements. Data was collected over a three-year period from 1 Feb 2008 to 31 March 2011.

Step 6 – Set up WaterTrack™ Whole-Farm Water Balance Model. Set-up WaterTrack Optimsier™ whole-farm water balance to enable the components of LSD to be determined for each site.

Step 7 – Literature values for Estimated Parameters. Choose appropriate values from the scientific literature for estimated parameters used in the water balance models.

Step 8 – Short-term Data Collection. Undertake short-term data collection to improve estimated parameters obtained from the scientific literature.

Step 9 – Model Calibration using three year's Data. Using measured and estimated data, calibrate the whole-farm water balance model for each site. Determine estimates of LSD for each site for the period from 1 February 2008 to 31 March 2011. To understand the implications of increasing the intensity of on-ground monitoring, a number of different "levels" of WaterTrack Optimsier™ modelling were undertaken. These levels ranged from the simplest data collection option possible (Level 1) to increasingly detailed and complex data collection and parameter fitting (Level 4).

Step 10 – Model Verification using 2010/2011 Data. Verify the performance and accuracy of the water balance model by calibrating the model against the on-farm storage volume using the first two years data and then by making no adjustment to the calibration parameters, calculate the LSD volumes for the remaining data collected from 1 Feb 2010 to 31 March 2011. This is referred to as Level 5 modelling.

Step 11 – Options for Simplified Implementation. A simple spreadsheet was developed as an option compared to the complex modelling above.

Most farms grew cotton although due to drought conditions and poor prices, cotton was not grown every year. A large volume of data was collected as all parameters were monitored continuously over the three-year period (1 February 2008 to 31 March 2011). Table 2 provides a summary of selected data for five farms over three years. In this table, the terms are:

FPH (Floodplain Harvesting) Floodplain harvesting is the diversion of water flowing across a floodplain. Floodplain harvesting applies to those flows that have originated from a watercourse and breakout during a flood (this includes the capture of receding flood waters). FPH is LSD.

LSD (Land Surface Diversion) Land Surface Diversion is the diversion of runoff into an on-farm storage (*OFS*) or for direct irrigation thus preventing that runoff from naturally entering a watercourse or infiltrating into the floodplain. LSD is to be measured (or estimated) at the *Point of Take* and at the *Point of Exit*. LSD includes *OFH, RRH, FPH.*

OFH (Overland Flow Harvesting) Overland flow harvesting is the diversion of rainfall runoff from land surfaces other than the farm's irrigation areas. OFH is *LSD*.

OFS (On-farm Storage) An on-farm storage is any privately-owned storage where the intended use is to store water.

OLF (Overland Flow) Overland Flow is water that has been unable to penetrate the soil profile during or after a rainfall event, at which point the water begins to flow to areas of lower elevations.

RRH (Rainfall Runoff Harvesting) Rainfall runoff harvesting is the diversion of runoff from areas of the farm that have been developed for irrigation. RRH is *LSD*.

Figure 7 shows the water flows into and out of a typical cotton farm in Australia and partitions this between "green" water and "blue" water as defined in Section 3.1. This model was used to measure whole-farm water balances on six Australian irrigation farms in the Murray-Darling Basin (FSA/ATC 2011). The results of this study are presented in Section 4.4.1.

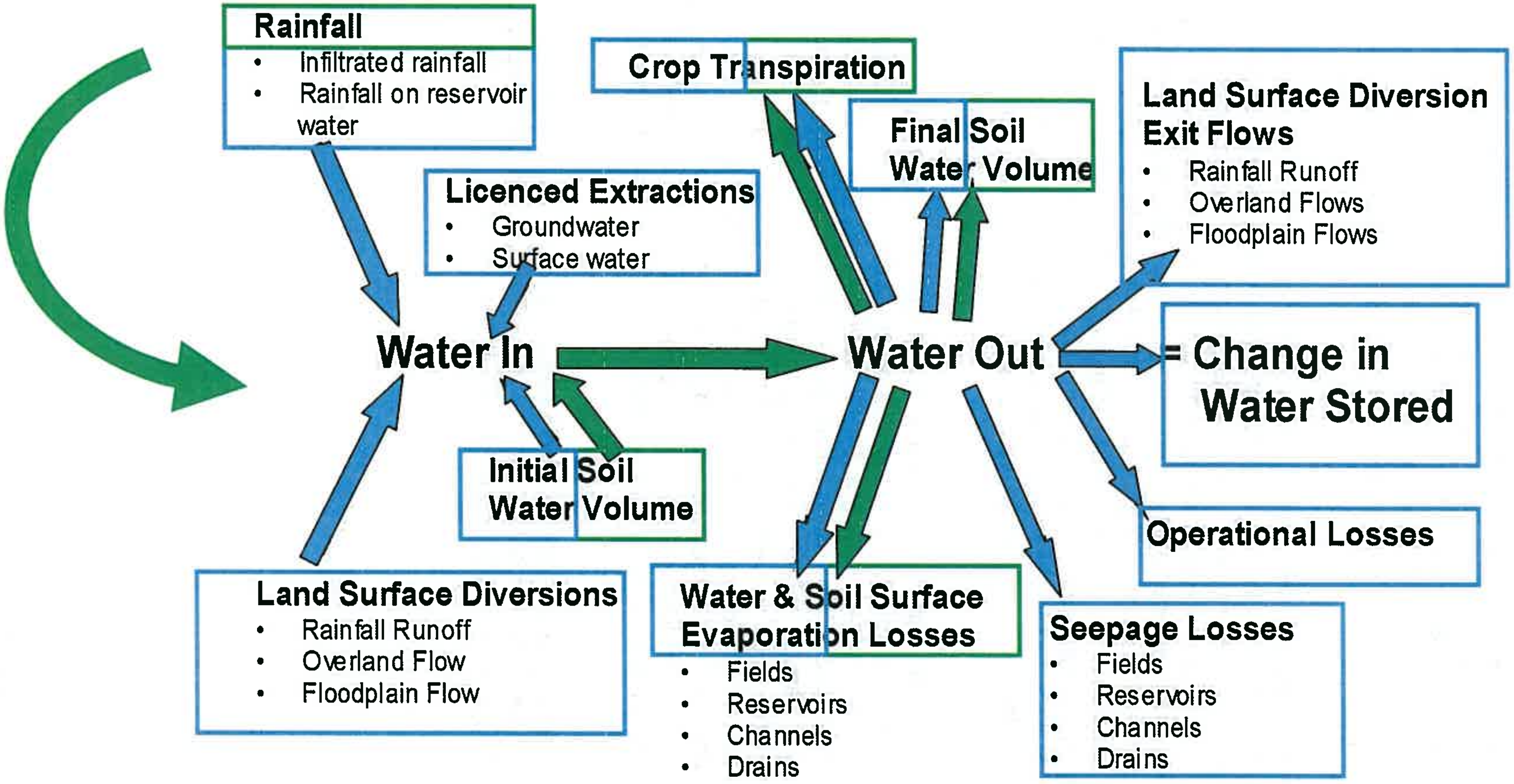


FIGURE 7 – WATER BALANCE OF A COTTON FARM (SHOWING GREEN AND BLUE WATER)

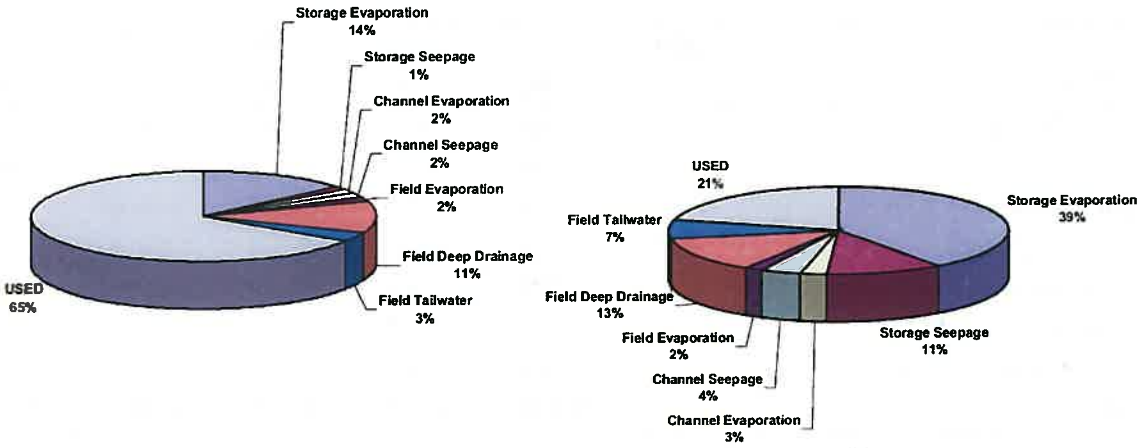
4.4.1. WATER SYSTEM LOSSES IN AUSTRALIAN COTTON PRODUCTION

In an LCA context, the issue is not the in-field water use efficiency of a crop but the volume of water extracted from the environment to produce that yield (and the impact of that extraction). Figure 7 shows schematically the water balance of an irrigated cotton farm. The sum of all blue-water extractions is the key issue, not the volume of water applied as irrigation. Very few studies have been undertaken that measure a full, measured water inventory of a cotton farm so that total extracted blue water can be determined. It is necessary to determine all losses on-farm including evaporation and seepage losses from storages, channels and drains.

When reviewing the work done to date, Dalton et al. (2001) noted that the only significant study on broader industry and whole-farm irrigation performance was that undertaken by Cameron & Hearn (1997). The reference for this work is not given. They quantified industry irrigation performance through a process of valley and individual farm data review (including crop yield, water meter, water provider and soil moisture data). Efficiency of irrigation was defined in two components: the engineering (volumetric) efficiency (or irrigation efficiency, IE) and the agronomic efficiency (or crop water use efficiency, CWUE). On three individual farms that were reviewed, IE averaged 75%. However, the overall mean for regional data was 58% IE with individual regions in the range of 41% for the McIntyre Valley and Emerald to 94% in the Gwydir Valley. The mean for individual farms in these regions was 63% ranging from 49 to 78% IE.

Dalton et al. (2001) conducted a large study for CRDC on best management practices for maximising whole-farm irrigation efficiency in the Australian cotton industry. Experimental work was undertaken on seven farms in the Border Rivers over the 1998-2000 cotton seasons. They determined whole-farm water balances as part of their study by measuring the water use efficiency of various sub-components of system and then combining them to create an overall whole-farm water use efficiency. The reporting is not clear but it appears that the whole-farm water use efficiency data presented is for the cotton-season period only, not for a complete 12 months. They note that "the proportion of the whole farm water which was used by the crop in an individual irrigation event ranged from 21% to 65%". Figure 8 shows the percentage breakdown of water use on their experimental sites for the best and worst case scenarios.

As it appears that this data only applies to the cotton season and not a full 12 month period, it is likely that this data understates the actual water losses. Evaporation and seepage from on-farm storages over the winter period is apparently not included.



(a) (b)

FIGURE 8 – COMPONENTS OF THE VOLUME BALANCE FOR (A) BEST AND (B) WORST CASE MEASURED WHOLE FARM EFFICIENCIES (DALTON ET AL. 2001).

The Australian water balance study by FSA/ATC (2011) showed that between 24% and 74% of the water taken from the environment for irrigation use was lost (i.e. not used for irrigation). In terms of whole-farm water use efficiency, this is a range of 26% to 76% efficiency. This was broadly similar to the results found by Dalton et al. (2001). The causes of the water losses are well known – on-farm storage and distribution system evaporation and seepage. However, the modelling undertaken by FSA/ATC (2011) has revealed that this is highly variable between farms and between seasons depending on climatic conditions.

TABLE 2 – SUMMARY OF IRRIGATION FARM INFLOWS AND OUTFLOWS (FSA/ATC 2011)

Farm	A	B	C2	D	E
INFLOWS	**ML**	**ML**	**ML**	**ML**	**ML**
Rainfall on OFS (a)	843	906	6 969	558	1 731
Off-farm OFH inflow at Point of Take (b)	13 249	0	333	43	682
Off-farm FPH inflow at Point of Take (c)	0	0	16 373	0	0
Off farm non-LSD inflow	0	5 363	0	7 014	3 207
Rainfall on remainder of farm less RRH	4 475	3 204	3 046	13 010	10 442
Rainfall Runoff (RRH) (d)	1 400	522	296	2 316	1 230
Rainfall Runoff (mm/ha/year)	18.6	6.6	5.1	10.8	7.5
(1) TOTAL	**19 966**	**10 023**	**27 017**	**22 941**	**17 292**
OUTFLOWS					
Evaporation from OFS (e)	964	1 273	13 258	993	2 465
Seepage from OFS (f)	172	266	4 503	369	204
Water loss from channel and drains (g)	81	111	80	1 119	423
Water loss from fields (soil seepage and evaporation)	3 512	3 102	2 617	9 427	9 112
Crop transpiration	1 280	1 186	2 759	10 626	3 289
Water transferred off-farm (non-LSD)	0	1 229	0	0	0
Water loss from Point of Exit (h)	13 026	16	4 077	322	0
(2) TOTAL	**19 034**	**7 183**	**27 294**	**22 856**	**15 493**
(3) NET INFLOWS(1) – OUTFLOWS (2)	932	2 841	(277)	85	1 799
CHANGE IN WATER STORED ON-FARM					
Change in OFS Volume	927	2 946	(1 328)	14	1 360
Change in OFS soil profile volume	30	34	(2)	(1)	32
Change in soil profile volume	(37)	(101)	(59)	121	292
(4) NET CHANGE IN ON-FARM VOLUME	921	2 878	1 322	139	1 685
NET CHANGE (3) – (4)	12	(38)	(1 599)	(54)	114
Percent Net Change	0%	0%	6%	0%	0.6%
Distribution System Net Water Loss (e) + (f) + (g) – (a)	373	744	10 872	1 923	1 361
Irrigation Volume	371	1 622	4 371	11 905	3 516
Irrigation Applied (ML/developed ha/year)	0.5	2.0	7.6	6.3	2.1
Irrigation as a % of Inflows (LSD + non-LSD)	23%	28%	26%	132%	69%
(5) Net RRH take (d)	1 400	522	296	2 037	1 230
(6) Net OFH take (b) – (h)	223	0	333	0	682
(7) Net FPH take (c)	0	0	16 373	0	0
TOTAL LSD Take (5) + (6) + (7)	**1 623**	**522**	**17 002**	**2 037**	**1 912**
Net Loss as a % of Inflows (LSD + non-LSD)	49%	24%	74%	26%	45%

4.5. WATER USE EFFICIENCY IMPROVEMENTS IN AUSTRALIAN COTTON PRODUCTION

In 1995, the Murray-Darling Basin Ministerial Council published an audit of water use in the Murray-Darling Basin (Murray-Darling Basin Commission 1995). This audit found that, since the 1950s, there has been a continuing increase in the quantity of water diverted from the rivers in the Basin. For example, from 1988 to 1994, water consumption across the Basin had increased by 8% and was continuing to grow. The audit concluded that the high level of water use in the Basin was a major factor in river health decline. In a normal year, flows at the end of the Murray were only 20% of their natural level. In response to the audit of water use across the Basin, Murray-Darling Basin Ministerial Council agreed on a cap on surface water diversions from the Murray-Darling Basin to limit future increases in such diversions. Since the introduction of the cap in 1995, there have been ongoing changes to water availability and cost. This has led to continuous research into improving the water use efficiency (WUE) of cotton production. Several programs in NSW and Queensland have been implemented with significant improvements in WUE due to changes in irrigation scheduling, irrigation application techniques and other management changes.

In order to achieve consistency in WUE measurement, the cotton industry has adopted standard measurements of WUE. These are given in the WATERpak manual (Cotton Catchment Communities CRC 2008) and are listed below.

- Crop Water Use Index (CWUI): lint produced per mm of evapotranspiration from a field during the cotton season.
- Gross Production Water Use Index (GPWUI): lint produced per ML of total water used on a farm or a field.
- Irrigation Water Use Index (IWUI): the lint produced per ML of net irrigation water applied to a field or supplied to a farm.
- Whole Farm Irrigation Efficiency (WFIE): the amount of irrigation water used by the crop for evapotranspiration as a percentage of that applied to the crop.

The WUE of the Australian cotton industry has been assessed several times in the past 20 years and are summarised in Table 3.

TABLE 3 – SUMMARY OF KEY WUE INDICES FOR AUSTRALIAN COTTON (1988 TO 2007) (ROTH 2010)

Year	Irrigation ML/ha	ET mm	Yield bales/ha	IWUI bales/ML	GPWUI bales/ML	CWUI kg/mm/ha	WFIE %
1988-95	5.37		6.73	1.48 (0.97-1.96)	0.82 (0.62-0.94)	3.05	63 (49-78)
1996-99	6.96	735	8.13	1.32 (0.65-1.71)	0.79 (0.47-0.93)	2.52	57 (20-85)
1998-00	7.5						(28-68)
2000-03		721	8.73	1.16	0.93	2.79	58
2006-07	7.51	733	11.12	1.31	1.13 (0.82-1.71)		85
Average	**6.8**	**730**	**8.68**	**1.32**	**0.91**	**2.79**	**66**

In order to highlight Australian cotton's superior water use efficiency, water use for international production was reviewed. The study by Ibragimov et al. (2007) aimed to measure cotton water use, and to quantify irrigation water use efficiency (IWUE) for Uzbekistan. Ibragimov et al. reported on irrigation requirements (ML/ha), yield of cotton lint (bales/ha) and irrigation water use efficiency (IWUE – bales per ML). This indicator is equivalent to the IWUI described previously. The data presented by Ibragimov et al. was modified to make it directly comparable with the Australian results in Table 3. Table 4 shows the results for furrow-irrigated cotton in Uzbekistan from 2003-2005. It shows that irrigation water use efficiency reported in this study is lower than in Australia. The cotton yield is also lower than Australian production.

TABLE 4 – IRRIGATION, SEED-LINT YIELD AND IRRIGATION WATER USE EFFICIENCY (IWUE) IN UZBEKISTAN

Year	Irrigation ML/ha	Yield bales/ha*	IWUE bales/ML
2003	5.15	5.06	0.98
2004	5.95	5.22	0.88
2005	5.92	5.82	0.98
Average	**5.67**	**5.37**	**0.95**

* Assumed one bale of cotton has a mass of 220 kg

Howell et al. (1987) looked at furrow and trickle irrigation for cotton cultivation in San Joaquin Valley in California. Seed-lint yields ranged from 601 to 2145 kg/ha which is equivalent to 2.73-9.75 bales/ha. The authors state that the yields at the upper end of the scale were unusually high for that area, with average yields at San Joaquin being approximately 5.45 bales/ha. These yields are lower than the yields reported for Australia from for all the time periods listed in Table 3. The average IWUI for this study was 0.292 kg/m^3 or 1.33 bales/ML. This is similar to the average IWUI reported for Australia (Table 3).

The study by Chapagain and Hoekstra (2004) reported on yield and water use in different countries. This data was used by Payero and Harris (2008) to obtain an estimate for the average IWUI for the main cotton producing countries. This study found that Australia had the third highest IWUI value after China and Israel.

The IWUI relates total production to the amount of irrigation water supplied only. Therefore, it is highly dependent on rainfall – the higher the fraction of rainfall used by the crop, the lower the irrigation water needed. Therefore, if data is compared from two seasons, the results can be skewed negatively for one data set if the season had been very dry. This would result in a higher proportion of irrigation water use. Therefore, care should be taken when comparing IWUI's from different countries and time periods, as this indicator may not be meaningful in some cases.

Zwart and Bastiaanssen (2004) describe crop water productivity (CWP) for four different crops including cotton. CWP is found by dividing the marketable crop yield (kg/ha) by the crop water consumption by evapotranspiration (m^3/ha). It is directly comparable to the Crop Water Use Index (CWUI). Zwart and Bastiaanssen (2004) reviewed 16 literature sources from nine different countries in order to determine the CWUI for cotton lint. CWUI was found to range between 0.62 bales/ML for Texas, USA to 4.67 bales/ML in Uzbekistan, with an average of 1.51 bales/ML. The value determined for Australia was 1.06 bales/ML. However, the more recent study by Montgomery and Bray (2010) determined that the average Australian CWUI is 1.41 bales/ML, which is similar to the average. It should be noted that CWUI values are highly variable due to variations in net irrigation requirements, yield potentials, crop management in different locations and growing seasons.

One of the most meaningful water use indicators for comparing water between countries and across seasons, is the GPWUI. This indicator accounts for the total amount of water (irrigation water, rainfall and soil stored moisture) used for total cotton production. Tennakoon and Milroy (2003) reported on water use and irrigation efficiencies for the Australian cotton industry. Data from 25 cotton farms was used from the six largest cotton production areas in Australia. The GPWUI averaged 0.76 bales/ML of total water. The later study by Montgomery and Bray (2010) determined that the average GPWUI for the Australian cotton industry for the 2008/2009 season was 1.14 bales/ML (range 0.64-1.58 bales/ML). This study used data from 46 irrigated cotton farms during the 2008/09 season for a benchmarking study. This study determined that the Australian GPWUI had improved by around 40% since the study by Tennakoon and Milroy (2003) was carried out. Hence, not only have cotton yields improved steadily in Australia, but water use efficiency has also improved per unit of production.

Payero and Harris (2008) collated information on the water use efficiency reported by several international studies so as to compare the efficiency of Australian cotton production. Table 5 shows the GPWUI reported by three international and two Australian studies. New (2005) uses a dataset from farmer's fields in Texas, USA. The data was based on cotton production between 1998 and 2005. The average yields are 5.0 bales/ha which is considerably lower than the Australian yields reported in Table 3. The average GPWUI reported was 0.86 bales/ML which is again lower than that reported by Montgomery and Bray (2010). Wanjura et al. (2002) examines water use in Texas cotton production from 1988 to 1999. As with New (2005), this study reports lower yields than Australian cotton. However, the GPWUI is higher, as drip irrigation is used in this study as opposed to surface irrigation in the Australian studies. Drip irrigation is more efficient as it minimises evaporation and hence reduces total water use. Horst et al. (2007) is based on research plots in Uzbekistan. The GPWUI is significantly higher than that reported by the Australian studies. The Australian studies were based on commercial farms. The results may be lower because of the inherent reduction in control of system conditions as compared to research trials.

TABLE 5 – COMPARISON OF INTERNATIONAL AND AUSTRALIAN GPWUI (PAYERO AND HARRIS (2008))

GPWUI bales/ML	Location	Reference
0.76	**Australia**	**Tennakoon and Milroy (2003)**
0.86	Texas, USA	New (2005)
1.14	**Australia**	**Montgomery and Bray (2009)**
1.16	Texas, USA	Wanjura et al. (2002)
1.90	Uzbekistan	Horst et al. (2007)

Australian irrigation water use efficiency is relatively high in a global context, with just China and Israel having higher indices. The most recent study on the Australian GPWUI found that it is similar or higher to cotton production in Texas, USA, but significantly lower than Uzbekistan production. However, in general Australian water use efficiency is better than the global average, with relatively high efficiency indicators resulting in higher production from the same water resources, which is of direct benefit to water users.

5. WATER INVENTORY AND IMPACT ASSESSMENT METHODOLOGIES IN LCA

5.1.1. INVENTORY METHODS

Inventory methods in LCA are closely linked to impact assessment. The key limitation to conducting a water balance or water footprint (both essentially inventory methods) is that neither give a clear indication of what impact will be caused by the water use activity. Inventory development in LCA has therefore focussed on refining the definitions of water use and determining what additional information is required to assess the impact of water use. The definition is to distinguish between freshwater and saline water. Because global freshwater reserves are limited and subject to pressure, this is the focus of all investigations.

Water in LCA can be classified using the standard classification for abiotic resources, based on the regeneration potential. The three main types of freshwater resources thus classified include deposits, funds and flows (Koehler 2008).

Freshwater deposits represent:

- Non-replenishing groundwater **stocks** (which are finite resources) and are only very slightly replenished during the lifetime of a human
- **Funds**, which may be characterised as sub-artesian groundwater supplies, lakes or dams (exhaustible resources), which are naturally replenished as long as they are not irreversibly impaired
- **Flows,** which refer to streams and rivers (non-exhaustible in principle).

In addition to describing the source type, the term ‘use’ requires clarification. Owens (2002) provided a number of different classifications to differentiate between consumptive and non-consumptive uses, and between uses that result in depletion. These are:

- **Water use** – water is used off-stream and is then released to the original river basin (downstream users are *not* deprived of any water volume)
- **Water consumption** or consumptive use – Off-stream water use where water release or return does not occur (i.e. evaporation from a storage, transpiration from crop production)
- **Water depletion** – Withdrawal from a water source that is not replenished or recharged (i.e. a water deposit).

Building on these definitions, Owens presents five water use and water depletion indicators:

- In-stream water use indicator (i.e. the quantity of water used for hydro-electric power generation)
- In-stream water consumption indicator (i.e. evaporative losses from storages and canals in excess of unrestricted river losses)

- Off-stream water use indicator (i.e. surface withdrawals from sustainable sources that are returned to the original basins and groundwater withdrawn from sustainably recharged aquifers and returned to surface waters)
- Off-stream water consumption indicator (i.e. evaporative losses and other conveyance losses, and transfers to another river basin)
- Off-stream water depletion indicator (i.e. withdrawals from overdrawn, unreplenished groundwater sources.

For agriculture, most extracted water represents a consumptive use, as it will be either evaporated, transpired, lost in conveyance or incorporated into a product and removed from the catchment. Water depletion may also be relevant for agricultural systems that withdraw water from the Great Artesian Basin (GAB), which may be classified as an unreplenished source. Owens represents one of the founding methodologies presented in the field of LCA.

Owens (2002) also presents a range of potential indicators for water quality, but does not detail impact categories for human health or ecosystems.

Bayart et al. (2010) provided a detailed framework for assessing water use in LCA at the inventory and impact assessment level. Their study proposed two categories of fresh water use:

1. Freshwater degradative use (water that is returned to the same catchment from which it was used, but with altered water quality)
2. Freshwater consumptive use (water that is not returned to the same catchment because it is evaporated, integrated into a product or discharged into a different catchment or the sea).

The authors consider both categories to be relevant for in-stream and off-stream uses. In-stream consumptive uses include evaporation losses from government managed water supplies, which will be relevant to an industry such as cotton.

Bayart et al. (2010) also differentiate between "competition for fresh water use" and "freshwater depletion" in the following way. Competition for fresh water use refers to the situation where availability is temporarily reduced for current uses. Depletion refers to the situation where the amount of freshwater in a watershed and/or fossil groundwater is reduced. Depletion is said to occur when the rate of consumptive use exceeds the renewability rate over an extended period of time.

In order to differentiate water use using the above categories, Bayart et al. (2010) recommend that a water balance is used to populate the inventory. The balance should also distinguish resource type (i.e. groundwater, surface water) and water quality. Mila I Canals et al. (2009) likewise advocates determining consumptive water uses and water returns to ecosystems using a water balance.

Water quality is an important consideration in agricultural systems, particularly for discharge water. Bayart et al. (2010) did not investigate water quality in depth, but did note that two approaches could be used; i) quality could be assessed using a 'distance-to-target' approach, or ii) a functionality approach could be taken.

The distance-to-target approach would investigate the equivalent effort necessary to process a water output to the same quality as the water input. This could take into account additional water required to dilute nutrient levels to acceptable (i.e. river health) levels prior to release. Alternatively, it could take into account the energy required to purify a resource to the same quality. The 'functionality' approach is a means by which quality categories are established and water use is defined in terms of the water category for inputs and outputs.

These recommendations are comprehensive and logical, and provide a robust framework for developing water use inventories. However, there are no examples yet provided for Australian agricultural products that use these classifications.

An additional component of the inventory is the relationship between land use and water availability. When assessing the impact of an agricultural system, it is important to identify whether the system alters the flow of runoff to the environment as this is a component of water use. Milà i Canals et al. (2009) proposes a method whereby the difference in evapotranspiration between the system investigated and a reference system (i.e. natural vegetation) is used to determine the effect of the system on the water balance. Where a system evapo-transpires more water than the reference system, this results in additional water use that is attributable to the product grown on that land. Likewise, if a production system utilised less water than the reference system (as is often the case in Australia) a negative flow (or credit) may be applied.

Consumptive freshwater use – This is water use where water release or return does not occur as it is either evaporated, transpired, lost in conveyance or incorporated into a product.

Non-consumptive freshwater use – This is water that is withdrawn and used off-stream but is then released to the original catchment area. However, it may have altered water quality after release.

5.1.2. IMPACT ASSESSMENT METHODS

The greatest contribution from the field of LCA to discussions on water use is the inclusion of an impact assessment in addition to reporting volumetric water use. Put simply, the '*the more you use, the worse you are*' principle is not universally applicable comparison of water use between different catchments. It is the impact of that water use in the catchment that really matters.

There is a considerable amount of methodology development underway to develop characterisation factors suitable for assessing the impact of water use, and two methods are operational for making such an assessment. Bayart et al. (2010) identify three elements that need to be considered in the impact assessment:

i. the sufficiency of freshwater resources for contemporary human users
ii. the sufficiency of freshwater resources for existing ecosystems
iii. sustainable freshwater resource base for future generations and the future use of present day generations.

Based on this, these authors recommend mid-point indicators for each category, measured in terms of 'cubic meters of freshwater equivalent'. Equivalence factors were not provided but the authors recommend that these should be based on indicators such as resource type or freshwater quality. The three mid-point indicators are:

- 'Cubic meters of freshwater equivalent unavailable for downstream users'
- 'Cubic meters of freshwater equivalent unavailable for ecosystems'
- 'Cubic meters of freshwater equivalent depleted'.

Regarding discharge water, Bayart et al. (2010) suggest that characterisation factors or functionality indicators be applied. In contrast, Milà i Canals et al. (2009) suggest omitting discharge water from the impact assessment.

Bayart et al. (2010) adopt the general approach of applying some form of 'stress weighting' to the water use assessment, as recommended by both Milà i Canals et al. (2009) and Pfister et al. (2009). This means the impact assessment is based on 'water equivalents' rather than volumetric water use. The method proposed by Pfister et al. (2009) has been applied in Australia to beef production by Ridoutt et al. (2011) and to pork production by Wiedemann et al. (2012). Pfister et al. (2009) focussed on blue water only. They provided a regionalised water stress measure proposing a new mid-point category 'water deprivation'. Water deprivation is a measure of the water use (abstracted and evaporative water use, or 'water consumption') related to the degree of water stress within a catchment. The water stress index (WSI) is a measure of the balance of freshwater withdrawals to hydrological availability. Moderate and severe water stress occurs above a threshold of 20 and 40% respectively. Pfister et al. (2009) provide a global, regionally specified database of WSI values, making application of the method relatively easy. Pfister et al. (2009) also provided a case study of the method based on global cotton production.

Mila I Canals et al. (2009) provide an alternative impact method that also uses a stress weighting approach, but differs from Pfister et al. (2009) in the characterisation factors used. Mila I Canals et al. (2009) identify four impact pathways:

1. Direct water use leading to changes in freshwater availability for humans, leading to changes in human health
2. Direct water use leading to changes in freshwater availability for ecosystems, leading to effects on ecosystem quality (freshwater ecosystem impact, FEI)
3. Direct groundwater use causing reduced long-term freshwater availability (freshwater depletion, FD)
4. Land use changes leading to changes in the water cycle (infiltration and runoff) leading to changes in freshwater availability for ecosystems, leading to effects on ecosystem quality (FEI).

Interestingly, Mila I Canals et al. (2009) include both green and blue water at the inventory level, but do not consider green water as part of the impact assessment. A useful methodological addition provided by these authors is the inclusion of changes to water availability as a result of changed land use. A second paper Mila i Canals et al. (2010) provides a case study example of the method applied to broccoli production in Spain and the United Kingdom.

5.2. INTERACTIONS BETWEEN WATER USE AND OTHER ENVIRONMENTAL IMPACTS

One strength of LCA is its multi-impact assessment approach. No resource or environmental issue exists in isolation. Water use relates to many issues including energy use, eutrophication (nutrient release to waterways), land use and even greenhouse gas. This is particularly true when investigating the impacts of changing a system, because investigating multiple impacts will help to understand and avoid 'burden shifting' between impacts.

An example of burden shifting can be readily shown between water and energy/GHG. Global fresh water reserves are essentially unlimited, provided adequate energy is available to treat saline water sources. If an investigation into water stress mitigation strategies was undertaken, this interaction and trade-off between energy and fresh water resources would be critical in gaining a clear understanding of the issue. The focus on a single impact area has clear limitations both because of the risk of burden shifting, and because of the extend of what is classified as 'water use'.

For example, where the WF methodology includes 'grey' water, LCA considers the same impact (release of contaminants to waterways) with specific impact areas that deal with those groups of chemicals, rather than considering it through a 'water only' framework. Water footprinting uses the term 'grey water' to define the water required to assimilate these materials. This is very difficult to define however, and much more difficult to measure. Several problems exist with this approach; firstly, the source and solution to the problem relate to chemical and fertiliser management, not water management *per se*. Secondly, the definition and quantification of 'grey water' is highly dependent on the release point for the water, and specifically, what that water is intended to be used for. For example, if nitrate leaches into saline groundwater, should an amount of this saline groundwater be considered 'grey water' and attributed to the production system that released the nitrate? LCA methods address this issue in two ways; firstly by characterising the suitability of 'non-consumptive' water uses / releases, and secondly, by directly accounting for the release of contaminants using dedicated impact assessment areas (eutrophication, toxicity etc). This aims to provide direct information regarding the issue of concern rather than considering it as a 'water use'. The real impact of nitrates and phosphate relate to ecosystem health and possibly human health (in some specific instances). It seems most logical to address these issues directly rather than indirectly via water use.

Similarly, most LCA practitioners suggest that the green water concept should be incorporated in an assessment of land use, as these are not separable. Where interactions occur (such as the change in 'blue' water runoff because of land use changes) these can be incorporated into LCA both with respect to land use and water use, explaining the dynamic trade-offs and impacts on both areas. Indeed, changing land use can dramatically increase run-off (increasing blue water), though other trade-offs with land condition are likely.

A third interaction exists between water 'use' and biodiversity. Clearly, the maintenance of open water storages on cotton farms provide some ecosystem services, most notably to water birds. This has not been investigated in detail to the author's knowledge, but it is an area of importance for the cotton industry. It may be possible for a proportion of the 'water use' in the cotton industry to be explained with reference to positive biodiversity outcomes if suitable indicators could be identified. Currently there are few case studies and limited knowledge in this area, but there is certainly scope for methodological advancements to be made here.

5.3. LCA WATER USE STUDIES OF COTTON AND OTHER FIBRE PRODUCTS

Cotton is the most commonly produced natural fibre in the world and represents about 46% of the world textile market. By comparison, wool accounts for 3% and other natural fibres such as silk, hemp and mohair make up a small proportion of textiles (<1% each). Synthetic or man-made fibres make up 51% of the global textile market and this proportion is increasing (Roth 2010). Studies of cotton, polyester and wool were reviewed. Both cradle-to-grave and cradle-to-consumer studies were included. Cradle-to-grave studies include every stage of the supply chain from the production of the raw material through to disposal or recycling. Cradle-to-consumer studies encompass the production of the raw material through to the final garment assembly.

The studies used different methods of determining water use and had different functional units and system boundaries. Consequently, comparisons were difficult to make.

5.3.1. WATER IN COTTON LCA STUDIES

We reviewed each study with respect to several key elements (as identified in Section 5.1.1): method and transparency used in developing the inventory of water use, identification of the source and geographical location of water used. Water use indicators (such as use of consumptive and non-consumptive water) were reviewed, as were the impact assessment methods applied (if any). In this section we use the term "water use" as the generic term for the total water use of a system – this term encompasses both consumptive and non-consumptive water use. In addition to this, some reference material reported the water use of just the cotton production stage (i.e. cradle-to-farm-gate). A total of five studies were found that carried out LCAs for water use in cotton and these are discussed in the following sections.

Pfister et al. (2009) developed a method for determining the environmental impacts of freshwater consumption. A case study on consumptive water use of global cotton production was carried out in order to demonstrate the relative impact of consumptive water use. This study demonstrated the importance of using regionalised characterisation factors when investigating consumptive water use as the impacts vary greatly with geographic location. Pfister et al. (2009) used estimates of blue water use for crop production available from global inventories. These are readily available, albeit limited in their accuracy. Using these consumptive water use data, water deprivation was measured using the water stress index for the catchment in which production occurs. This provides an indication of the effect that production of a given product is having on actual water stress, rather than simply determining the consumptive water use.

Pfister et al. (2009) reported that consumptive water use for cotton in Australia (3.92 m^3/kg) was lower than water use for cotton production in Mali (4.07 m^3/kg). However, they showed that water deprivation in Australia (1.42 m^3/kg) was higher than Mali (0.99 m^3/kg). This shows the ability of the method to provide information on catchment-specific impacts as opposed to simply estimating total volumes of water used. As such, this is a major advancement in freshwater impact categories.

Two studies carried out a full cradle-to-grave life cycle assessment for cotton products; Cartwright et al. (2011) and Levi Straus & Co. (2009). The LCA by Levi Straus & Co. (2009)

used a functional unit of "one pair of Levi 501 jeans" which included a two-year use phase with 104 washes (once per week for two years). The consumptive water use data over the whole life cycle was collected from Levi Strauss & Co. suppliers and background data were supplied from LCA inventories. It is important to note that the cotton used for these jeans can come from a variety of different countries, resulting in a high degree of variability within the water consumption dataset.

This study found that the cotton production on farm accounted for 49% (equal to 1704 L/kg of jeans) of the total consumptive water use impacts for the full product life cycle. The total water consumption for the full life cycle of a pair of Levi 501 jeans was found to be 3481 L.

Cartwright et al. (2011) carried out a cradle-to-grave LCA for a shirt made of 65% polyester and 35% cotton with a mass of 227 g i.e. 79 g of cotton. During the use stage of the life cycle, it was assumed that there were 52 washings for the two-year lifespan of the product. The life cycle included disposal in landfill after the use phase. This study used a methodology that splits total water use into consumptive and non-consumptive fractions. The authors defined consumptive water use as water that is permanently removed from a system through the processes of transpiration or evaporation or integration into a product.

Similar to the findings of Levi Straus & Co. (2009), the on-farm cotton production phase used the majority of the consumptive water (54%). This is mainly due to water evapotraspiration during cotton production. The cotton production process consumed 210 L of water per shirt and non-consumptively used 90 L. This study determined that the shirt's use phase contributed to 72% of water use (consumptive and non-consumptive). The total water use for the shirt supply chain was 2729 L, of which, 17% (453 L) was consumptive and 83% (2276 L) was non-consumptive.

Kalliala & Nousiainen (1999) carried out a life cycle assessment to determine the environmental impact of producing a 100% cotton sheet for hotel textile services in Finland. This work focused on all of the life cycle stages up to and including the production of the cotton fabric. Literature sources were used to determine water use during cotton production. The water use of textile (fabric) production was based on meter readings and measurements from one Finnish textile manufacturing company converted to average values for the year 1996. The total water use for the full life cycle of the 100% cotton sheet (mass assumed to be 1 kg in the study) was found to be 26 100 L with approximately 85% (22 000 L) of this due to cotton production.

Cherrett et al. (2005) compared the water use for the production of five fibre types: polyester, conventional cotton, organic cotton, conventional hemp and organic hemp. With regards to conventional cotton, globally, it typically uses between 7000 and 29 000 L of water (averaging about 10 000 L) to grow one kilogram of cotton. This study also reports that between 30 and 200 L of water are needed to process one kilogram of woven or knitted dyed cotton fabric. This assessment provided a case study for cotton fabric imported into the UK and determined that 9758 L/kg cotton was used

Table 6 presents the water use for the five life cycle assessment studies focussed on in this review. Each of the functional units were changed to 1 kg of textile i.e. shirt or jean, to allow for ease of comparability between the studies. It should be noted that the results provided by Cartwright et al. (2011) are not comparable with the other studies, as the functional unit used is so different.

TABLE 6 – COTTON AND COTTON-MIX PRODUCT WATER USE– LCA STUDIES

Water use (L)	Consumptive or non consumptive water use	Measured Unit and scope	Water measurement methodology	Research location	Reference
3480.5	Only consumptive use reported	1 kg levi 501 Jean Cradle to grave – full life cycle	Inventory output	USA	Levi Straus & Co. (2009)
26 100	Both consumptive and non-consumptive water uses – however not differentiated in study	1 kg 100% cotton sheet Cradle to factory gate	Inventory output	Finland	Kalliala & Nousiainen (1999)
9758	Both consumptive and non-consumptive water uses – however not differentiated in study	1 kg cotton textile Cradle to factory gate	Inventory output	UK	Cherret et al. (2005)
3920	Only consumptive use reported	1 kg cotton textile Cradle to factory gate	LCA – provides water stress impacts	Study based in Switzerland but data specific to Australia	Pfister et al. 2009
12 018 (total)	Both consumptive and non-consumptive water uses 10 026 L (non-consumptive) 1992 L (consumptive)	**1 kg Shirt (65% polyester & 35% cotton)** Cradle to grave – full life cycle	Inventory output `	Western US	Cartwright et al. (2011)

Bayart et al. (2010) included an assessment of water use for cotton production in their study which focussed mainly on LCA methodology issues. The assessment included a case study of water use for cotton grown in Pakistan. This country produces 8.5% of the world's cotton and requires 25 000 L/kg cotton in irrigation water, though not all of this is represents consumptive use. 15 000 L/kg was determined to be degradative water use that is reduced in water quality. Bayart et al. (2010) highlighted that the water 'use' would be different depending on how the degradative portion of water use was classified. They advocate classing the water used and the water released by functionality. In this way, cotton could be said to use 25 000 L of water classed as 'functional for agriculture, domestic, and industrial' uses, and release 15 000 L water 'functional for agriculture, industrial, transport, and hydropower' (non-consumptive use). Net consumptive water use would be 10,000 L / kg cotton.

Table 7 shows the water use (L) for the production of 1 kg of raw cotton fibres. It was decided to report this as water consumption for raw cotton fibre production is important for LCA research. In addition to this, most of the literature did not use the same functional unit or system boundaries and so comparisons were more meaningful at this level.

TABLE 7 – TOTAL WATER USE FOR COTTON PRODUCTION (ON-FARM)

Water Use (L)	Consumptive or non consumptive water use	Measured Unit and Scope	Water measurement methodology	Research location	Reference
22 000	Both consumptive and non-consumptive water uses – however not differentiated in study	1 kg raw cotton fibres	Inventory output	Finland	Kalliala & Nousiainen (1999)
25 000	Both consumptive and non-consumptive water uses included. These were reported separately as 15 000 L (non-consumptive) and 10 000 L (consumptive) / kg product.	1 kg raw cotton fibres	Inventory output	Pakistan	Bayart et al. (2010)
1322	396 L (non- consumptive). 925 L (consumptive)	1 kg raw cotton fibres	Inventory output	Western US	Cartwright et al. (2011)
1704	Only consumptive use reported	1 kg raw cotton fibres	Inventory output	USA	Levi Straus & Co. (2009)
10 000 (Range: 7000-29 000 L)	Both consumptive and non-consumptive water uses – however not differentiated in study	1 kg raw cotton fibres	Inventory output	Global	Cherret et al. (2005)

The large water use reported by Kalliala & Nousiainen (1999) reflects the fact that both consumptive and non-consumptive water use may be encompassed in this volume. This total water use is similar to the use reported by Bayart et al. (2010) and the upper end of the water use range reported by.Cherret et al (2005). These results are much larger than those reported by Levi Straus & Co. (2009). This may be due to the fact that only consumptive water use is reported by Levi Straus & Co.

The only studies which classified water in a standardised manner were Cartwright et al. (2011), Pfister et al. (2009) and Bayart et al. (2010). Pfister et al. (2009) included an impact assessment method to interpret the consumptive water use data reported for cotton in two regions, and was the only study to apply a impact assessment method.

5.3.2. LCA WATER USE STUDIES FOR POLYESTER

Polyester is a polymer with the specific scientific name polyethylene terephthalate (PET). There are many processes involved in the production of polyester. These include the production of a resin from long chain hydrocarbons such as petroleum. To produce the fibres, the resin is heated and pushed through tiny holes under pressure in a spinneret. Figure 9 shows a flow chart for polyester production.

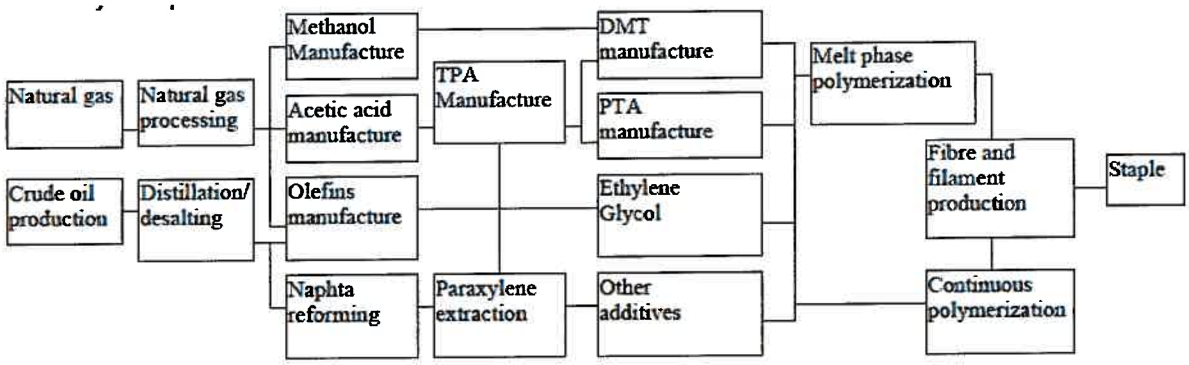


FIGURE 9 – POLYESTER PRODUCTION (KALLIALA & NOUSIAINEN 1999)

Only three LCA studies were found that considered water use. The LCA study by Kalliala & Nousiainen (1999) covered all of the life cycle stages up to and including polyester fibre production. The functional unit was 1 kg of polyester fibre and the data used for the study was based on literature references. The water use of textile (fabric) production was based on meter readings and measurements from one Finnish textile manufacturing company converted to average values for the year 1996. The study found that polyester has much lower water use (17.2 L/kg polyester fibre) than cotton fibre production.

Vink et al. (2003) used LCA to quantify the amount of water used in the production of polyester (PET AM – polyethylene terepthalate, amorphous (fibers and film grade) in their study). This study used data derived from the Association of Plastics Manufacturers of Europe (APME) that is based on ten years of published eco-profiles for polymers.

This study distinguished between cooling, process and irrigation water. The functional unit was 1 kg of PET AM fibres and the scope covers all the processes up to and including fibre production. This study found that the process of producing these fibres uses 25 L water/kg. This is similar to the results from Kalliala & Nousiainen (1999). The majority of the water use was associated with cooling (which is non-consumptive), while the remainder is process water. There was no impact assessment carried out for this study.

Cherrett et al. (2005) compared the water requirements for the production of five fibres types: polyester, conventional cotton, organic cotton, conventional hemp and organic hemp. The study assumed water use for polyester was minimal and didn't report a value.

The LCA report by Airdye Solutions (2009) studied the water consumption to produce 1 kg of coloured polyester at three different fabric weights (3.5 oz/m^2, 7.75 oz/m^2, and 12 oz/m^2). This cradle-to-consumer study investigates all the stages of production from the manufacture of raw materials up to the final dyeing process. The total consumptive water requirement per kg of fabric was 300 L. This is considerably more than that reported by Kalliala & Nousiainen (1999) and Vink et al.(2003). This can be explained by the fact that this study took into account the dyeing process which consumes a significant amount of water, while the other two did not. As was the case with the studies by Kalliala & Nousiainen (1999) and Vink et al.(2003), there is no water use impact assessment carried out for this study. Table 8 shows a summary of the polyester water use studies used in this report.

TABLE 8 – POLYESTER WATER USE IN LCA STUDIES

Water use (L)	Consumptive or non consumptive water use	Measured Unit and scope	Water measurement methodology	Research location	Reference
17.2	Both consumptive and non-consumptive water uses – however not differentiated in study	1 kg polyester fibre Cradle to factory gate	Inventory output	Finland	Kalliala & Nousianinen 1999
25	Both consumptive and non-consumptive water uses – however not differentiated in study	1 kg PET AM fibre Cradle to factory gate	Inventory output	The Netherlands and the U.S.	Vink et al. 2003
300	Only consumptive use reported	1 kg coloured polyester at three different fabric weights (3.5 oz/m^2, 7.75 oz/m^2, and 12 oz/m^2). Cradle to factory gate	Inventory output	Data based on information from ten European colouration facilities (five in Italy and five in Belgium) in 2002.	Airdye Solutions (2009)

5.3.3. WATER USE IN WOOL PRODUCTION

Only one wool production study was identified that included water use, by Brent & Hietkamp (2003). The remaining studies focussed on GHG emissions and/or energy use only. Brent & Hietkamp (2003) determined the water use for 1 kg of dyed two-fold wool yarn produced in South Africa. The data used was collected from South African literature and international publications. This cradle-to-grave study investigated all of the impacts of wool production excluding consumer use and disposal.

In general, the main contributions to water use for wool are the on-farm phase and the use phase. In addition to this, the mills used to produce the woollen fabric may have a high water use. On the farm, the main water inputs are drinking water and the production of nitrogenous fertilisers. Quantifying water use for wool production is difficult due to the lack of reliable data for the on-farm phase and drinking data for sheep. In addition to this, production is typically reliant on creek or farm dam water storages and water use is seldom quantified.

The drinking water at the farm, wastewater from the scouring and shrink-resist processes and the wastewater effluent from the dyeing process were all included within the boundaries of the system. The study found that the total extracted water use per functional unit is 519.4 L. Approximately 15% of this total was attributed to the wool processing, while the remainder is attributed to wool production (on-farm). There was no water use impact assessment method applied.

6. COMPARISON OF WATER ASSESSMENT METHODOLOGIES

Traditionally, water has been considered by applying water inventory definitions and principles. However, the introduction of the virtual water and water footprint concepts represents a new paradigm in considering water use, which has shifted the focus in several ways. Firstly, water footprinting is generally done at a broad scale rather than locally. Secondly, it is focussed on a product (i.e. a kilogram of cotton), not a system (i.e. a cotton farm or farming region). Thirdly, it includes not only irrigation water (blue water) but also rainfall (green water), which traditionally has not been included in discussions of water use. The introduction of water footprinting, while useful in a narrow context, can also be misleading. In particular, the connection between water footprint and water scarcity and environmental impact is weak. Therefore, water footprint results cannot be used to comment on these issues.

Water inventory methods are very useful in the context of irrigation system design and efficiency. However, this approach can only be used at one stage in the supply chain at a time (i.e. one water balance for the farm, another for the cotton gin etc) and are not generally intended for tracking the impacts of a product throughout the supply chain. Water inventories can provide very detailed inventory data but do not provide insight into the consequences of using water (the impact) on either the environment or on humans beyond a simple assessment of 'total volume of water used'.

On review and comparison of these methods, the authors felt LCA to be the most robust and useful method for conducting supply chain water use assessments in the Australian cotton industry. The reasons for this were:

vi) State-of-the-art LCA research specifies the use of a detailed water balance to identify flows of water at each stage in the supply chain. This is a robust approach for quantifying water use in cotton production. Data are readily available and results can be communicated easily with the industry and the consumer.

vii) LCA has a robust methodology and framework for handling water 'uses' such as green water and grey water. This may be done excluding these from the impact assessment and including additional impact assessment methods that deal directly with the issue of concern (such as contaminant release). This results in a more readily understandable and meaningful result.

viii) Taking point ii) into account, LCA is able to include green and grey water use at the inventory level in order to provide a comparable result with a WF method *if this is desired.*

ix) Impact assessment methods are available in LCA that can quantify not only the total water used, but also the impact of using this water on either the environment or on other competitive users. This is an important advance on the water footprint method.

x) LCA is able to incorporate additional impact assessment areas such as energy use and GHG emissions to provide a broader assessment.

Table 9 provides a comparison of the three broad approaches to water assessment and the strengths and weaknesses of each approach.

TABLE 9 – COMPARISON OF THE WATER INVENTORY, VIRTUAL WATER AND LCA APPROACHES

	Water Inventory		Virtual Water and Water Footprinting		Life Cycle Assessment	
	Strengths	**Weaknesses**	**Strengths**	**Weaknesses**	**Strengths**	**Weaknesses**
Inventory Methodology	Strong set of quantifiable definitions and methods within a limited scope.	Time consuming to generate and reliant on either detailed experimental work or numerous assumptions.	Able to identify where trading products between countries can reduce local water use impacts by balancing blue/green water sources.	Ongoing lack of consensus regarding methodologies. Inclusion of grey water introduces another set of variables related to chemicals and pesticides rather than water use.	Inventory method can be modified depending on the goal of the study (from broad to very detailed). Detailed methods rely on water balances with full differentiation of blue and green water and also factors that contribute to the impact of water use.	LCA is not proscriptive in specifying inventory methods so there is a wide range in the detail provided from one study to the next.
Detail of assessment	This is the standard framework for irrigation management and water use efficiency. Able to identify water loss pathways and offer mitigation options at the farm level.	Site specific nature of the data collection and modelling may limit usefulness of the results at a broader scale unless this objective is specified – then catchment scale approaches may be applied.	Able to provide rapid global assessments that may be useful for water stressed economies and regions.	Retrospective methodology based on consumption requirements . Not generally aimed at providing detailed results, or identifying inefficiencies in the production system.	Full supply chain analysed through to a set end point (i.e. farm gate, processor gate, garment use and end life etc). Detail is dependent on the goal and scope of the study. LCA can be done at a detailed level based on actual farm data if specified.	Non-proscriptive approach regarding detail means that LCA studies are variable and must be carefully defined goal and scope to ensure the correct data are collected.

	Water Inventory		Virtual Water and Water Footprinting		Life Cycle Assessment	
	Strengths	**Weaknesses**	**Strengths**	**Weaknesses**	**Strengths**	**Weaknesses**
Ability to communicate to general public and government	Widely understood and robust method which can be readily compared with commonly reported water use data from the ABS. Comparable to the common understanding of water use by the general public, and fits with the working definitions used in government policy and initiatives.	Some ambiguity exists in the term 'water use' (can be based on inputs or outputs from a water balance). A water balance does not generally report water use 'per unit of product' and is not often applied across a diverse supply chain.	Findings are catchy and attract media attention – the water footprint concept is easy to grasp at the product level and is fairly well recognised.	Can be grossly misleading. Water 'use' is not comparable to the concept of water that the public have in their mind (which is blue water).	LCA is able to present results at an inventory level (i.e. volumetric water use) and for the *impact* of water use, which is a strong advantage compared to either a water engineering or water footprint approach.	LCA methods are not always well understood and can be complicated if not communicated well. Some methods are broad (i.e. globally applicable) and these may be difficult to interpret at a local level without adding to the complexity of the study.
Water resource assessment	Able to determine accurately the use of blue water in a system.	May or may not separately quantify the soil moisture (green water) from rainfall.	Quantifies the total water required in different countries regardless of source type. Rapid assessment possible.	Ambiguous when blue, green and grey water are not presented separately.	Does differentiate between blue and green water use, and quantifies the *impact* of blue water use.	Can be difficult to source detailed data for all stages of the supply chain and can be time consuming to conduct.
Usefulness as an environmental indicator	Can be used at the farm or catchment level to determine flows that influence the environment, i.e. water abstractions, evaporative uses, seepage and deep drainage etc. Can be used at the catchment scale to balance needs between competing users.	Does not actually determine the environmental impacts, or likely impacts of water use at a specified level, i.e. it 'just presents the facts'.	Not the primary original intent of the tool. Can be used in water stressed economies to reduce pressure on local water supply through importation of water intensive products.	This tool is not well suited to considering environmental impacts, particularly where blue, green and grey water use are combined. Extrapolating such results to draw conclusions about environmental impacts from a production system is misleading.	This is the major strength of LCA. A framework and functional methods are available to quantify the impact of water use on the environment based on assessment of water stress and other indicators. LCA can also account for other impacts in addition to water.	Research in this area is still underway and methods are expected to continue to improve over time – the 'state of the art' has not yet been reached or widely agreed on in this area.

7. RELEVANCE OF SUPPLY CHAIN WATER ASSESSMENTS

Water scarcity is a growing issue worldwide, and is the subject of a growing body of research. With a growing human population, it follows that stress on water reserves will increase dramatically in the next 30-40 years (Rockström et al. 2007). It is estimated that by 2050, as much as 59% of the world's population may face shortages of blue water and 36% will face shortages of blue and green water combined (Rockström et al. 2009). As in other parts of the world, the vast majority of water resources in Australia are used for agriculture (for 65-70% of water use nation-wide, ABS 2006). While Australia does have adequate water resources nation-wide, demand is very high in some regions and not others. Water allocation and use is a topic of political and social discussion and is therefore an issue that will need to be addressed both at the industry level and possibly at the product level for cotton products.

Water use is an important issue for the cotton industry at the farm level. However, less attention has been given to water use throughout the supply chain for the product. Supply chain water use research has rapidly developed in the past five years and a number of methods have been used to quantify water use for Australian livestock and plant products. Studies have been commissioned by all major livestock species (beef, lamb, pork, chicken meat, eggs, dairy) and some research has been done for cereal grain production. The drivers for this research have been two-fold;

- To assist the industries in understanding the true impact of their water use on the environment and other competitive users throughout the whole production supply chain.
- To provide credible data that provides an alternative view to the published water footprint / virtual water results that have been quoted widely in the media.

Similar drivers are expected to exist for the cotton industry either now or in the near future. The industry is in a position to benefit from the preceding research and methodology development done in Australia and internationally.

In addition to industry led research, a number of interest groups and international government led initiatives have commissioned supply chain water research. Much of this work has used some form of water footprinting or virtual water, with different degrees of rigour and transparency. Some of the drivers for this research include; informing national policy regarding the management of scarce water resources, environmental concerns related to water scarcity, food security concerns related to water scarcity, human health and welfare concerns related to water scarcity.

Internationally, the following groups have been active in commissioning supply chain water assessments:

- The United Nations Educational, Scientific and Cultural Organisation (UNESCO-IHE).
- Waterwise (A United Kingdom not-for-profit organisation specifically chartered with the goal of reducing water consumption, including from supply chain sources).
- The International Water Management Institute – a branch of the Consultative Group on International Agricultural Research (CGIAR).

- The Food and Agriculture Organisation (FAO).
- The World Wildlife Fund (WWF).

Research funding from the UNESCO-IHE has been instrumental in developing the water footprint concept, which has largely focussed on identifying concerns around water scarcity and global food / fibre trade. To date, the water footprint of most globally significant trade products (including cotton) have been quantified, as have the 'water footprints' of most of the world's major economies.

At the company / brand level, a number of cotton product companies have conducted supply chain water analyses. The most notable of these is Levi Straus & Co. The aim of these studies was to determine the water use of their product and find where the largest consumptive uses lay, in order to become more water use efficient. For example, Levi Straus & Co used their study to show that if jeans are washed every two weeks as opposed to every week, consumers can decrease their water consumption by 23%, while reducing washings to once a month reduces water consumption by 35%.

Several other multi-national companies have engaged in water assessment research. For example, Coca-Cola conducted water footprint assessments for a 0.5 L bottle of Coca-Cola (in a PET bottle). The company has the aim of becoming a water-sustainable business on a global scale (The Nature Conservancy 2010). Similar to Levi Strauss & Co, the aim of this study was to determine the water use of its operations, in order to assess the water risks facing the business. This resulted in the development of water protection plans which have to put into action at all plants by 2013.

Warsen et al. (2011) conducted a study to determine the freshwater use of three Volkswagen models (Polo, Golf and Passat) throughout the product lifecycle. The aim of this study was to determine and compare the water use of the three products and find where the largest consumptive uses lay, in order to become more water use efficient.

The presence of groups such as the Water Footprint Network ensure that issues related to water scarcity and water trade with products will continue to be on the agenda for industries and companies alike.

8. CONCLUSIONS

Water use is an important economic, social and environmental issue for Australia in general and the cotton industry in particular. The Australian cotton industry is among the world leaders in yield and fibre quality, and yields have increased steadily over the past 20 years. In recent years, the industry has proactively improved the management of its water resources. It has invested substantial resources in research and extension programs expected to improve the cotton produced per unit of water input. However, less attention has been placed on supply chain water assessment, or investigating the water use for a cotton product.

This review found the term 'water use' to be ambiguous and highly dependent on definitions. Traditionally, water use in agriculture has meant the volume of water extracted for use (broadly consistent with terms used in water engineering and by the ABS). However, since the introduction of the concepts of virtual water and water footprinting beginning in the late 1990's, there has been a shift in the focus of the discussion. Water footprinting includes irrigation (blue water), stored moisture from rainfall (green water) and water used to assimilate contaminants released by a production system (grey water). Consequently, the whole nature of the discussion is changed. Life cycle assessment has also been used to provide supply chain water analyses, and recent methodological advances have provided a useful, robust framework for assessing water use and the impact of water use throughout a supply chain.

The comparison of water methods presented in this report highlighted the strength of the LCA approach for assessing water use in cotton. LCA is well suited to drawing information from water use inventories determined using site specific water balances and can extend the interpretation of water use beyond a simple assessment of the total volume used, to the impacts of this use. Most advances in LCA water methodology have been made in the last three years. Hence, few of the studies reviewed used the state-of-the-art methods. However, other Australian industries such as beef cattle and pork have conducted detailed water assessments with LCA, including the use of the impact assessment method 'stress weighted water use'. This method is useful for defining the impact of water use on competitive users and the environment. LCA is an approach that can provide both insights to the industry and information to inform retailers, consumers and the general public as required. The advances in LCA methodology and the availability of detailed water inventory data for the cotton industry mean that an Australian LCA focussed on water use is achievable and timely. LCA research may focus on a single issue such as water use, however one of it's main strengths lies in multi-impact assessment. Water footprinting includes several other factors such as the issue of contaminant release in their approach to water use. The authors consider this to be less useful than a direct investigation of eutrophication of toxicity. A broader analysis of impact areas would also highlight some potential benefits, such as the benefits to biodiversity provided by cotton water storages. While not advanced, this would be an interesting and valuable methodological advance that could be made using LCA.

An analysis of groups applying supply chain water use assessments showed a range of interest groups and drivers for this type of work. In Australia, a considerable amount of research has been funded by the livestock industries in this area using LCA. Internationally, several inter-governmental research groups including the UNESCO-IHE and CGIAR have been active in commissioning supply chain water assessments. Several large multi-national companies, as diverse as Coca-Cola and Volkswagon have commissioned such assessments as a means of reducing water use impacts throughout their supply chains. For cotton, the iconic Levi Straus & Co have commissioned research in this field using LCA as the research framework. Considering almost all research has been commissioned in the past eight years, this is an indication of rapid growth and widespread interest in the topic. Interest groups and NGOs have contributed to this debate, though not the methods of research and rigour of assessment have not always been a strength of such efforts.

As a water consuming industry, it is in the interests of the cotton industry to understand supply chain water use for a number of strategic reasons. The following is a non-exhaustive summary:

- To ensure the industry has the most detailed understanding of their own system (both the positive and the negative aspects); i.e. to be 'information powerful'.
- To guide future research efforts (as needed) that go beyond the farm gate.
- To have methods and frameworks that will ensure interested groups or researchers conduct meaningful and accurate research.
- To understand the requirements of supply chain water use assessments, in order to inform later stages within the supply chain for cotton.
- As a tool (potentially) to communicate with consumers regarding the way they handle clothing and the impact they have on water use (i.e. via washing).

9. RECOMMENDATIONS

The key findings of this report relate to the comparison of supply chain water use assessments, the application of this work to cotton production internationally, the relevance of this work and the implications for the Australian cotton industry.

Based on these findings, we recommend that the industry commission a detailed supply chain water use assessment using state-of-the-art methods developed in the field of LCA. At the farm and catchment level, this study should be based on detailed water balance inventories. We recommend use the impact assessment method (stress weighted water use) developed by Pfister et al. (2009).

Regarding the system boundary; the industry may choose to limit the assessment to a 'farm gate' or processor gate study, or extend this to the consumer to investigate the (often substantial) impact of garment washing on total water use. Alternatively, a study could be commissioned to investigate the primary production system in detail, and literature values could be used to extend this through garment manufacture to the consumer.

Regarding the scope of the assessment; the an extensive database of water inventory data is available from FSA/ATC (2011). This is intended to form the basis for a detailed investigation. Farms in both Queensland and northern NSW were included in this study and will be included in the water use LCA. We also recommend including dryland cotton production (1-2 farms) into the assessment in order to provide a comparison and to provide a more comprehensive assessment of Australian cotton production.

Because of the prevalence of water footprinting analyses, we recommend that the industry include an assessment of 'green water' and 'grey water' at the inventory level for comparison. Additionally, we recommend the industry consider expanding the study to include additional impact categories relevant to water use, including:

- Eutrophication (i.e. nutritification)
- Land use (and the interaction between land use, water dynamics and both blue and green water).

Additionally, we recommend a preliminary investigation into the relationship between water use and positive biodiversity outcomes. This could include a review of the literature and (if available) application of relevant indicators to the cotton industry.

Lastly, we suggest the industry consider expanding the scope of the study to include impacts from greenhouse gas and energy use. This would allow a more robust assessment of interactions between environmental impacts and trade-offs that might exist. Additionally, it would expand the dataset currently available to the industry and advance the previous study commissioned by using a methodology that is more closely aligned with other publically available studies for agricultural products in Australia and internationally. Considering the data required are reasonably similar, this may be achieved in a cost effective manner during the water use study.

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