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# Technological change in the Australian irrigation industry: implications for future resource management and policy development

**Shahbaz Mushtaq and Tek N. Maraseni**

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Waterlines

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## Waterlines

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Authors: Shahbaz Mushtaq and Tek N. Maraseni

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# Abbreviations and acronyms

| | |
|---|---|
| BCR | benefit–cost ratio |
| BE | break-even |
| CPRS | Carbon Pollution Reduction Scheme |
| DCCEE | Department of Climate Change and Energy Efficiency |
| DEEDI | Department of Employment, Economic Development and Innovation |
| ETS | emissions trading scheme |
| GHG | greenhouse gas |
| IE | irrigation efficiency |
| IPCC | Intergovernmental Panel on Climate Change |
| IWE | irrigation water efficiency |
| IWUI | irrigation water use index |
| NPV | net present value |
| NSW | New South Wales |
| NT | Northern Territory |
| SA | South Australia |
| SDI | subsurface drip irrigation |
| USA | United States of America |
| WUE | water use efficiency |

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# Executive summary

The irrigation industry contributes significantly to the Australian economy. The irrigation sector has faced many challenges over the past decade including severe and prolonged drought, reduced water availability and ongoing reform of government water policies. At the same time, climate change and increasing climate variability are likely to increase the uncertainty of water supply. As a result, irrigated agriculture is under considerable pressure to adopt best practice methods to increase efficiency in terms of water use and productivity.

Until now, investment in innovative onfarm irrigation technologies has played a significant role in accommodating the reduction in agricultural water use, by increasing water use efficiencies and contributing to increases in the value of irrigated agriculture. Additional investments are needed to increase irrigation efficiency at the field, farm and irrigation-area scales to fill the supply and demand gap and ensure robust adaptation to climate change. To help fill the investment gap, the Australian Government is meeting the challenge of water scarcity and climate change through its Water for the Future initiative. A major component of this initiative is the $5.8 billion Sustainable Rural Water Use and Infrastructure Program that is helping to upgrade irrigation infrastructure and secure long-term water supply.

The conversion to pressurised systems is a valid option due to the potential increase in efficiency of pressurised systems and the subsequent water savings, but these new irrigation technologies will change the patterns of onfarm energy consumption and generate considerable greenhouse gas (GHG) emissions. If the Australian Government is successful in introducing a price on carbon, this may influence the extent to which new irrigation technologies are adopted.

This study explored the trade-offs between water savings, economics, energy consumption and GHG emissions, critical elements of both Water for the Future and any future price on carbon. We developed an integrated economic framework to assess the effectiveness of different irrigation technologies used at farm level. This framework was used to evaluate trade-offs between various choices of irrigation technology adoption in terms of irrigation requirements, water savings, energy consumption and GHG emissions and the relative costs of irrigation and associated equipment. The integrated framework has three main components: hydrological modelling, energy and GHG modelling, and cost and benefit estimation, and highlights trade-offs between energy consumption (and GHG emissions) and water savings at various levels of investment. We also applied the integrated framework to farm-level case studies and irrigation transformation scenarios. It is important to realise that there is unlikely to be just one ideal choice; there may be many alternatives, any one of which might be quite appropriate, depending on the priorities set by the individual farmers and governments.

## Crop-level modelling results

- The SWAP (soil–water–atmosphere–plant) model simulation results indicated that a range of water savings were possible. Water savings ranged from 0.1 to 1.3 megalitres per hectare (ML/ha) for different broadacre crops under sprinkler irrigation systems, and from 3.0 ML/ha for cotton to about 4.2 ML/ha for lucerne under drip irrigation systems. Overall, the simulation results indicated average water saving potential under sprinkler irrigation was about 24% for wheat, 29% for barley, 14% for maize, 18% for sorghum, 14% for lucerne and 18% for cotton. Similarly, average water saving potential under drip irrigation was about 25% for lucerne and 23% for cotton.

- Energy consumption and GHG emissions depend on the type of irrigation system, energy source (diesel or electricity) and water use. For example, lucerne requires large volumes of water and produces more GHGs under both drip and sprinkler irrigation systems.
- Assuming that surface irrigation systems ran on gravity and did not require energy, the results from energy and GHG modelling showed that, on average, centre-pivot irrigation systems using electric pumps would increase GHG emissions by 906 kilograms of carbon dioxide equivalent per megalitre (kg $CO_2$-e/ML) of irrigation water when compared with surface irrigation systems. Similarly, drip irrigation systems using electric pumps would increase GHG emissions by 568 kg $CO_2$-e/ML.
- Our results showed that drip irrigation systems required 28% less energy, depending on the scale and farming system, compared with centre-pivot and lateral-move systems. Similarly, drip irrigation produced around 25% less GHG emissions compared with centre-pivot and lateral-move sprinkler systems.
- The economic modelling indicated that, in general, conversion of irrigation technology could be economically viable for horticultural crops if water savings could be achieved and used to expand the area under irrigation. However, under average water saving conditions, sprinkler technology was not economically beneficial for most grain crops. Irrigation technology adoption on grain crops was an economically viable option when used with double cropping.
- Sensitivity analysis was performed for a range of parameters. Economic returns were found to be most sensitive to water savings, yield increases and labour savings. The sensitivity analysis for 50/50 water sharing, using permanent water trading pricing as a substitute for the water price, showed that farmers were better off using water savings on their land rather than trading water.
- The results indicated that a carbon price, for example $10 per tonne of carbon dioxide equivalent (t $CO_2$-e) on the increased GHG emissions would reduce economic returns. However, considering the benefits of technology adoption, the reduction was minimal. For example, conversion to a sprinkler irrigation system using electric motors would increase costs by $60/ha for cotton and by about $102/ha for lucerne.

We prepared five farm case studies to collect information on finer-scale farm-level variability and to inform the more generalised analyses of water and energy use, productivity and economics associated with the adoption of new irrigation technologies. All five case studies operate under the highly seasonal and variable climatic conditions typical of southern inland Queensland. New irrigation technologies provide greater control over water application rates and timing and are a critical component of risk management strategies on these properties. The benefits of new technologies as perceived by the farmers include:

- greater water use efficiency achieved by applying less water (volumes of water savings)
- flexibility in production systems
- increase in yield and quality of the produce
- better controlled water application (volume, frequency) to ensure timely application in response to crop requirements
- technology automation, allowing remote control of pumps and irrigation equipment and saving time and labour
- better application of crop additives (in particular fertilisers) over time through the irrigation system (fertigation)
- with better water application, reduced off-site risk in terms of nutrient leaching and/or run-off during rain periods

- labour savings, however this was often negated by the requirement for more highly-skilled (and expensive) labour to service the new technologies
- fewer machinery operations were generally noted for crops grown using new irrigation technologies.

Detailed hydrological modelling was only conducted for the lettuce crop. Instead farmers' estimates, which were close to the estimates obtained through simulation of SWAP models, were used in an integrated framework. The results from the integrated model are summarised below.

- All five case studies generated positive economic returns, mainly due to water savings, increased productivity and labour savings.
- Although new irrigation technologies required additional energy and consequently increased GHG emissions, changes in farm-level machinery and input uses could offset increases in GHG emissions. Four of the case studies showed that, overall, the adoption of new irrigation technology reduced GHG emissions. This was mainly due to the reduced use of inputs. In addition, the conversion of older, inefficient and energy-intensive sprinkler irrigation systems (hand shift and roll-line) to drip and efficient sprinkler irrigation technologies saved considerable energy (and reduced GHG emissions). This creates a win–win situation where water savings and GHG reductions can be achieved both as a result of technology adoption and farm-level input.
- The case study interviews provided feedback that farmers in the study region were not keen on permanent water trading or sharing through the government water sharing or buyback program. Evidence from the case studies indicated that expanded onfarm water use was a more economically efficient option than permanent trading, given the potential for yield increases, and labour and input savings. However, temporary water trading or seasonal water sharing for environmental purposes could be an option at a suitable water price where this is possible. In many cases, physical constraints on water transfers would not enable trade to occur.

We used three irrigation water transformation scenarios to evaluate industry-wide trade-offs between water savings, energy consumption (and GHG emissions), and economic returns associated with irrigation technology transformation. For the scenario simulation, farm-level changes in the form of inputs and machinery used were not modelled. Two of the three scenarios showed trade-offs between water savings and GHG emissions. For example, 120 GL of water savings through conversion of surface irrigation system to drip irrigation for cotton cropping would increase energy consumption by 889 terajoules (TJ) and GHG emissions by 250 000 t $CO_2$-e. On the other hand, the conversion of portable and hose sprinkler irrigation systems to drip and efficient sprinkler irrigation systems would save over 226 GL of water. Since portable and hose sprinkler irrigation are energy-intensive and labour-intensive systems, their replacement would be likely to result in energy savings, especially when they are replaced with drip irrigation systems; as a result, GHG emissions would be likely to decrease.

# 1. Introduction

The irrigation industry contributes significantly to the Australian economy. Nationally, irrigated agriculture provides approximately 50% of the value of production from less than 5% of the productive land area. The irrigation sector is struggling due to prolonged droughts that have caused considerable changes in water supplies, creating a considerable gap between the supply and demand for water. In addition to the stressors of climate variability and climate change, there is a growing awareness of the need to provide water for the environment by moving over-allocated systems back towards more sustainable levels. These combined factors are significantly reducing the water that is available for irrigation purposes.

Managing water more effectively is one of the most important and urgent challenges facing Australia. The agricultural sector is the largest consumer of water, consuming 65% of total water use in 2004–05 (ABS 2006a, 2008b). Due to reduced water availability in 2008–09, irrigating agricultural businesses in Australia applied 31% less irrigation water—equivalent to 7286 gigalitres (GL)—to agricultural land compared with water usage in 2004–05 (11 147 GL) (ABS 2010). Despite the reduction in water use, the gross value of irrigated agricultural production rose from an estimated $13.97 billion in 2000–01 (in 2005–06 dollars) to $14.99 billion in 2005–06 (Mackinnon et al. 2009).

Investment in onfarm irrigation technologies has played a significant role in accommodating the reduced availability of agricultural water, by increasing water use efficiencies (WUEs) and contributing to increases in the value of irrigated agricultural output per megalitre (ML) of water used (Mackinnon et al. 2009). Investments are needed to increase irrigation efficiency (IE) (the total water consumed by the crop divided by the total irrigation water applied) at the field, farm and irrigation area scales to address the supply and demand gap, thus ensuring sustainable farming enterprises.

Converting flood irrigation systems to more efficient pressurised systems has been heralded as an integral way of increasing Water Use Efficiency (WUE) (the crop yield per unit of irrigation water applied) and creating water savings in irrigation systems (Green et al. 1996; Zehnder et al. 2003; Lal 2004). Two-thirds of irrigators in the Murray–Darling Basin changed their water management practices during 2004–05 (ABS 2008c), and of these, 35% adopted more efficient irrigation techniques. Mackinnon et al. (2009) examined investment patterns of irrigated farms in the Murray–Darling Basin during 2006–07, and found that despite the effects of the drought on farm profitability, around 7% of irrigation farms made new investments in onfarm irrigation infrastructure during 2006–07. They suggested that investment patterns over this period were influenced by the extended drought conditions and widespread water scarcity, and that future climate change and ongoing water and environmental reforms would continue to play a part in driving investment decisions on irrigation farms.

Conventional irrigation practices are generally characterised by low WUEs, creating the potential for significant water savings that could result in either increased productivity or increased water availability for alternative uses (e.g. environmental flows to maintain ecosystem services). However, adverse economic and environmental consequences could result from water savings that increase energy consumption and greenhouse gas (GHG) emissions by agriculture.

The conversion to pressurised systems is a valid option due to the potential increase in efficiency of pressurised systems and the subsequent water savings (Baillie et al. 2007), but new irrigation technologies will change the patterns of onfarm energy consumption and generate considerable GHGs. The decision to invest in irrigation technology depends on two major factors: the water conservation benefits of the new technologies, and the costs associated with implementing technology change (Quereshi et al. 2001; Pratt Water 2004; Mackinnon et al. 2009). Other significant factors, such as increasing concerns to reduce energy dependency and reduce GHG emissions (Zillman et al. 2008), have been largely ignored in decision-making to adopt irrigation technology.

Irrigation is a primary consumer of energy on farms (Naylor 1996), and despite the water saving benefits due to the increased efficiency of pressurised irrigation systems (Phocaides 2001), these conversions will change the pattern of onfarm energy consumption. For example, delivering 10 ML of water needed by 1 hectare (ha) of irrigated corn from surface water sources requires 880 kilowatt hours (kWh) of fossil fuel (Batty and Keller 1980). In contrast, pumping groundwater from a depth of 100 metres (m) to irrigate the same 1 ha corn crop, the energy cost increases to 28 500 kWh, 32 times the cost of surface water (Gleick et al. 2002). Energy use by the agricultural sector depends on the amount of arable land and the level of mechanisation (Ozkan et al. 2004). Increasing the level of mechanisation by installing pressurised irrigation methods will affect the level of energy consumption, and has implications for production costs, energy infrastructure requirements and associated GHG emissions.

The potential change in onfarm energy use patterns is particularly important with the possible introduction of a carbon price through an emissions trading scheme (ETS), such as the Australian Government's proposed Carbon Pollution Reduction Scheme (CPRS). Through an ETS, the Government has proposed to make strong commitments to reduce Australia's carbon pollution levels. It has proposed to use an ETS as the basis for meeting Australia's commitment to reduce GHG emissions by between 5 and 25% below 2000 levels. However, an ETS poses significant social, economic, and environmental challenges for regional communities in Australia. Even if agriculture were excluded from a CPRS-style ETS, it would still be affect by changes in energy cost. At the time of writing this report, the Government's proposed CPRS had been suspended indefinitely.

Irrigation development brings considerable environmental change, but past expectations were that the economic and social benefits would be greater than the environmental costs. Considering the effects of climate change and the proposed implementation of policies such as an ETS, the perception of net economic and social benefits may now be invalid. It is imperative that the criteria used to assess the sustainability of agricultural systems reflect current issues (Lal 2004). It is therefore necessary to evaluate the consequences of changes to the irrigation industry in terms of water use, changes to energy requirements and economic effects. Methods to increase productivity by converting to pressurised irrigation methods must be considered in terms of water savings, economic considerations and energy consumption. Analysis of trade-offs between water efficiency and energy use in irrigated agriculture is critical to maintain the economic efficiency of agricultural production and minimise the environmental effects.

## 1.1 Aims and objectives

The main aim of the project was to use an integrated analysis to quantify the trade-offs between water savings, economic impact and energy consumption at field, farm and system level due to the technological change in the Australian irrigation industry.

Our detailed objectives were to:

- comprehensively review the potential of new irrigation technologies for increasing WUE, water productivity and economic efficiency
- estimate water savings for different crops under different soil and climatic condition using hydrological modelling

- evaluate the economics of new irrigation technologies, particularly using break-even (BE) analysis to calculate the BE water saving
- quantify the energy requirements and GHG emission resulting from new irrigation technologies that use surface and groundwater systems, using energy audit methods
- upscale integrated field-level analysis to develop various irrigation technology scenarios for determining the trade-offs between water savings, economic gains, energy consumption and GHG emissions
- make policy-level recommendations for the effective implementation of water and environmental reforms, particularly for any proposed carbon price.

## 1.2 Scope of the study

This study was funded as a fellowship project under National Water Commission's Raising National Water Standards Program. The project was funded for eight months with the project proposal limiting the integrated analysis to quantifying the trade-offs between water saving, economic impact and energy consumption at field, farm and system level as a result of technological change in the Australian irrigation industry. The focus of the study was the southern inland Queensland region with insights provided for the broader Australian irrigation industry through national water transformation scenarios using an integrated framework. The project did not evaluate improved management strategies for each irrigation system, rather evaluating changes from converting one system to another by introducing a new irrigation technology.

## 1.3 Outline of the report

Section 2 presents an overview of the Australian irrigation industry. Section 3 reviews the literature on irrigation system efficiencies (Australia and internationally), potential water savings, water use and energy efficiency, and the implications of a carbon price for agriculture, while section 4 describes the project methodology, trade-off analysis and its components: hydrological, energy and GHGs, and economic modelling. It also details the application of the integrated framework using field-, farm- and national-scale approaches. Section 5 provides empirical estimation of the range of water savings, energy consumption and GHG emissions as a result of new irrigation systems, and analyses of the economic viability of a new irrigation system at a range of water savings and carbon prices. Section 6 discusses technological change, water reforms and consequences, particularly regarding a carbon price. A discussion and recommendations are presented in section 7.

## 1.4 Overview of the Australian irrigation industry

### 1.4.1 Source of water

Across most of Australia, surface water—including water supplied by public and private irrigation schemes—remains the major source of water used for agricultural purposes. During 2008–09, surface water accounted for 63% (45.8 GL) of the all water used for agricultural purposes (Table 1). Groundwater accounted for 33% of water use, but the proportion of groundwater used has increased as a result of decreased surface water availability. During 2008–09, over 34% (24.9 GL) of the water used nationally was extracted from groundwater resources. Town or country reticulated mains supply and recycled or reused water from off-farm sources largely supplied the remainder of water used in agriculture over the 2004–2009 period.

During 2008–09, groundwater was the major source of water used for agricultural purposes in South Australia (SA) (62%) and the Northern Territory (NT) (80%), while surface water was the major source of water used for agricultural purposes in all other states and territories. In the Murray–Darling Basin, surface water was the major source of water used for agricultural purposes, totalling 2604 GL. This represented 70% of agricultural water use in the region and 57% of all surface water used for agricultural purposes nationally.

Table 1: Sources of agricultural water, 2004–05 to 2008–09

| *Source of agricultural water* | *2004–05* | *2005–06* | *2006–07* | *2008–09* |
|---|---|---|---|---|
| Water supplied by government or private irrigation schemes (ML) | na | na | 3 275 943 | 2 604 922 |
| Surface water (ML) | 7 906 737 | 8 996 546 | 2 256 927 | 1 976 082 |
| Groundwater (ML) | 2 459 836 | 2 391 845 | 2 740 011 | 2 490 346 |
| Town or country reticulated mains supply (ML) | 140 520 | 125 667 | 46 133 | 58 560 |
| Recycled or reused water from off-farm sources (ML) | 128 388 | 114 702 | 104 335 | 109 671 |
| Other (ML) | 47 272 | 60 032 | 98 078 | 46 053 |
| Total all sources (ML) | 10 682 753 | 11 688 792 | 8 521 427 | 7 285 634 |

Source: ABS (2005a,b, 2006a, 2008a,b, 2009, and 2010); 2007–08 detailed data is not available

## 1.4.2 Irrigation technology used on Australian farms

Farmers use a variety of irrigation techniques to apply water to their crops and pastures. An overview of onfarm irrigation water technology used in irrigated agriculture from 2002–03 to 2008–09 is shown in Table 2. Surface (i.e. furrow, basin or border check), drip or trickle and sprinkler systems (i.e. micro sprinklers, travelling guns, booms, centre-pivots, lateral-moves and solid set systems) were common. Detailed descriptions of the various types of irrigation technology used in Australian irrigation systems are given in Appendix A. Drip irrigation was the most common method of irrigation in Australia during 2008–09, when 11 401 (22.6%) of agricultural businesses used this method. Surface irrigation methods, such as border check and furrow, were the second most common, used by 16.5% of irrigating agricultural businesses during 2008–09.

Table 2: Number of establishments (sites) and irrigation methods in Australia, 2002–03 to 2008–09

| *Onfarm technology* | *2002–03* | | *2008–09* | | *Change (2002–03 to 2008–09)* | | | |
|---|---|---|---|---|---|---|---|---|
| | *Sites* | *Area ('000 ha)* | *Sites* | *Area ('000 ha)* | *Sites* | | *Area* | |
| | | | | | *No.* | *%* | *('000 ha)* | *%* |
| Surface | 12 970 | 1 344 | 7 674 | 804 | –5 296 | –40.8 | –540 | –40.2 |
| Drip or trickle (above ground) | 9 632 | 180 | 10 515 | 217 | 883 | 9.2 | 37 | 20.6 |
| Drip or trickle (subsurface) | 1 156 | 23 | 886 | 26 | –270 | –23.4 | 3 | 13.0 |
| Sprinkler - Micro spray | 6 469 | 80 | 5 915 | 85 | –554 | –8.6 | 5 | 6.3 |
| Sprinkler - Portable irrigators | 6 231 | 123 | 3 243 | 81 | –2 988 | –48.0 | –42 | –34.1 |
| Sprinkler - Hose irrigators | 8 122 | 289 | 5 515 | 214 | –2 607 | –32.1 | –75 | –26.0 |
| Sprinkler - Large mobile machines | 2 730 | 209 | 2 653 | 253 | –77 | –2.8 | 44 | 21.1 |
| Solid set | 5 487 | 91 | 2 921 | 51 | –2 566 | –46.8 | –40 | –44.0 |
| Other | 848 | 14 | 7 188 | 95 | 6 340 | 747.6 | 81 | 578.6 |
| Total | 53 645 | 2 353 | 46 510 | 1 826 | –7 135 | -13.3 | –527 | –22.4 |

Source: ABS (2006b, 2010)

Surface irrigation accounted for 44% of the total land area irrigated (ABS 2010). From 2002–03 to 2008–09, the area under surface irrigation decreased by 40%, mainly due to the overall reduction in irrigation area due to water shortages associated with drought conditions. Many establishments ceased irrigation altogether, with the greatest decline evident in the number of establishments (40.8%) and area (40.2%) under furrow irrigation. However, there is also evidence of significant adoption of more efficient irrigation technologies over this period. Between 2002–03 and 2008–09, the number of establishments irrigated by above-ground drip irrigation systems increased significantly (9.2%), as well as the area (20.5%). There was an overall decrease observed in the number of establishments and area under sprinkler irrigation systems, however this occurred predominantly in the older, less efficient portable and hose sprinkler irrigation systems. In contrast, there was a 21% increase in the area under large mobile sprinkler systems (Table 2).

The variability of irrigation water use from year to year mainly depends on rainfall, water availability and climatic conditions. Drought conditions and farmers' adjustments to crops and irrigation practices significantly affect crop area and production. Inherent flexibility in farming enterprises allows a shift from dryland or irrigated farming during dry or wet years. In 2008–09, Australian agricultural businesses applied 3% more irrigation water to agricultural land than in 2007–08, while the area irrigated decreased 5% to 1 761 000 ha (ABS 2009). However, the water use to agricultural land was 7.8% lower when compared with 2003–03 water use. Pasture for grazing accounted for the greatest amount of irrigated land (419,000 ha) in 2008–09, with the volume of irrigation water applied representing 21% of the national total (Table 3).

Table 3: Irrigated cropping area 2002–03 and 2008–09

| | *2002–03* | | *2008–09* | |
|---|---|---|---|---|
| | *Area irrigated ('000 ha)* | *Volume applied (GL)* | *Area irrigated ('000 ha)* | *Volume applied (GL)* |
| Pasture for grazing | 710 | 2 827 | 419 | 1 337 |
| Pasture for hay | 66 | 246 | 99 | 363 |
| Pasture for silage | 162 | 683 | 34 | 101 |
| Pasture for seed production | 32 | 139 | 40 | 180 |
| Cereal crops for hay | 66 | 246 | 23 | 57 |
| Cereal crops for grain or seed | 365 | 1 002 | 293 | 824 |
| Cereal crops not for grain, seed or hay | 42 | 127 | 25 | 54 |
| Rice | 44 | 615 | 7 | 101 |
| Sugar cane | 238 | 1 293 | 192 | 761 |
| Cotton | 234 | 1 526 | 142 | 880 |
| Other broadacre crops | 68 | 172 | 52 | 145 |
| Fruit trees, nut trees, plantation or berry fruits | 138 | 660 | 128 | 598 |
| Vegetables for human consumption | 112 | 439 | 100 | 420 |
| Vegetables for seed | 4 | 8 | 5 | 13 |
| Nurseries, cut flowers and cultivated turf | 13 | 78 | 13 | 65 |
| Grapevines | 150 | 589 | 172 | 543 |

Source ABS (2006b, 2009)

# 2. Literature review

Irrigation is a vital part of world agriculture, particularly in semi-arid and arid cropping areas. Potentially twice as productive as rainfed agriculture (Entry et al. 2002), it contributes significantly to global food production. Irrigated agriculture in Australia has faced many challenges over the past decade, including severe and prolonged drought, reduced water availability, fluctuations in commodity prices and ongoing reform of government water policies. As a result, managing uncertainty in water availability has been a key challenge for irrigators (Dale 2010). With global population growth comes pressure to further increase food production; at the same time, global climate change is likely to increase uncertainty about the security of water supply for irrigation. Growing competition for scarce water resources is likely to see the cost of water increase. As a result, irrigated agriculture is under considerable pressure to adopt best practice methods to increase WUE and productivity.

Conventional irrigation practices are generally characterised by low WUEs (Clemmens 1998; Robinson 2004), creating the potential for significant water savings (Green et al. 1996; Khan et al. 2004a). Widespread adoption of more efficient technology or management practices would result in significant water savings, which could help convert more land to irrigation. Alternatively, reduced onfarm water use would result in increased water availability for alternative uses (e.g. environmental flows to maintain ecosystem services) (Robinson 2004).

Investment in irrigation infrastructure and technologies—particularly those that reduce onfarm water use—have become a major focus of irrigation industry and government programs (McClintock 2009). Particular attention has been given to increasing the uptake of 'water saving' technologies among irrigators. However, potential uncertainly regarding water availability, water savings and the value of water influence investment decisions (Khan et al. 2010; McClintock 2009).

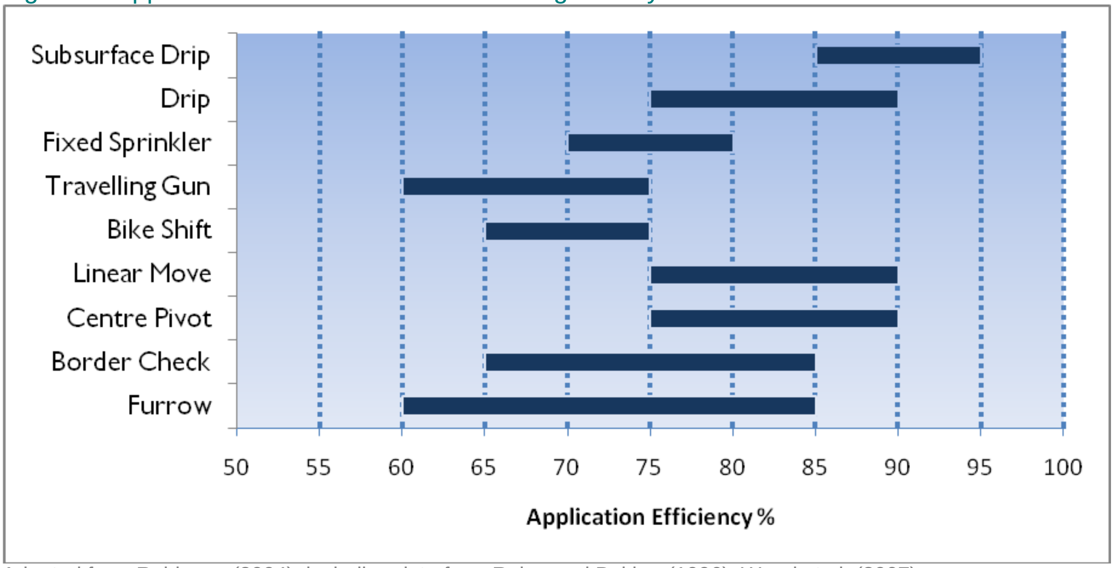
Furthermore, water savings achieved must be balanced against potential increases in energy consumption by agriculture, as well as environmental consequences, such as increased GHG emissions (Jackson 2009). Agriculture relies heavily on the use of fossil fuels. Given 'peak oil' predictions and the potential introduction of an ETS, current agricultural technologies and practices are likely to be increasingly challenged by higher energy costs (Foran 1998). Analysis of the trade-offs between water efficiency and energy use in irrigated agriculture is critical to maintaining the economic efficiency of agricultural production and minimising the environmental effects (Jackson 2009).

## 2.1 Comparing the efficiency of irrigation systems

### 2.1.1 Australia

System design and management can have a big affect on application efficiency. For example, a flood irrigation system using border check irrigation design, a sprinkler irrigation system using centre-pivot or linear move and a drip system can have the same level of application efficiency (Figure 1) depending on the system design and level of management. This has been demonstrated in farm trials in Victoria, where all components of the water balance were measured for flood and centre-pivot systems; both systems had an application efficiency of around 82% (Wood et al. 2007). This means that conversion from a flood irrigation system to a pressurised system may not deliver the expected increase in application efficiency if management is poor. However, as the percentile bands for sprinkler and drip systems are higher than for flood systems, the benefit of greater financial investment in a pressurised system is that it will be much less susceptible to water losses from poor management.

Figure 1: Application efficiencies for various irrigation systems




Adapted from Robinson (2004), including data from Raine and Bakker (1996), Wood et al. (2007)

Skewes and Meissner (1997) investigated IEs of pressurised systems (drip, undervine sprinklers, overhead sprinklers) for citrus and wine-grape production in the Riverland (SA) and Sunraysia (NSW, Victoria) districts. Efficiencies in these systems were 65–95% for citrus and 44–96% for wine grapes. The study identified that high IEs did not necessarily equate to high WUEs (i.e. using economic efficiency indicators such as gross return per ML).

Under experimental conditions, Wigginton and Raine (2001) found that the application efficiency for a travelling irrigator was 78% with a distribution uniformity of 76%. Solid set sprinklers increased the application efficiency to 90% but reduced the distribution uniformity to 43% (i.e. a quarter of the irrigated area had less than half of the average depth of water applied to the whole area), resulting in significant over and under watering within the irrigated area. This example illustrates why it is important to evaluate various measures of irrigation system performance to determine its overall efficiency in water distribution.

Irrigation development induces considerable environmental change, but past expectations were that economic and social benefits would be greater than the environmental costs (Christen et al. 2006). Qureshi et al. (2001) conducted an economic evaluation of furrow, pivot and drip irrigation systems for sugarcane in the Burdekin River Delta, Queensland. The study cited evidence from Holden (1998) and Tilley and Chapman (1999) that application efficiency for furrow irrigation varied from 10 to 90%, and that low efficiencies could be improved with better management practice. The paper also referred to other studies (reviewed by Thorburn et al. 1998) that indicate conversion to drip irrigation has delivered IEs ranging from 50 to 80%, and a 5–20% increase in sugar cane yield. However, it concluded, from the economic analysis conducted, that irrigation technologies with potentially greater efficiencies had high investment costs, and that the net benefits attributed to improved WUEs obtained from the installation of the pressurised irrigation systems were not substantial enough to outweigh the initial capital cost of these systems. A benefit–cost analysis investigating the net benefit of converting from furrow to a pivot or drip irrigation system found that all systems resulted in a positive net present value (NPV), but the furrow irrigation system returned the highest NPV despite the presumption that it was least efficient. The study concluded that growers in the area had little incentive to become more water use efficient while water charges remained low. The main driver for conversion from furrow to drip or trickle systems in the region has been water supply constraints.

Finger et al. (2002) compared the irrigation water efficiency (IWE) of four systems (border check, surge, sprinkler and subsurface drip) for perennial pasture production at an experimental site in Tatura, Victoria. Data collected from July 2000 to July 2002 showed that no significant difference in yield and IWE between the two flood systems (border check and surge) or between the two pressurised systems (sprinkler and subsurface drip). However, the pressurised systems used 20% (2.0 ML/ha) less water than the flood systems in both years and produced 10% (1.9 t DM/ha) more pasture in the second year. As run-off was captured and reused, the water savings were attributed to less evaporation and deeper drainage, but these components were not measured separately. The higher production levels under the pressurised systems were possibly due to the more frequent but smaller applications of water, which alleviated waterlogging and water stress problems associated with border-check irrigation. Conversion to pressurised irrigation systems may create water savings but they may not be economic. Bethune et al. (2003) and Bethune (2004) stated that it was only economically viable for a dairy farm in Victoria to convert from border check to pivot irrigation if:

- water savings could be used to expand the area of irrigated pastures on the property
- water savings greater than 3 ML/ha were achievable
- the cost of water increased substantially.

Where possible, groundwater pumping and reuse to minimise water losses and affects on the regional groundwater system may be more cost-effective than converting to sprinkler systems. Armstrong et al. (1998) surveyed a sample of 170 dairy farmers in northern Victoria and southern NSW to determine WUE of pasture production within this region, where border check is the most common irrigation system used. The two measures of efficiency used in the analysis were:

- production WUE—the amount of milk produced (milk fat plus protein, kg) from the total amount of applied water (irrigation plus effective rainfall, ML)
- economic WUE—the dollar margin of milk production (milk gross income less pasture variable costs) per ML of applied water.

The survey (Armstrong et al. 1998) revealed a strong relationship between the production WUE and economic WUE, which indicated that increasing milk production per ML of water would also lead to a higher dollar margin return per ML. A threefold difference in both efficiency measures was noted between the top 10% and bottom 10% of farms. Total water applied to the pastures was not significantly greater than pasture requirements on the majority of farms. The authors suggested that irrigation systems alternative to flood irrigation were unlikely to reduce water use per ha on the majority of farms, but could offer improved WUE through higher pasture production.

Foley and Raine (2001), Raine et al. (2000) and Baillie et al. (2007) looked at the WUE of centre-pivots and lateral-move machines and subsurface drip irrigation (SDI) compared to traditional furrow irrigation in the Australian cotton industry. For centre-pivot and lateral-move machines, the study reported an average increase in crop WUE of 0.80 bales/ML (72%) of irrigation water and an average decrease in water applied of 3.10 ML/ha (44%) compared to furrow irrigation methods. For subsurface drip, the study reported an average increase in crop WUE of 1.29 bales/ML (118%) of irrigation water and an average decrease in water applied of 2.56 ML/ha (38%) compared to furrow irrigation methods. The key drivers for the adoption of spray and SDI systems identified by the growers were the potential water savings, labour savings, yield increases due to reduced waterlogging and better irrigation management, and improvements in germination.

From the survey of cotton growers using subsurface drip systems, Raine et al. (2000) concluded that subsurface drip systems were not inherently more efficient than surface or spray systems for water application, as poorly managed drip systems may result in lower efficiencies and greater deep drainage losses than standard systems. The average cost of a SDI system is $3500–4500/ha, double the average cost of a centre-pivot or lateral-move. Therefore, investment in better surface irrigation performance or adoption of low-pressure, overhead spray systems will generally provide better returns. However, economics may not be the only driver for the adoption of subsurface drip systems, as agronomic, environmental, site-specific and lifestyle issues may also be important.

To cater for highly uncertain circumstances regarding water savings, water availability and the value of water, McClintock (2009) recommended that subsidy rates needed to be higher to encourage faster uptake of these technologies over those indicated by traditional NPV analysis. This is further complicated when irrigators are required to relinquish water entitlements in return for the subsidy.

In summary, pressurised systems have the potential to increase WUE. In terms of maximum possible efficiencies, drip technology outperforms sprinkler systems, and both deliver greater maximum efficiencies than surface irrigation. However, it is evident that irrigation application efficiency is not an inherent characteristic of specific irrigation technologies. The efficiencies achieved are often highly dependent on management, with high efficiencies possible in all systems, including surface irrigation. Flood systems can have efficiencies equivalent to the pressurised systems if they are well designed on appropriate soils and well managed, and a pressurised system can be less efficient if poorly managed. Studies comparing irrigation systems in the horticulture, sugar, dairy and cotton industries in Australia have illustrated the wide range of onfarm efficiencies, and in some cases, very little difference between irrigation systems. In addition, where increased efficiencies were obtained, there is evidence to show that in some cases, it could be uneconomic to convert from traditional flood irrigation systems to a pressurised system.

### 2.1.2 International

A review of research comparing the efficiencies of various irrigation systems around the world has revealed that greater WUEs are generally achieved with pressurised systems (Sammis 1980; Dawood and Hamad 1985; Hanson et al. 1997; Camp 1998; Al-Jamal et al. 2001; Schneider and Howell 2001). However, benefits achieved from a pressurised system may not offset the additional capital and operating costs compared to a surface system (Hanson et al. 1997; Hutmacher et al. 2001). Economic analysis is required to determine the economic efficiency (profitability) of any irrigation system, and this will be influenced by many factors, including system type, design, operational life and cost, field size (Bosch et al. 1992; O’Brien et al. 1997), topography and soil type (Sousa et al. 1999), crop type and value, water delivery (O’Brien et al. 1998, 2001) and irrigation system management (Al-Jamal et al. 2001). Following is a summary of international research comparing the efficiency and profitability of various irrigation systems.

Hanson et al. (1997) compared furrow with surface and subsurface drip on lettuce yield and volume of water applied on a farm in the Salinas Valley, California, USA. The overall performance showed similar lettuce yield for the furrow and subsurface drip, but lower yields for the surface drip system. However, greater WUEs were evident for the drip methods with water applications 43–74% of the furrow method. Input costs such as water, fertiliser and cultivation were lower for the drip systems but insufficient to offset their capital and maintenance costs.

O’Brien et al. (2001) determined the profitability of converting from furrow surface irrigation to centre-pivot irrigation systems under different well pumping capacities (236–754 gallons per minute [gpm]) and weather conditions for corn production in Kansas, USA. The analysis calculated the annual net return over the life of the alternative irrigation systems by incorporating the change in capital and operating costs of the conversion, the change in irrigated area (160 acres to 125 acres [65 ha to 51 ha]), the comparative irrigated crop yields for each system, labour savings and the impact of tax deductions and debt repayments on annual cash flows. The study found that yields for each system decreased with lower pumping capacities, and average yields on furrow were less than those on centre-pivot for the comparative pumping capacities. The difference in yields was large enough to offset the conversion costs, making it economically profitable, as the centre-pivot system had greater net return per acre than the furrow system. Profitability increased further if the value of labour savings was incorporated into the analysis.

Sousa et al. (1999) conducted a cost–benefit comparison of surface irrigation systems and a sprinkler system in undulating land representative of South Portugal. The study found that the surface irrigation systems tested attained net values 17–46% higher than the pressurised sprinkler systems. The surface systems outperformed the sprinkler systems due to the annual investment cost of the sprinkler system being more than double of the surface systems while all had similar operating costs and achieved similar net benefits. Where topography becomes irregular and slopes become greater than 3%, sprinkler systems may be a more viable alternative.

Rodriguez and Orono (2004) compared the productivity and profitability of centre-pivot and power roll pressurised irrigation systems with the conventional surface irrigation method for alfalfa production in the north of Mexico. The results concluded that greater profits could be achieved using sprinkler systems rather than surface irrigation. The centre-pivot system had the greatest marginal return of 266% as a result of a 56% increase in alfalfa production, and the power roll system had a marginal return of 224% as a result of a 36% increase in alfalfa production.

Hutmacher et al. (2001) evaluated the potential for water savings and yield increases for forage alfalfa with SDI compared to furrow irrigation at a USDA research station in California, USA. The research showed that the SDI system averaged a 20% increase in WUE compared to the furrow irrigation, but the higher WUEs were largely attributed to increases in yield and not from reductions in applied water. The SDI system had the advantage of continued water applications during each harvest period, resulting in faster regrowth and larger yields than in the furrow irrigated plots. The study did not undertake an economic analysis but concluded that a 20% increase in potential yield may not warrant the cost of conversion to a SDI system in forage markets where land values and water costs were low.

Camp (1998) conducted a comprehensive review of SDI systems. Yield response for over 30 crops indicated that crop yield for SDI was greater than or equal to that for other irrigation methods, including surface drip, and required less water in most cases. Fertigation (application of fertilisers or water-soluble products through an irrigation system) with SDI provided positive crop results in many cases, and reduced nutrient amounts without yield reduction were reported for SDI relative to other irrigation system types. Profitability and economic aspects of SDI was not conclusively determined and would depend greatly on local conditions, system design and obtainable yield or water-saving benefits.

Sammis (1980) compared the WUE of sprinkler, trickle and SDI systems for potato and lettuce production in New Mexico, USA. For potatoes, the highest WUE was obtained with the trickle and SDI systems. For lettuce, comparable yields and WUEs were achieved with all three pressurised systems. The furrow system also achieved comparable WUEs with proper management and short furrow runs.

Al-Jamal et al. (2001) compared sprinkler, SDI and furrow IEs for onion production in the Mesilla Valley of southern New Mexico, USA. Previous research had shown that for onion production, the pressurised irrigation systems achieved a greater irrigation water use index (IWUI), which is the yield divided by the total irrigation water applied. This study also reached the same conclusion, with sprinkler achieving the highest IWUI of 0.084 t/ha per millimetre (mm) with an IE of 97%, whereas the SDI produced the highest yield per ha but had a lower IWUI of 0.04 t/ha/mm due to a much lower IE of 45%. As Al-Jamal et al. (2001) point out, both IE and IWUI can be increased by practising deficit irrigation, but the most economical deficit irrigation level will depend on the costs associated with the irrigation system, the uniformity of application of the irrigation water, and the value of the crop. SDI yielded a 29% return on investment when operated at an IE of 45%. If the SDI system operated at an IE of 79%, yields declined to the same level as furrow irrigation and the system became uneconomical. The sprinkler had a greater return on investment of 36%, mainly due to the much lower capital cost of the system.

Pyle and Moore (1985) outlined the difference in water use, yield and operating costs for a sugar plantation in Hawaii using furrow, sprinkler and SDI. Data collected between 1977 and 1984 showed that yields under SDI were 22% higher than furrow, and used 33% less water. The sprinkler yields were 13% less than furrow but used 58% less water. The furrow system had low IEs due to the porous volcanic soils on the plantation. Converting to SDI proved to be very economical; greater yields were achieved with less water, resulting in an 80% increase in WUE, which enabled the plantation to increase the production area. The conversion to SDI also cut operational costs (weed control and labour) by 60%.

Bosch et al. (1992) compared water use, yields and the relative profitability of fixed and towable centre-pivot irrigation and subsurface micro-irrigation for a corn and soybean rotations in eastern Virginia, USA, over three different field sizes. The study found little difference in yield for the two crops between the different irrigation systems, although subsurface micro-irrigation used less water. The profitability of the systems depended on the field size. Subsurface micro-irrigation was the most profitable system for areas less than 60 ha, and towable centre-pivot was most profitable for 60–120 ha areas. The towable centre-pivot was more profitable than the fixed centre-pivot for all field sizes. Micro-irrigation was more profitable for smaller systems due to lower pumping costs and lower investment cost per unit area, whereas centre-pivots became more profitable for larger areas as its investment cost per unit area declined with increasing field size. Micro-irrigation systems had an advantage over centre-pivots in that the field size or shape didn't affect its per unit area investment costs. Higher site preparation costs required to make a field compatible with a centre-pivot system may make micro-irrigation the most profitable alternative even for large system sizes.

Dawood and Hamad (1985) compared the WUE of trickle, solid-set sprinkler and furrow irrigation systems growing lima beans on a clay loam soil in Baghdad, Iraq. In their study, the trickle system had the highest IE and distribution uniformity. The sprinkler system had greater IE than furrow but distribution uniformity was the same. The trickle system had the highest WUE, which was 142% greater than the furrow system due to increased yields with less than half the water applied. The sprinkler system had lower yields than the furrow system but was achieved with a greater reduction in water use, resulting in a 25% increase in WUE. The furrow IE could have been significantly improved with the recycling of run-off.

Battikhi and Abu-Hammad (1994) compared the application efficiency of citrus production under surface and sprinkler irrigation systems and vegetable production under surface and drip irrigation systems in the Jordan Valley, Jordan. The average application efficiencies for the citrus surface and sprinkler irrigation systems were 82 and 88%, respectively, with the high surface IEs attributed to good irrigation management. The average application efficiencies for the vegetable surface and drip irrigation systems were 64 and 91%, respectively.

In summary, global studies indicate that greater WUEs are generally achieved with pressurised systems, but, as in the Australian examples, management can have a significant affect on the relative efficiencies of the different technologies. In some cases, the benefits achieved from a pressurised system may not offset the additional capital and operating costs compared to a surface system, particularly where the input costs (e.g. land values, water price) are low, but additional benefits such as savings on labour and weed control may improve the profitability of conversion.

## 2.2 Potential onfarm water saving

Surface irrigation has the reputation for having low IEs (Clemmens 1998), which implies considerable water savings could be achieved through the adoption of water saving irrigation technology. Converting typically low efficiency flood systems to pressurised systems has been cited as a method for increasing WUE in irrigation systems as a whole (Green et al. 1996). Khan et al. (2004a) have estimated the potential onfarm water savings associated with reducing farm channel losses, onfarm recycle and storage systems, laser levelling, matching crop with soils and depth to groundwater and conversion to drip or sprinkler irrigation systems. Table 4 provides estimates of average and potential water saving using the SWAP (soil–water–atmosphere–plant) model and other field-based methods. A water saving of 1.0–3.0 ML/ha is possible, but highly dependent on the technology, soil type, climate and crop.

Table 4: Water use and potential water savings for different crops under different irrigation technologies

| *Crop* | *Level of water use (ML/ha)* | | | *Range of water savings (ML/ha)* | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Surface** | | | *Sprinkler* | | | *Drip* | | |
| | *Low* | *Avg.* | *High* | *Low* | *Avg.* | *High* | *Low* | *Avg.* | *High* |
| Wheat | 0.5 | 2.4 | 4.2 | 0.1 | 0.7 | 1.2 | na | na | na |
| Barley | 0.7 | 2.4 | 4.3 | 0.1 | 1.0 | 1.4 | na | na | na |
| Maize | 4.3 | 7.5 | 10.2 | 0.4 | 1.0 | 1.4 | na | na | na |
| Soybean | 3.6 | 5.4 | 6.6 | 0.4 | 0.7 | 1.0 | na | na | na |
| Sunflower | 3.5 | 5.0 | 7.0 | 0.4 | 0.7 | 1.0 | na | na | na |
| Lucerne | 12.0 | 13.0 | 16.0 | 1.5 | 2.3 | 3.5 | 2.5 | 3.5 | 4.5 |
| Cotton | 7.0 | 8.0 | 9.0 | 1.0 | 1.2 | 2.0 | 1.7 | 2.2 | 3.0 |
| Vines | 7.0 | 8.0 | 9.0 | 1.0 | 0.9 | 1.5 | 1.5 | 2.2 | 3.0 |
| Citrus | 9.0 | 10.5 | 12.0 | 1.0 | 1.2 | 1.5 | 1.2 | 1.5 | 2.5 |
| Onions | 4.0 | 5.2 | 6.0 | 0.5 | 0.8 | 1.0 | na | na | na |
| Carrots | 3.5 | 4.0 | 5.0 | 0.7 | 0.9 | 1.2 | na | na | na |
| Tomatoes | 6.5 | 8.1 | 10.0 | na | na | na | 1.0 | 1.5 | 2.0 |
| Melons | 6.5 | 8.0 | 10.0 | na | na | na | 0.8 | 1.2 | 2.0 |

* Surface includes flood and furrow irrigation systems.
Source: Khan et al. (2004a; 2008a); Khan and Abbas (2007); ACIL Tasman (2003); Rendell McGuckian (2002); Qureshi et al. (2001), Jackson (2009); Reynolds and Jackson (2007); EconSearch (2005); O'Neill et al. (2008) Harris (2007); Wood and Finger (2006); Foley and Raine (2001); DPI NSW (2010); Hickey et al. (2006)

## 2.3 Water use and energy efficiency

### 2.3.1 Australia

Crop water use under Australian conditions is well understood but research into energy use and associated GHG emissions in agriculture is limited (Jackson 2009). Existing studies provide a preliminary overview of the Australian situation.

By comparing case study farms in two irrigated regions—the Coleambally Irrigation Area (CIA) in NSW, which uses surface water, and the south-east of SA, a groundwater-dependent region—Jackson (2009) estimated WUE, energy consumption and GHG emission relationships for these irrigation systems. She reported a general trend of increasing energy consumption with increasing water use. That trend was more pronounced in groundwater-dependent regions. In places where conversions were made from gravity to pressurised irrigation methods, water consumption was reduced but energy consumption and GHG emissions increased, especially in surface water irrigation regions. The opposite was true in groundwater dependent irrigated regions, as the use of pressurised irrigation methods can reduce water and energy consumption and GHG emissions. Jackson suggested that farms needed to play multiple functions, not only to produce food but to protect the environment and reduce the effects of climate change.

In the context of rising energy costs and concerns over GHG emissions, Chen et al. (2008) identified a considerable opportunity to increase onfarm energy efficiency. For example, suitable design improvements and engine speed adjustments could realistically save up to 10–50% of pumping energy. They concluded that there was a lack of systematic research for energy use in agriculture and quantified ‘rules of thumb’ and guides to estimate energy performance and return of energy improvement for different agricultural machinery. They recommended developing a detailed model report or manual to enable effective and widespread energy audits in agriculture. It is reported that some of the energy use data published previously might over-estimate energy use by more than 100%. Therefore, there is evidently a significant need for case studies and critical evaluation of the different irrigation technologies to enable the establishment of energy use benchmarks.

Baillie (2009) conducted a case study on ‘Keytah’, an irrigated cotton and grain-farming operation west of Moree, NSW. In a normal year, Keytah relies on 7.0–7.5 ML/ha of water for irrigation, which is applied by surface (furrow) irrigation and two lateral-move irrigators. In response to limited irrigation supplies (1 ML/ha) in 2007–08, a radical change in farming practices was pursued towards reduced and zero till cultivation systems. The study compared energy use from three scenarios on Keytah: a benchmark of energy use from 2000, current practices or reduced tillage and progression towards zero till farming methods. Baillie concluded that the reduced tillage operations could result in 12% energy savings, compared to the 2000 benchmark. If the farming system moved towards zero till, a further energy saving of 13% was possible (Table 5). The study did not assess energy use or GHG emissions due to production, packaging, transportation and application of agrochemicals and machinery, all of which vary significantly in different types of farming systems.

Table 5: Energy implication for different farming systems

| | *Total energy (GJ/ha)* | *Energy costs ($/ha)* | *GHG emission (t $CO_2$-e)* | *Since 2000* |
|---|---|---|---|---|
| 2000 benchmark | 16.31 | 402 | 6 389 (1 226 kg/ha) | |
| Reduced till | 14.33 | 353 | 5 600 (1 076 kg/ha) | −12% |
| Towards zero till | 12.44 | 306 | 4 862 (935 kg/ha) | −24% |

Source: Baillie (2009)

Undertaking seven case studies, Chen and Baillie (2007) estimated operational energy usages from different cotton production processes including fallow, planting, in-crop, irrigation, harvesting and post harvest. They reported that the total energy inputs for these farms were significantly influenced by the management and operation methods adopted, and ranged from 3.7–15.2 GJ/ha of primary energy, at a cost of $80–310/ha, and generated 275–1404 kg $CO_2$-e/ha of GHG emissions. Among all the farming practices, irrigation water energy use was found to be the highest contributor (typically 40–60% of total energy costs wherever water was pumped). The study did not cover energy use and GHG emissions due to the production, packaging, transportation and application of agrochemicals or machinery.

### 2.3.2 International

Irrigation increases crop yield and thus energy productivity. Topak et al. (2005), in a study of sprinkler irrigation in Turkey, reported that the amount of energy obtained through the increased harvest for winter wheat, dry bean and sugar beet exceeded 4.85, 3.63 and 11.65 times, respectively, the energy input through irrigation application. For this study, Topak et al. (2005) used a handheld portable sprinkler system. The sprinkler irrigation energy consumption per unit volume of water pumped was about 2.95 megajoules per cubic metre ($MJ/m^3$).

Other studies of energy requirements for surface irrigation report that the energy requirement for surface irrigation is around 0.65 $MJ/m^3$ (Mittal and Dhawan 1989; Yaldiz et al. 1993; Mrini et al. 2001). As a result, there could be a saving of 78% of total energy by switching from sprinkler irrigation to surface irrigation. Energy savings could be even higher if we consider the energy consumption estimations for sprinkler irrigation from Dalgaard et al. (2001) and Mrini et al. (2001), which were 4.2 and 5.2 $MJ/m^3$, respectively.

## 2.4 Australia's proposed CPRS and the agricultural sector

The Australian Government plans to implement a comprehensive range of climate strategies, which includes mitigation, adaptation and assisting other countries in seeking global solutions. As a mitigation strategy, the Australian Government is committed to reducing Australia's GHG emissions below 2000 levels by 5–25% (5% unconditional; 25% if the world agrees to an ambitious global deal to stabilise levels of GHGs in the atmosphere at 450 ppm equivalent carbon dioxide or lower) by 2020 (DCC 2010). To meet this target, the Australian Government proposed a CPRS that would have affected about 1000 Australian companies (out of 7.6 million registered companies) that produce more than 25,000 t $CO_2$-e/year. Currently, the Australian Government is committed to establishing a price on carbon. This may or may not involve an ETS, but here we use the proposed CPRS as of late 2009 to illustrate its potential affect on the irrigation industry.

The proposed CPRS was very comprehensive compared to other ETSs in its treatment of the number of GHGs being addressed, the degree of sectoral coverage and the proportion of total national GHGs being considered. The proposed CPRS would have encompassed the effects of all six major GHGs recognised by the Kyoto Protocol, that is, carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), methane, sulfur hexafluoride, hydrofluorocarbon and perfluorocarbon. By comparison, the European Union ETS (EU ETS)—the largest carbon market in the world—only included $CO_2$ in the first phase (2005–2007) and $CO_2$ and $N_2O$ in the second phase (2008–2012) (European Commission 2008). The CPRS would have covered over 75% of Australia's GHG emissions, whereas the EU ETS only deals with 50% of the EU's GHG emissions (DCC 2008). The CPRS would have been, by international comparison, far more comprehensive in terms of sectoral coverage.

The Australian agricultural sector in 2007 accounted for 16.3% (88.1 Mt $CO_2$-e) of national GHG emissions and was the second largest source of emissions (DCC 2009a); this contribution rises to 23% when we include energy and transport inputs in agricultural production (Hatfield-Dodds et al. 2007). This figure is significantly higher than the corresponding values for agricultural sectors in Central and Eastern Europe (3%), the former Soviet Union (3%) and the USA (5.5%) (NFF 2007; Smith et al. 2008). From 1990 to 2005, Annex I countries (to the United National Framework Convention on Climate Change) collectively decreased their agricultural emissions by 10% (Smith et al. 2008), whilst Australia's emissions from agriculture between 1990 and 2007 increased by 1.5% (DCC 2009a). Increases in GHG emissions in agriculture are directly related to rising farm inputs (Graham and Williams 2005). For example, between 1987 and 2000, nitrogen (N) fertiliser use increased by 325% (Dalal et al. 2003). However, over half of the N applied is either lost through leaching into the soil or released into the atmosphere as $N_2O$ (Verge et al. 2007), which has 298 times more global warming potential than $CO_2$ (IPCC 2007). Similarly, the increasing use of farm machinery is another major source of GHGs (Stout 1990). Of the total energy used in agriculture globally, 51% is expended in farm machinery manufacture and 45% in the production of chemical fertiliser (Helsel 1992). Significant amounts of GHG emissions occur due to the production, packaging, storage, transportation and use of farm inputs, which is poorly researched.

The inclusion of agriculture is a contentious issue in all domestic ETSs (Cowie et al. 2007; NFF 2007; PMTG 2007; IETA 2008). The agricultural sector has many unique features that make it less suitable to include in an ETS, such as the widely distributed nature of agriculture, the difficulty in measuring small changes in annual fluxes over wide areas, the nonpermanence and reversibility of agriculture, and high transaction and administration costs (Gunasekera et al. 2007a; LWA 2007). In Australia, when the CPRS was initially designed in 2008, the agricultural sector was to be included by 2015. However, after a series of meetings with the Opposition, the Australian Government changed its policy in November 2009 to exclude agriculture indefinitely from the CPRS, but committed to introducing agricultural offset markets alongside the CPRS that comply with Australia's international climate change obligations and provide credits for agricultural emissions abatement (ABARE 2010). The Government also opened the door for a voluntary carbon market for offsets. With these amendments to the proposed CPRS policy, the Government would have expected agriculture to contribute to Australia's unconditional target of a 5% reduction in GHG emissions by 2020, relative to 2000 levels (ABARE 2010). While the issue of the CPRS is important contextually, this research is purely based on the science rather than policy at this stage.

## 2.5 Summary and conclusions of literature review

### 2.5.1 Summary

Irrigated agriculture is under considerable pressure to adopt best practice methods in order to ensure efficiency in terms of water use and productivity. Current irrigation practices are generally characterised by low WUEs, creating the potential for significant water savings, resulting in either increased productivity or increased water availability for alternative uses (e.g. environmental flows to maintain ecosystem services). However, water savings achieved must be balanced against potential increases in agricultural energy consumption and environmental consequences, such as increased GHG emissions. Analysis of trade-offs between water efficiency and energy use in irrigated agriculture is critical to maintain the economic efficiency of agricultural production and minimise the environmental effects.

This review highlights the complexity associated with achieving onfarm WUE. There is significant potential for saving waters through the adoption of improved technologies such as sprinkler and drip irrigation systems, however the efficiencies achieved are highly dependent on management practices, and need to be considered in light of soil characteristics and crop types. Economic efficiency is also a major consideration, both in Australia and overseas. The initial capital costs associated with conversion potentially limits the rate of adoption of new technologies, while operating costs can mean that the overall financial position of farmers is compromised; significant costs may be associated with energy requirements to operate particular types of systems.

There has been little attention given, both nationally and globally, to WUE–energy interactions in irrigated agricultural production systems. The potential GHG emissions associated with the energy embedded in—and the energy required to operate—new irrigation technology aimed at improving onfarm WUE need to be fully assessed to ensure that economic and environmental trade-offs are minimised. This is of particular significance to individual irrigation enterprises in the context of rising water and energy prices, and where there is potential for a price to be placed on GHG emissions.

### 2.5.2 Conclusions

Irrigation development brings considerable environmental change, but past expectations were that economic and social benefits would be greater than the environmental costs. Considering the effects of climate change and the proposed implementation of policies such as an ETS, the perception of net economic and social benefits may now be invalid.

The review indicates that a primary goal of crop production systems is the pursuit of economic efficiency. This is contradicted by the view expressed by Jackson (2009) and van der Werf et al. (2007) that farming has entered a new era, whereby it is not simply enough that a farm produces food and fibre as economic goods, but its second important function is to produce or protect environmental services. This role is even more important under a changing climate, as agriculture is responsible for significant GHG emissions.

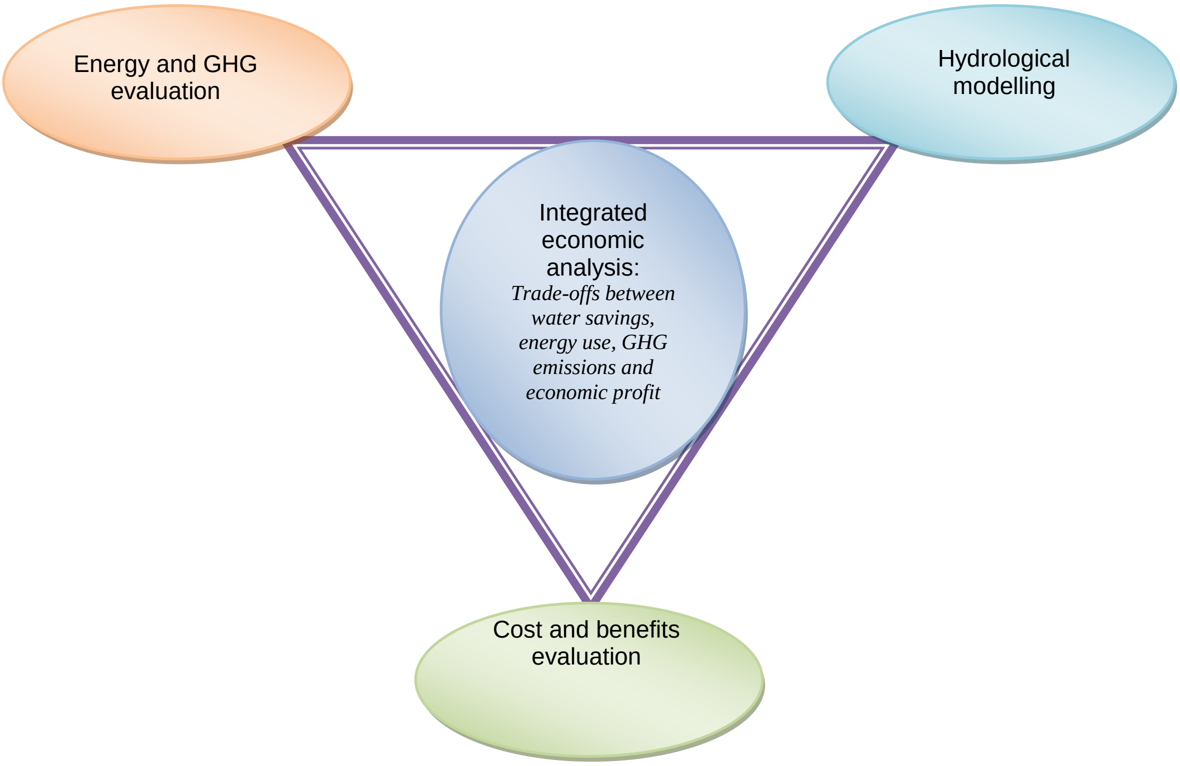
Global climate change is no longer a ‘what if’ exercise. The financial effects for irrigators are real and potentially very serious, and reducing GHG emissions should be a main strategic and operational priority in the industry. Where policy and investment ignore information regarding the predicted dimensions of climate change risks and their potential effects, these may lead to unintended consequences (maladaptation) and increase the vulnerability of irrigators.

# 3. Methodology

## 3.1 Integrated modelling

We developed an integrated framework to assess the effectiveness of different irrigation technologies used at farm level. The integrated framework evaluates trade-offs between various choices of irrigation technology adoption in terms of irrigation requirement, water savings, energy use, GHG emissions and the relative costs of irrigation and associated equipment. As a general principle, trade-off analysis shows that for a given set of resources and technology, to obtain more of one desirable outcome within a system, less of another desirable outcome is obtained (Stoorvogel et al. 2004). The integrated economic framework has three main components: hydrological modelling, energy and GHG modelling, and cost and benefits estimations (Figure 2). The integrated framework reliably estimates water savings and GHG implications, as well as trade-offs between achieving water security and environmental security. The integrated framework has been applied to farm-level case studies and irrigation transformation scenarios. It is important to realise that one ideal choice is unlikely; any one of many alternatives might be appropriate, depending on the priorities set by the individual farmers and governments.

Figure 2: Proposed integrated framework trade-offs between water savings, economics, energy use and greenhouse gas (GHG) emissions




### 3.1.1 Hydrological modelling

Modernisation of surface irrigation systems can deliver real gains in application efficiency and thus water savings. In general, irrigation systems with higher application efficiencies require larger investments and are found in areas where high value, water-sensitive crops are grown, or where water supply may be limited or expensive (Khan et al. 2004a; Jackson 2009). For this study, irrigation technologies were grouped under two broad system types: drip and sprinkler irrigation systems. Each of these systems has varying degrees of efficiency in terms of applying water to meet crop requirements throughout the growing season. This is influenced by factors such as soil type, topography, system design, water delivery, crop type, system maintenance and irrigation management (Khan et al. 2004a,b).

While field experiments may be the most accurate method for determining potential water savings (Wood and Finger 2006), crop models such as SWAP and APSIM (Agricultural Production Systems sIMulator) can also provide useful estimates (Khan et al. 2004a; 2008; P DeVoil 2010, pers. comm. 06/2010). Khan et al. (2004a; 2008a,b) and Khan and Abbas (2007) have effectively used SWAP models to estimate potential water savings from improved water management and new technologies (drip and sprinkler irrigation systems) under different soil and climatic conditions.

The SWAP model calculates water and solute balances in the saturated and unsaturated zones of cropped soils, and recommends solutions to address practical questions in the field of agricultural water management and environmental protection (Khan and Abbas 2007; Kroes et al. 2008). Input may consist of meteorological, crop growth and drainage data. The SWAP model is described by Khan et al. (2004a), Khan and Abbas (2007) and Kroes et al. (2008).

The SWAP model offers both detailed and simple crop growth models. The simple crop model is useful if accurate simulation of crop water use is more important than accurate simulation of crop yield (Kroes et al. 2008). Given that the objective of our study was to estimate the potential water saving, we used the simple crop growth model. SWAP simulates crop growth from emergence to the end of active growth (maturity) using 1-day time steps. Crop model growth parameters include leaf area index (LAI) or soil cover fraction (SCF), crop height (CH) or crop factor (CF), rooting depth (RD) and yield response as a function of development stage (DVS).

Different types of irrigation can be specified in SWAP, such as fixed irrigation, irrigation for a specific crop according to a set of criteria, or a combination of fixed and calculated irrigations. Following Khan et al. (2004a), we selected a mixture of irrigation, with fixed irrigation followed by irrigation scheduling, to reflect common best practice in the field. SWAP's field capacity option is useful in the case of sprinkler or drip irrigation. In this option, the soil moisture profile is brought back to field capacity. An over (positive) or under (negative) irrigation amount can also be specified as a function of the crop development stage (Kroes et al. 2008).

SWAP model inputs include climate, crop, water availability and soil type. We obtained the climate data, including daily and monthly maximum and minimum temperatures, rainfall, evaporation, vapour pressure and radiation, from the Bureau of Meteorology (BoM 2010). Crop and soil data were obtained through the Queensland Government Department of Employment, Economic Development and Innovation (DEEDI, formerly Department of Primary Industries) and CSIRO Ecosystems. Soils data were selected for soil types commonly occurring in the key study area—grey Vertisol, brown clay, and black Vertisol types—that support highly productive agricultural systems within Queensland.

### 3.1.2 Energy and GHG modelling

One of the key objectives of our study was to quantify the energy requirements and GHG emissions as a result of new irrigation technologies, and use this information to estimate emission costs. Our first approach to estimate energy consumption and GHG emissions was to interview irrigation auditors, experts and dealers experienced in irrigation instruments (Appendix B), and our second approach was to complete case studies of farmers who had recently moved from one irrigation system to another (Appendix B).

## Estimates of changes to energy consumption: a general approach

Data collected from irrigation auditors, experts and dealers were more general in nature and applicable to a larger area. Some key data we collected included minimum and maximum energy consumption for pumping 1 ML of water, pumping efficiency, total dynamic head, flow rate, pump derating factor and average installation, maintenance and decommissioning energy required for all irrigation machinery, accessories and infrastructure. Where an interviewee provided maximum and minimum energy consumption figures for pumping 1 ML of water, these data were used directly. In some cases where they provided alternative information, energy required for pumping and pressurising water for irrigation was determined using Equation 1, an expansion of Bernoulli's equation (Mott 1994).

$$P(kW) = \frac{(h_A \gamma Q)}{1000 \times \text{pump efficiency} \times Dr} \tag{1}$$

where $P$ is the power added to the fluid in kW, $h_A$ is the total head (m) (the sum of pressure head and elevation or suction head; pressure head was assigned using accepted data from existing systems (O'Neill et al. 2008), and elevation head was the depth [m] from which the water was pumped); $\gamma$ is the specific weight of fluid (assumed to be 9810 N/m$^3$ for water at 15°C) and $Q$ is the flow rate (m$^3$/s) (Jackson et al. 2010). *Dr*, the engine derating, accounts for efficiency losses between the energy required at the pump shaft and the total energy required. To calculate pumping energy (kWh) for 1 ML of water, the quantity of energy (kW) estimated from Equation 1 was multiplied by the total pumping time (hours) required to pump 1 ML of water, with the pumping time (hours) for 1 ML was estimated from flow rate. We used this approach in one of the case studies.

In cases where energy consumption values were given in kWh, where necessary, we converted them into a diesel amount by multiplying by 0.25 (0.25 L/kWh). The energy content factor and GHG emissions factor were taken from different sources (Table 6). On the basis of this information, we estimated the amount of GHG emissions generated from pumping 1 ML of water.

Table 6: Energy content factor in diesel and electricity and their emissions factors

| *Input* | *Energy content factor* | *GHG emissions (g $CO_2$/MJ)* |
|---|---|---|
| Diesel and diesel oil (MJ/L) | 38.6* | 75.2* |
| Aviation gas (MJ/L) | 33.1* | 72.4* |
| Electricity (MJ/kWh) | 11.93† | 281.0* |

Source: *DCC (2009b); † Ozkan et al. (2004), Mandal et al. (2002)

Note: Emissions factors for diesel and aviation gas include both combustion emissions factors (69.9 g $CO_2$-e/MJ), and indirect emissions factors related to extraction, production, transport and delivery lost (5.3 g $CO_2$-e/MJ). Similarly, the emissions factor for electricity includes both emissions factors due to consumption (Scope 2) and due to indirect emissions attributable to the extraction, production and transport of electricity and emissions attributable to the electricity lost in delivery in the network (Scope 3). Emissions factors for electricity vary by energy mix, which is significantly different in different states. As all data for this study is extracted for Queensland, Queensland's emissions factor has been used here.

Emissions factors for energy use depend on the mix of energy sources, whether renewable or otherwise. For example, in Tasmania, most of the energy comes from hydroelectricity and thus emissions factors are very low. The Department of Climate Change and Energy Efficiency (DCCEE) regularly updates emissions factors for each state of Australia, because the energy mix—and thus emissions factors—may change over time. Based on the mix of energy use in different states and territory, emissions factors change every year. For this study, we used the latest emissions factors (sum of Scopes 2 and 3) for Queensland, the case study state (DCC 2009b; Table 6).

Some amount of energy is also used for the production and transportation of irrigation machinery, accessories and infrastructures in different irrigation systems. This study did not consider these energy consumptions or associated GHG emissions.

## Estimation of energy consumption and GHG emissions: case study approach

The comparison of energy consumption of various irrigation technologies could not give a complete picture without analysing energy consumption (and thus GHG emissions) data due to the use of primary farm inputs, as the frequency (and amount) of farm inputs used for the same crop vary significantly in different irrigation systems. Farm inputs include farm machinery, machinery fuel and agrochemicals (e.g. fertilisers, insecticides, herbicides, fungicides, plant regulators). To cover those variations, we undertook five case studies that investigated the type and quantity of farm inputs used, and the amount of energy consumed (and GHG emissions) due to production, packaging, storing, transportation and application of farm inputs for the same crop before and after using particular irrigation technology.

Once the GHG emissions from the changes in farm inputs were quantified for using different irrigation technologies, it was assumed that an introduced carbon price would increase the price of these farm inputs directly proportional to their associated GHG emissions, and this increase in price would be passed on in full to the farmer. In reality, this assumption may serve as a reasonable proxy for how a carbon price might affect farm production as the demand curve for essential farm inputs is highly inelastic.

We acknowledge that within one season or crop, one irrigation technology could consume different amounts of energy and water than in other years. Similarly, the use of farm inputs (fuels, agrochemicals, machinery)—and thus the energy consumption and GHG emissions due to use of those farm inputs—could vary significantly by irrigation types. Therefore, without analysing all crops in a full rotation, it is difficult to derive a complete picture of energy consumption for a particular farming enterprise. However, due to limitations in time and funding, and also due to the complexity of cropping patterns used under different irrigation systems in the case study farms, we could not effectively capture those variations.

Energy use data in published studies (Stout 1990; Helsel 1992; Lal 2004; Maraseni et al. 2007, 2009b) are in diverse forms such as volume (g or L) of diesel, weight (kg, Mg) of coal, calories (kcal, Mcal), joules (MJ, GJ), other units of energy (BTU) and electricity (kWh). This makes it difficult to compare the GHG emissions from different farm practices (Lal 2004). In this study, we converted all emissions data into $CO_2$ equivalent ($CO_2$-e) units using the following methods for calculating GHG emissions from the various technologies.

## GHG emissions due to the extraction, production and use of electricity

The amount of electricity used for different farming operations was taken from the farm surveys. Energy content factors and GHG emissions factors per unit of energy content factor were taken from different sources (see section 3.1.2 and Table 6). On the basis of this information, we were able to estimate the GHG emissions due to the extraction, production and use of electricity.

## GHG emissions due to the production and combustion of fossil fuels

Details of the consumption of diesel and aviation gas in operating farm machinery were gathered from farmers. There are a number of studies that document GHG emissions resulting from the production and combustion of fossil fuels (Beer et al. 2002; Lal 2004; Maraseni et al. 2007, 2009b) but they do not provide the energy content factor. For this study, we used the DCC (2009b) database was used, which provides both the energy content factor and GHG emissions per unit of energy content factor (Table 7), allowing the amount of GHG emissions due to use of fuels to be estimated.

## Emissions from production, packaging, storage and transportation of agrochemicals

The production, packaging, storage and transportation of agrochemicals requires energy and contributes to GHG emissions. The types and amounts of agrochemicals used on various farms were collected from the farm survey. The energy content factors for different types of agrochemicals were taken from various sources (Table 7).

Table 7: Energy content factor for agrochemicals

| *Fertiliser* | *Energy content factor (MJ/kg)* | *Chemical* | *Energy content factor (MJ/kg)* |
|---|---|---|---|
| N | 66.1400* | Insecticides | 200‡ |
| P | 12.4400* | Herbicides | 240‡ |
| K | 11.1500* | Fungicides | 92‡ |
| S | 5.0000† | Plant regulator* | 109§ |
| Lime | 0.6000† | | |
| Manure | 0.3031* | | |

* Note: calculated from O'Halloran et al. (2008). The energy content factor for calcium was not available so we used the energy content factor of potassium, *K*, its closest element. Amount of key fertiliser element estimated from given amount of fertiliser used, using atomic and molecular weights. Similarly, as suggested by O'Halloran et al. (2008), each chemical was multiplied by a conversion factor (0.5 for herbicides; 0.25 for insecticides, fungicides and plant growth regulator) to obtain the approximate active ingredients in the mix. We applied Lal (2004) and O'Halloran et al. (2008) to estimate GHG emissions due to use of agrochemicals (Table 8).
Source: * Hatirli et al. 2006; † Wells 2001; ‡ FAO 2000; § O'Halloran et al. 2008

Table 8: GHG emissions due to use of agrochemicals, including production, packaging storage and transportation (kg $CO_2$-e/kg fertiliser element, *fe*, or active chemical ingredient, *ai*)

| *Fertiliser* | *kg $CO_2$-e/kg fe* | *Chemicals* | *kg $CO_2$-e/kg ai* |
|---|---|---|---|
| N | 4.7700 | Insecticides | 18.7 |
| P | 0.7300 | Herbicides | 23.1 |
| K | 0.5500 | Fungicides | 14.3 |
| S* | 0.3000 | Plant regulator† | 10.5 |
| Lime | 0.5872 | | |
| Manure | 0.0075 | | |

* Calculated using information from Wells (2001) and Barber (2004). † Calculated using information from O'Halloran et al. (2008, p.15). Emissions for calcium were not available so we used emissions for potassium, *K*, its closest element.
Source: Adapted from Lal (2004)

## Soil emissions of $N_2O$ due to N fertiliser and manure application

The Intergovernmental Panel on Climate Change (IPCC) has set a default emissions factor of 1.25% nitrite nitrogen (NO2-N) emissions per kg of applied nitrogen (N). However, research has shown large variations from the IPCC default emissions factor. In Australia, the Cooperative Research Centre (CRC) for Greenhouse Accounting has established a set of emissions factors suitable for Australian agricultural systems (DCC 2005 cited in O'Halloran et al. 2008). The values used in the our study were: all irrigation crops, 2.1% (2.1 kg $N_2O$-N/100 kg-N); irrigated pasture, 0.4%; and all horticulture and vegetables, 2.1% (DCC 2005 cited in O'Halloran et al. 2008; Table 9). The total amount of $N_2O$-N was calculated and converted into $N_2O$ by multiplying by 1.57 (the molecular weight of $N_2O$/mole wt of molecular N), and then converted into $CO_2$-e.

Table 9: Nitrous oxide ($N_2O$) emissions factors for synthetic fertiliser

| *Production system* | *Emissions factor (kg $N_2O$-N/100 kg N)* |
|---|---|
| Irrigated pasture | 0.4 |
| Irrigated crops | 2.1 |
| Vegetables/horticultures | 2.1 |

Source: DCC (2005) cited in O'Halloran et al. (2008)

While estimating $N_2O$ emissions, we acknowledge that there could be some variation in the $N_2O$ emissions factor for the applied N fertilisers for the same crops under different irrigation systems. However, due to limited research in Australia, we could not provide any estimation. Similarly, the application of manure emits some amount of $N_2O$ from the soil. Since the overall amount of GHG emissions for manure is already considered under the section 'Emissions from production, packaging, storage and transportation of agrochemicals', above, it is not discussed separately.

## Soil emissions of $N_2O$ due to biologically fixed N

Legume crops can fix N and make it available to the companion crop or the next crop, thus saving use of synthetic N fertiliser and reducing GHG emissions. However, not only synthetic N fertilisers contribute to $N_2O$ emissions from the soil; part of the biologically fixed N escapes into the atmosphere in the form of $N_2O$. There is a debate within the scientific community about whether the biologically fixed N emits as much GHG as N fertiliser. Dalal et al. (2003) suggest that the $N_2O$ emissions from legume crops exceed those from N fertiliser due to frequent wetting and drying cycles over a longer period. Crews and Peoples (2004) argue that the biologically fixed N is ultimately derived from solar energy while N fertiliser requires significant amounts of fossil fuels, thus legumes should have a lesser effect. Despite this debate, the IPCC (2001) considers $N_2O$ emissions factors to be equal (at 1.25% of total N) for all inorganic N fertiliser and biologically fixed N.

Nitrogen fixation by legumes depends on soil nitrate conditions, the legume species and cultivar, soil moisture, crop and soil management practices and whether the legume was inoculated with rhizobium (Peoples et al. 1992; Rochester et al. 1998). Many Australian studies have estimated the amount of N fixation by legume crops (see Henzell et al. 1967; Peoples et al. 1992; Bell et al. 1994; Rochester et al. 1998; Armstrong et al. 1999; Peoples and Griffiths 2009) but we cannot readily apply these studies to our sites and crop species due to the variation described above. Only one of our case studies contains a legume crop (lucerne). We acknowledge that a large amount of $N_2O$ would have been emitted from N biologically fixed by the lucerne crop in case study 5 because its biomass and yield was very high.

## Emissions due to the production of farm machinery

Several studies have estimated GHG emissions resulting from the production of 1 kg of farm machinery (Stout 1990; Helsel 1992; Maraseni et al. 2007, 2009b). Maraseni et al. (2007) investigated peanut–maize cropping in south-east Queensland, Australia, and calculated GHG emissions due to the production of each kg of farm machinery and their accessories using Equation 2:

$$GHG\ emission\ (kgCO_2\ /\ ha) = Weight\ of\ machine\ (kg) \times GHG\ emission\ /\ kg \times proportion\ of\ lifespan\ of\ machinery\ used\ for\ a\ given\ activity \quad (2)$$

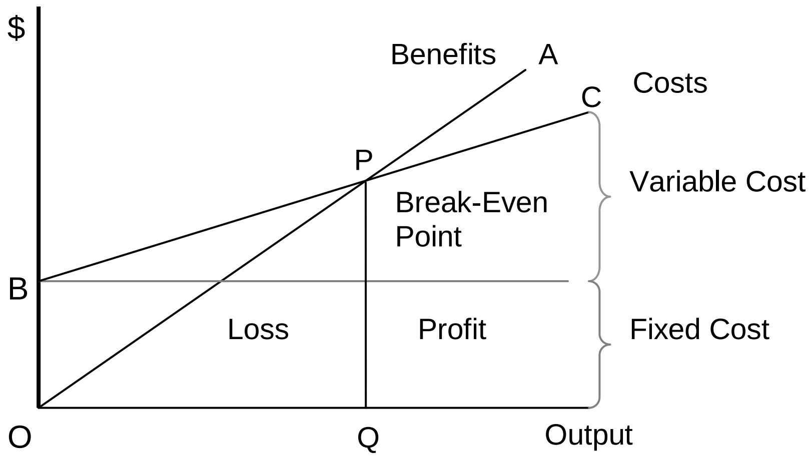
Data for peanut and maize cropping machinery and their life spans were taken from various sources and verified by relevant landholders and extension officers. Details about the weight of machines and accessories were sourced from the production companies, John Deere and Amadas Industries. The fraction of time a particular machine was used for a particular operation was derived from crop management notes and independently verified by landholders and extension officers. The study concluded that GHG emissions due to farm machinery usage were directly related to fossil fuel consumption: the greater the use of farm machinery, the higher the fuel consumption. According to Maraseni et al. (2007, 2010a,b), GHG emissions due to farm machinery usage and accessories accounted for 14.4% of emissions due to fossil fuels in peanut–maize cultivation systems. Given limited time and the difficulty in data collection, we followed Maraseni et al. (2007, 2010a,b) for the estimation of GHG emissions from the production of farm machinery. Negligible quantities of GHGs are emitted while transporting machinery and accessories, as discussed by Maraseni et al. (2007, 2010a,b), and were not considered in this study.

## 3.1.3 Economic modelling: benefit–cost analysis

A key component of the integrated framework was to undertake benefit–cost analysis. In addition to the main economic evaluation indexes, NPV, internal rate of return (IRR), benefit–cost ratio (BCR), payback period (years), and BE water saving (ML/ha) were used to assess the economic viability of conversion from an existing, less efficient irrigation system to a new, more efficient one. New irrigation systems are sophisticated and require a significant initial capital investment. The stream of benefits flows over the life of a system, usually 15–25 years depending on the type of system. To measure economic returns from the onfarm investment in such technologies, the benefits from a new system were measured, taking into account the total effects of the option (improvement in yield, quality, shifts in cropping rotation, reductions in input costs, labour savings, water savings and other benefits). We used sensitivity analysis to validate the robustness of the economic analysis by systematically changing the values of key benefit parameters, but sensitivity analysis results are mainly discussed using NPV as an evaluation criterion. We used Waterwork, a farm-level irrigation technology modernisation model (Khan et al. 2010), to evaluate the economics of technology adoption, costs and benefits. The model was simulated for 25 years with an interest rate of 5%. In addition, the current temporary and permanent water-trading price, as a substitute for a water price through the water sharing and buyback program, was used in the economic modelling.

BE analysis is a technique that shows the product price or level of production at which an irrigation technology will become unprofitable. BE analysis is a particularly useful means of studying the effects of uncertainty because it provides vital information on the sensitivity of key variables in the budget. Using this information, the decision-maker can judge the risk involved by considering the likelihood of lower prices and production occurring. In Figure 3, the line *OA* represents the variation of income at varying levels of production activity, and *OB* represents the total fixed costs in the business. As output increases, variable costs are incurred, meaning that total costs (fixed plus variable costs) also increase. At low levels of output, costs are greater than income. At the intersection point *P*, known as the 'break-even point', costs are exactly equal to income, and hence neither profit nor loss is made. Using this analysis, it is possible to determine the minimum water saving (in ML/ha) for a given water trading price, carbon price, commodity price and yield, before returns on investment on new irrigation technology are deemed satisfactory.

Figure 3: Conceptual representation of break-even (BE) analysis




## 3.2 Application of the integrated framework

The integrated framework was applied to field, crop, farm and national scales to evaluate trade-offs between water savings, energy use and GHG emissions and economic returns.

### 3.2.1 Field and crop-level approaches

The field-level approach focused on major crops for more generalised analyses of water and energy use, productivity and economics associated with the adoption of new crop irrigation technologies. However, to validate the hydrologic, economic and energy analyses, we conducted a number of case studies to 'road test' the results of the integrated analysis. The crop-level analysis primarily focused on south-east Queensland, given that robust estimates of water savings are already available (mainly in NSW and Victoria) (see Table 4) and because our case studies focused on irrigators in the Darling Downs and Lockyer Valley regions.

The crop-level approach quantified the range of water savings for different crops under a range of climate and soil conditions using the SWAP model, estimated energy consumption and GHG emissions linking with volumes of water savings, and conducted economic evaluations based on water savings, energy consumption and GHG emissions for all major crops.

### 3.2.2 Farm level case study approach

Five case studies were undertaken to collect information on finer-scale farm-level variability and to inform the more generalised integrated analysis associated with the adoption of new crop irrigation technologies. The case studies involved a detailed face-to-face interview from those irrigators who had converted their conventional irrigation system to one of the newer pressurised irrigation systems.

These case studies were mainly based around a questionnaire, but also involved a less formal conversation (recorded in note form) regarding additional information about individual enterprises. Farmers were asked to provide information on irrigation water use and technology, crop yields, income, energy usage, etc. The case studies included three cotton farms on the Darling Downs, a vegetable (lettuce) farm in the Lockyer Valley and a pasture–cropping (lucerne, oats) and vegetable (onion) farm on the southern Downs, all in southern Queensland. Irrigation technology transitions were from flood (furrow) to overhead sprinkler (lateral-move and/or centre-pivot), from flood (furrow) to drip (trickle), from overhead sprinkler (hand-shift) to drip (trickle), and from overhead sprinkler (roll-line) to improved overhead sprinkler (centre-pivot) systems.

We conducted four additional interviews with irrigation auditors, experts or irrigation instrument dealers for irrigation instruments regarding costs of irrigation systems, pump efficiencies, suction head, elevation head, flow rates and details of irrigation machines and accessories. Data obtained through this questionnaire were used to estimate energy consumption, GHG emissions and economic evaluations. The details of the questionnaires are given in Appendix B.

### 3.2.3 National-scale approach

A scenario approach was adopted to quantify trade-offs between water savings, energy consumption and GHG emissions, and economic returns associated with wide-scale adoption of more water-efficient technology to manage irrigation water onfarm. We developed three irrigation transformation scenarios after detailed discussions with irrigators and industry experts.

- Scenario 1—Reducing the total area of surface irrigation systems from 44% during 2008–09 to 25%, and replacing them with drip irrigation (40%) and sprinkler irrigation systems (60%).
- Scenario 2—Reducing the total irrigation area under a ‘portable irrigators sprinkler irrigation system’ and a ‘hose irrigators sprinkler system’ from 16% during 2008–09 to 8%, and replacing them with a drip irrigation system.
- Scenario 3—Increasing the drip irrigation area on horticultural crops from 13.3% during 2008–09 to 20% of the total irrigated area.

# 4. Empirical results

## 4.1 Estimation of potential water savings at crop level

To estimate water savings for different irrigation systems under a range of climatic conditions, irrigation technologies were grouped under two broad system types: drip and sprinkler irrigation systems. For south-eastern Queensland, the SWAP model was simulated for the January 1980 – December 2007 period under three different soil types, two groundwater levels and three irrigation timings. Table 10 provides the estimates of average and potential water savings derived from the SWAP model.

Table 10: SWAP model simulation results for average water use and potential water savings for different crops grown under different irrigation technologies in south-eastern Queensland

| *Crop* | *Water use (ML/ha)* | | | *Water savings (ML/ha)* | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Surface** | | | *Sprinkler* | | | *Drip* | | |
| | *Low* | *Avg.* | *High* | *Low* | *Avg.* | *High* | *Low* | *Avg.* | *High* |
| Wheat | 0.7 | 2.5 | 3.8 | 0.1 | 0.6 | 1.0 | na | na | na |
| Barley | 0.7 | 2.1 | 3.8 | 0.1 | 0.6 | 1.3 | na | na | na |
| Maize | 4.0 | 7.1 | 9.0 | 0.5 | 1.0 | 1.2 | na | na | na |
| Sorghum | 2.8 | 3.8 | 4.2 | 0.4 | 0.7 | 1.1 | na | na | na |
| Lucerne | 11.0 | 12.5 | 14.0 | 1.5 | 2.0 | 3.2 | 2.1 | 3.1 | 4.2 |
| Cotton | 5.5 | 6.8 | 7.8 | 0.5 | 1.2 | 2.0 | 1.0 | 1.5 | 3.0 |

* Surface includes flood and furrow irrigation systems.

The results show that potential water savings ranged from 0.1 to 1.3 ML/ha for different broadacre crops under sprinkler irrigation systems, and from 3.0 ML/ha (cotton) to about 4.2 ML/ha (lucerne) under drip irrigation systems. Our results indicated that the average potential water savings under sprinkler irrigation were about 24% for wheat, 29% for barley, 14% for maize, 18% for sorghum, 14% for lucerne and 18% for cotton. Similarly, average potential water savings under drip irrigation were about 25% for lucerne and 23% for cotton.

## 4.2 Estimation of energy use and GHG emissions

The results of the various irrigation technologies present a generalised comparison of relative energy consumption and GHG emissions associated with these technologies. The energy consumption for installation, maintenance and decommissioning of irrigation machinery, accessories and structures differs with the different irrigation systems, as shown in Table 11.

Table 11: Energy consumption for installation, maintenance and decommissioning of irrigation machinery, accessories and infrastructure in different irrigation systems as a percentage of total energy values per megalitre of irrigation water

| *Energy requirements* | *Centre-pivot (%)* | *Lateral-move (%)* | *Drip (%)* |
|---|---|---|---|
| Installation | 2.1 | 2.5 | 16.0 |
| Maintenance | 2.2 | 3.0 | 5.4 |
| Decommissioning | 3.2 | 3.5 | 1.8 |
| Total | 7.5 | 9.0 | 23.2 |

Source: Experts survey (this study)

Installation, maintenance and decommissioning energies, combined with the pumping energy, were used to calculate the total energy (and GHG emissions) for different irrigation systems. There was considerable variation associated with the use of electric and diesel pumps for different irrigation systems. Where three-phase electric power is available, farmers indicated they were moving to electric pumps. In the Darling Downs region, 90% of lateral-moves are diesel based and 90% of centre-pivot and drip irrigation systems are electric, but in cotton areas, the ratio of electric to diesel is 60:40 due to more limited availability of three-phase power in these areas. However, the GHG emissions per ML of water due to the use of electric and diesel pumps differ significantly. To capture the variation and present some potential scenarios, all irrigations systems were analysed using both diesel and electric pumps. Considering the current practices, final analyses for lateral-move sprinkler systems were based on diesel pumps, while analyses for the other two (centre-pivot and drip) were based on electric pumps. The total energy consumption and GHG emissions for pumping 1 ML of water are given in Table 12. Even within the same irrigation system, energy consumption and GHG emissions varied enormously. This was mainly due to large variation in total dynamic heads, pump sizes and flow rates.

Surface irrigation systems were assumed to run on gravity-based system, to not require any energy and therefore not emit GHGs. On average, centre-pivot irrigation systems run by an electric pump increased GHG emissions by 906 kg $CO_2$-e/ML when compared with surface irrigation systems (Table 12). Similarly, drip irrigation systems run by an electric pump increased GHG emissions by 568 kg $CO_2$-e/ML. However, drip irrigation systems required 28% less energy (777–3262 MJ/ML), depending on the scale and farming system, compared with centre-pivot (2321–4127 MJ/ML) and lateral-move (2884–4195 MJ/ML) systems. Similarly, drip irrigation produced around 25% less GHG compared with centre-pivot and lateral-move. There was little difference in energy use and GHG emissions between centre-pivot and lateral-move. Irrigation technology generated less GHG when used with diesel because electricity is mainly generated through burning of coal, which implies a high emissions factor. As mentioned earlier, the inclusion of agriculture under the proposed CPRS has been a contentious issue in Australia. After much debate, the Australian Government decided to exclude agriculture indefinitely from its proposed CPRS in November 2009. However, if agriculture were to be have been included in the CPRS, it is unlikely that the irrigation industry would have been directly affected as it would only have affected industries exceeding 25 000 t $CO_2$-e/year. However, there could certainly be a flow on effect to the irrigation industry if the CPRS were to be implemented. Setting aside all these issues, this study analysed different carbon price scenarios solely based on science rather than policy.

We based our carbon price on the main drivers such as reduction targets, the Government's benchmark price and the international carbon price. With emission reduction targets of 5% and 15%, the starting prices could be around \$20 and \$29/t $CO_2$-e, respectively, in 2010, increasing at 4%/year (Lawson et al. 2008; Burns et al. 2009), However, in order to manage a safe transition to the CPRS, the Australian Government had benchmarked the starting price at \$10/t $CO_2$-e. Results based on three carbon price scenarios (\$10/t $CO_2$-e, \$20/t $CO_2$-e and

\$30/t $CO_2$-e) are presented in the bottom three rows of Table 12. The table shows that net return will decrease by \$9/ML at a carbon price of \$10/t $CO_2$-e under centre-pivot irrigation systems run by an electric pump. This implies that net return will decrease by about \$54/ha for a crop that requires about 6 ML during the entire cropping season. At \$30/t $CO_2$-e, net return will decrease by \$162/ha.

Table 13 presents an average crop-wide estimate of GHG emissions per ha for new high-tech irrigation technologies. Since lucerne consumes high amounts of water, it produces more GHGs on drip and sprinkler irrigation systems. On the other hand, conversion of a wheat crop to sprinkler irrigation produces relatively small amounts of GHGs. As discussed earlier, high-tech irrigation technologies operated on diesel produce, on average, 3.5 times less GHGs compared with those operated by electricity.

Table 12: Energy consumption and greenhouse gas emissions in different irrigation systems after considering installation, maintenance and decommissioning energy

| *Description* | *Electric* | | | | | | *Diesel* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Centre-pivot* | | *Lateral-move* | | *Drip* | | *Centre-pivot* | | *Lateral-move* | | *Drip* | |
| | *Min* | *Max* | *Min* | *Max* | *Min* | *Max* | *Min* | *Max* | *Min* | *Max* | *Min* | *Max* |
| Pumping energy (electric pump kWh/ML diesel pump L/ML) | 180 | 320 | 220 | 320 | 50 | 210 | 45 | 80 | 55 | 80 | 13 | 53 |
| Pumping energy (MJ/ML) | 2 147.4 | 3 817.6 | 2 624.6 | 3 817.6 | 596.5 | 2 505.3 | 1 737.0 | 3 088.0 | 2 123.0 | 3 088.0 | 501.8 | 2 045.8 |
| Installation, maintenance and decommissioning energy (MJ/ML) | 174.1 | 309.5 | 259.6 | 377.6 | 180.2 | 756.8 | 140.8 | 250.4 | 210.0 | 305.4 | 151.6 | 618.0 |
| Total energy (MJ/ML) | 2 321.5 | 4 127.1 | 2 884.2 | 4 195.2 | 776.7 | 3 262.1 | 1 877.8 | 3 338.4 | 2 333.0 | 3 393.4 | 653.4 | 2 663.8 |
| Total GHG emissions (kg $CO_2$-e/ML) | 652.3 | 1 159.7 | 810.5 | 1 178.8 | 218.3 | 916.7 | 141.2 | 251.0 | 175.4 | 255.2 | 49.1 | 200.3 |
| Emissions cost ($/ML) @ $10/t $CO_2$-e | 6.5 | 11.6 | 8.1 | 11.8 | 2.2 | 9.2 | 1.4 | 2.5 | 1.8 | 2.6 | 0.5 | 2.0 |
| Emissions cost ($/ML) @ $20/t $CO_2$-e | 13.0 | 23.2 | 16.2 | 23.6 | 4.4 | 18.3 | 2.8 | 5.0 | 3.5 | 5.1 | 1.0 | 4.0 |
| Emissions cost ($/ML) @ $30/t $CO_2$-e | 19.6 | 34.8 | 24.3 | 35.4 | 6.5 | 27.5 | 4.2 | 7.5 | 5.3 | 7.7 | 1.5 | 6.0 |

Table 13: Greenhouse gas emissions estimates based on average water use under sprinkler and drip irrigation technology

| *Crop* | *Irrigation technology* | *Average water use (ML/ha)* | *Centre-pivot* | | *Lateral-move* | | *Drip* | |
|---|---|---|---|---|---|---|---|---|
| | | | *Electric (kg $CO_2$-e/MJ)* | *Diesel (kg $CO_2$-e/MJ)* | *Electric (kg $CO_2$-e/MJ)* | *Diesel (kg $CO_2$-e/MJ)* | *Electric (kg $CO_2$-e/MJ)* | *Diesel (kg $CO_2$-e/MJ)* |
| Maize (grain) | Sprinkler | 6.5 | 5 889 | 1 275 | 6 465 | 1399 | – | – |
| Cotton | Sprinkler | 6 | 5 436 | 1 177 | 5 968 | 1292 | – | – |
| Cotton | Drip | 5.5 | – | – | – | – | 3 121 | 686 |
| Wheat | Sprinkler | 1.7 | 1 540 | 333 | 1691 | 366 | – | – |
| Soybean | Sprinkler | 4.7 | 4 258 | 922 | 4 675 | 1012 | – | – |
| Lucerne | Sprinkler | 10.7 | 9 694 | 2098 | 10 643 | 2304 | – | – |
| Lucerne | Drip | 9.5 | – | – | – | – | 5 391 | 1 185 |
| Sorghum | Sprinkler | 3.1 | 2 809 | 608 | 3 083 | 667 | – | – |
| Barley | Sprinkler | 1.4 | 1 268 | 275 | 1 393 | 301 | – | – |
| Tomato | Drip | 6.6 | – | – | – | – | 3 746 | 823 |
| Grape | Drip | 5.8 | – | – | – | – | 3 292 | 723 |
| Citrus | Drip | 7.2 | – | – | – | – | 4 086 | 898 |
| Wheat–maize | Sprinkler | 8.2 | 7 429 | 1608 | 8 156 | 1 765 | – | – |
| Cotton–maize | Sprinkler | 12.5 | 11 325 | 2451 | 12 433 | 2 691 | – | – |
| Cotton–wheat | Sprinkler | 7.7 | 6 976 | 1510 | 7 659 | 1 658 | – | – |

## 4.3 Economics of new irrigation technology

A key element of the project (and integrated analysis) was to undertake economic evaluations of new irrigation technologies. Four economic evaluation indexes—NPV, BCR, payback period and BE water savings—were used to assess the economic viability of new irrigation technology. To evaluate the economics of technology adoption, we calculated costs and benefits using Waterwork, a farm-level irrigation technology modernisation model. The model was simulated for 25 years with a 5% interest rate. The data for the analysis were taken from the expert survey, manufacturers' information and the literature review.

### 4.3.1 Cost of irrigation

Installation of systems such as centre-pivot or drip involves significant initial capital investment, maintenance and replacement costs (Hickey et al. 2006). For this study, the costs of irrigation technology were divided into fixed costs (machinery, soil moisture monitoring equipment, pipes, concrete, etc.) and variable costs (mainly for operation and maintenance such as power, fuel, usual maintenance and losses, if any). The capital cost of drip irrigation systems was $4500–6000/ha (Table 14). Capital costs are influenced by soil type, climatic conditions and economies of scale (Khan et al. 2010), while variable costs vary with economies of scale and soil type. The variable costs for drip irrigation include maintenance ($40–45/ha) and power ($45–55/ha). The capital costs of sprinkler irrigation systems were $2200–3500/ha. The variable cost varied with the size of the sprinkler irrigation system, and included maintenance ($22–38/ha), power ($15–19/ha) and corner production losses (about $31/ha).

### 4.3.2 Benefits of new irrigation technologies

The benefits that drip and pivot irrigation systems offer to irrigators can vary depending on soil type, climatic conditions, groundwater level and groundwater system (EconSearch 2005; Khan and Abbas 2007; Khan et al. 2010). The main benefits include water savings, labour savings, yield increases, lower input costs and quality improvements leading to increased output prices. The benefits indicated in the case studies (section 5.4) included water savings, yield increases and labour savings.

Table 14: Capital and operational costs of irrigation technology

| *Parameters* | *Drip irrigation* | | | *Sprinkler irrigation* | | |
|---|---|---|---|---|---|---|
| Capital cost | Low | Avg.* | High | Low | Avg.* | High |
| Drip/pivot ($/ha) | 4 500 | 5 500 | 6 000 | 2 200 | 2 500 | 3 500 |
| Soil moisture monitoring ($/ha) | 62 | 62 | 62 | 62 | 62 | 62 |
| Variable cost ($/ha) | | | | | | |
| Maintenance ($/ha) | 47 | 42 | 40 | 38 | 30 | 22 |
| Power ($/ML) | 43 | 46 | 55 | 15 | 16 | 19 |
| Corner production losses ($/ha) | na | na | na | 31 | 31 | 31 |

* Average based on 20 ha of drip–sprinkler irrigation technology convergence
Source: Expert survey (this study), Khan et al. (2010), Jackson (2009), EconSearch (2005), Pratt Water (2004) and Quereshi et al. (2001)

### 4.3.3 Parameters and assumptions for economic analysis

- Yield benefits: a change in irrigation technology increases production (Khan et al 2004a); we have assumed a 5–7% yield increase (depending on crop and technology) in this study (Table 15).

- Labour savings: based on labour savings of around 4.5–6.0 hours/ha (expert survey, this study; Khan et al. 2004a) we have assumed an average of 5.0 hours/ha in this study.
- Water savings: we conducted the economic evaluation on average water savings (see Tables 4 and 6) and the sensitivity analysis was conducted on the full range of water savings.
- Water trading prices: based on information from Watermove (www.watermove.com.au), Water Exchange (www.waterexchange.com.au/) and irrigation provider websites (e.g. SunWater, Murray Irrigation), we assumed average temporary (allocation) water trading prices to be about $300/ML and average permanent (water entitlement) water trading prices to be about $1500/ML (Murray Irrigation Limited 2009).

### Other assumptions

We made the following assumptions based on a literature review and consultation with irrigation experts, irrigation technology providers (through the survey) and irrigators.

- Irrigation efficiency: IEs of 90% for drip irrigation, 85% for sprinkler irrigation and 70% for surface irrigation (see Figure 1).
- Commodity prices and fuel prices remained constant over the period of analysis.
- The life of the technology was 25 years with a 5% interest rate.
- An average of 20 ha area was used to manage economies of scale.
- Although possible, tax savings were not included in the analysis.

Table 15: Yields and gross margins of major crops

| *Crop* | *Yield (t/ha)* | *Gross margin ($/ha)* | *Price* [*] *($/t)* |
|---|---|---|---|
| Wheat | 5.0 | 325 | 190 |
| Barley | 4.5 | 240 | 160 |
| Maize (silage) | 10.0 | 580 | 180 |
| Maize (grain) | 11.0 | 2 080 | 320 |
| Sorghum | 8.0 | 480 | 170 |
| Cotton | 7.0 [†] | 1 140 | 400, 275 [‡] |
| Soybean (human consumption) | 3.0 | 1 176 | 610 |
| Lucerne | 13.5 | 1 990 | 350 |
| Vines (grapes) | 14.0 | 3 750 | 500 |
| Citrus | 30.0 | 3 271 | 300 |
| Tomato (processing) | 60.0 | 2 250 | 120 |

* 2003–2008 average prices
† cotton (bales/ha)
‡ $400/bale for lint and $275/t for seed
Source: DPI NSW (2010), DPI Vic (2010), DEEDI (2010), ABARE (2010)

## 4.3.4 Economic evaluation

The results indicate that, under average levels of water savings, sprinkler technology is not economically beneficial for most grain crops (wheat, soybean and barley) (Table 16). However, sprinkler technology is economically feasible at high levels of water savings. The estimated BE water saving from converting surface irrigation to sprinkler irrigation (primarily for grain) was 0.60–1.6 ML/ha. On the basis of these results, drip irrigation of horticultural or vegetable crops is an economically feasible option. This was due to the relatively higher level of water savings under an average level of water use and increased productivity. The estimated BE water saving from converting surface irrigation to drip irrigation (mainly for horticultural crops) was 0.23–2.41 ML/ha.

Table 16: Economic evaluation of irrigation technology based on crops

| *Crop* | *Irrigation technology* | *Average water saving (ML/ha)* | *Economic evaluation indexes** | | | | |
|---|---|---|---|---|---|---|---|
| | | | *NPV ($)* | *BCR* | *IRR* | *Payback period (years)* | *BE water saving (ML/ha)* |
| Maize (silage) | Sprinkler | 1.0 | 42 187 | 1.35 | 10.7 | 10.2 | 0.62 |
| Maize (grain) | Sprinkler | 1.0 | 56 986 | 1.48 | 12.6 | 10.6 | 0.56 |
| Cotton | Sprinkler | 1.0 | 42 157 | 1.35 | 10.7 | 12.4 | 0.80 |
| Cotton | Drip | 1.5 | 40 580 | 1.20 | 8.76 | 15.1 | 1.10 |
| Wheat | Sprinkler | 0.6 | –45 180 | 0.59 | na | <25.0 | 1.60 |
| Soybean | Sprinkler | 0.7 | 10 001 | 1.01 | 6.4 | 20.8 | 0.63 |
| Lucerne | Sprinkler | 2.3 | 113 795 | 1.83 | 20.0 | 6.8 | 1.20 |
| Lucerne | Drip | 3.5 | 135 979 | 1.54 | 17.6 | 7.9 | 2.41 |
| Sorghum | Sprinkler | 0.7 | –31 051 | 0.71 | na[‡] | <25.0 | 0.96 |
| Barley | Sprinkler | 0.6 | –43 933 | 0.57 | na[‡] | <25.0 | 0.98 |
| Tomato | Drip | 1.5 | 173 718 | 1.82 | 20.4 | 6.7 | 0.23 |
| Grape | Drip | 2.2 | 170 378 | 1.84 | 20.1 | 6.8 | 0.81 |
| Citrus | Drip | 1.5 | 130 757 | 1.83 | 21.9 | 7.2 | 0.78 |

* Net present value (NPV), benefit–cost ratio (BCR), internal rate of return (IRR), payback period (years), break-even (BE) water saving (ML/ha)

Although most of the grain crops under sprinkler irrigation technology show negative economic returns with average water savings, the technology can be used for more than one crop during the cropping (calendar) year, doubling the cropping intensity and increasing the overall water savings during the crop year. Table 17 presents an evaluation of irrigation technology using crop rotations. The results indicate that if sprinkler irrigation technology is used on two crops per year, it would yield economic benefits. The BE water saving with two crops per cropping year was 0.18–0.48 ML/ha, mainly due to increases in crop productivity, cropping intensity and labour savings.

Table 17: Economic evaluation of irrigation technology based on cropping pattern

| *Crop rotation* | *Irrigation technology* | *Average water saving (ML/ha)* | *Economic evaluation indexes** | | | | |
|---|---|---|---|---|---|---|---|
| | | | *NPV ($)* | *BCR* | *IRR* | *Payback period (years)* | *BE water saving (ML/ha)* |
| Wheat–maize | Sprinkler | 1.7 | 79 648 | 1.90 | 19.10 | 7.3 | 0.41 |
| Cotton–maize | Sprinkler | 2.0 | 140 713 | 30.50 | 2.59 | 6.1 | 0.18 |
| Cotton–wheat | Sprinkler | 1.7 | 92 111 | 1.72 | 21.30 | 7.8 | 0.48 |

* Net present value (NPV), benefit–cost ratio (BCR), internal rate of return (IRR), payback period (years), break-even (BE) water saving (ML/ha)

## 4.3.5 Sensitivity analyses

The economic evaluation strongly depends on the use of saved irrigation water. The irrigator has a number of choices concerning the rational use of saved water. Farmers may use the water to increase the crop area or intensity growing high value cash crops, trade the saved water temporarily or permanently through the water market, or sell it to share water savings with the government on a 50/50 basis. Another key factor that was expected to influence the economics was the energy use and GHG emissions. An emissions tax may reduce the economic benefits and make technology adoption unattractive. In addition, the level of water savings, interest rate and technology life also affect the economic returns. We used the following key parameters in our scenarios:

- water trading
- water savings
- carbon price
- yield benefits
- technology life
- interest rate.

### Water trading

We applied the following water-trading scenarios to average saved water:

- S1—total water saving temporarily traded at $300/ML
- S2—total water saving permanently traded at $2000/ML
- S3—half the total water saving traded temporarily at $100/ML and the other half traded permanently at $800/ML
- S4—half the total water saving traded temporarily at $1000/ML and the other half traded permanently at $2500/ML
- S5—half the total water saving traded temporarily at $300/ML and the other half traded permanently at $2500/ML (a scenario similar to government's onfarm water sharing and buyback plan).

The NPV of irrigation technology under different water trading and water sharing prices is presented in Table 18. The high temporary ($1000/ML) and permanent ($2500/ML) water trading prices in scenario (S4) make irrigation technology highly feasible, whereas the low water trading prices scenario (S3) is infeasible except for tomatoes and grapes. Scenario 5 is mainly feasible for horticulture crops and for double cropping during one crop year.

Table 18: Net present value (NPV) of irrigation technology under various water trading prices and water sharing plans

| *Crop* | *Irrigation technology* | *Average water saving (ML/ha)* | *Net present value (NPV)* ($)* | | | | |
|---|---|---|---|---|---|---|---|
| | | | *S1* | *S2* | *S3* | *S4* | *S5* |
| Maize (grain) | Sprinkler | 1.0 | 56 986 | 8 194 | –9 008 | 141 180 | 37 590 |
| Cotton | Sprinkler | 1.0 | 42 157 | –6 635 | –23 036 | 126 351 | 22 761 |
| Cotton | Drip | 1.5 | 40 580 | –32 608 | –58 410 | 166 872 | 11 486 |
| Wheat | Sprinkler | 0.6 | –45 180 | –74 385 | –74 385 | 5 407 | –56 747 |
| Soybean | Sprinkler | 0.7 | 10 001 | –24 154 | –36 195 | 68 937 | –3 576 |
| Lucerne | Sprinkler | 2.3 | 113 795 | 1 574 | –37 989 | 307 443 | 69 185 |
| Lucerne | Drip | 3.5 | 135 979 | –34 793 | –94 997 | 430 660 | 68 093 |
| Sorghum | Sprinkler | 0.7 | –1 051 | –65 205 | –77 246 | 27 886 | –44 628 |
| Barley | Sprinkler | 0.6 | –43 933 | –73 208 | –83 529 | 6 584 | –55 570 |
| Tomato | Drip | 1.5 | 173 718 | 100 530 | 74 728 | 300 009 | 144 624 |
| Grape | Drip | 2.2 | 170 378 | 63 036 | 25 193 | 355 606 | 127 707 |
| Citrus | Drip | 1.5 | 130 757 | 48 377 | 19 334 | 272 910 | 174 447 |
| Wheat–maize | Sprinkler | 1.6 | 79 648 | 17 296 | –13 328 | 204 868 | 56 567 |
| Cotton–maize | Sprinkler | 2.0 | 140 713 | 67 357 | 31 329 | 288 030 | 113 559 |
| Cotton–wheat | Sprinkler | 1.7 | 92 111 | 29 758 | –866 | 217 330 | 69 030 |

* Assumptions: 5% interest rate; 25 year technology life; 5% (sprinkler) and 8% (drip) yield increase; $300/ML temporary water trading price

## Water savings

We conducted the sensitivity analysis for low, medium and high water savings (Tables 4 and 10). The sensitivity analysis indicated that adoption of irrigation technology at a low level of water savings was not an economically viable option for grain and cotton. However, drip irrigation technology for horticulture crops (vegetables, vines and citrus) and double crops such as cotton–maize and cotton–wheat were still viable options (Table 19).

Table 19: Net present value (NPV) of irrigation technology under various water savings

| *Crop* | *Irrigation technology* | *Water saving (ML/ha)* | | | *Net present value (NPV)* ($)* | | |
|---|---|---|---|---|---|---|---|
| | | *Low* | *Avg.* | *High* | *Low* | *Avg.* | *High* |
| Maize (grain) | Sprinkler | 0.4 | 1.0 | 1.4 | –9 487 | 56 986 | 101 399 |
| Cotton | Sprinkler | 0.5 | 1.0 | 2.0 | –15 802 | 42 157 | 160 938 |
| Cotton | Drip | 1.0 | 1.5 | 3.0 | –24 263 | 40 580 | 283 071 |
| Wheat | Sprinkler | 0.1 | 0.6 | 1.0 | –103 068 | –45 180 | 1 376 |
| Soybean | Sprinkler | 0.4 | 0.7 | 1.0 | –4 589 | 10 001 | 43 237 |
| Lucerne | Sprinkler | 1.5 | 2.3 | 3.5 | 20 824 | 113 795 | 253 252 |
| Lucerne | Drip | 2.5 | 3.5 | 4.5 | 6 293 | 135 979 | 265 665 |
| Sorghum | Sprinkler | 0.4 | 0.7 | 1.1 | –66 063 | –31 051 | 15 435 |
| Barley | Sprinkler | 0.1 | 0.6 | 1.4 | –102 188 | –43 933 | 2 553 |
| Tomato | Drip | 1.0 | 1.5 | 2.0 | 108 874 | 173 718 | 191 945 |
| Grape | Drip | 1.7 | 2.2 | 3.0 | 105 535 | 170 378 | 274 127 |
| Citrus | Drip | 1.2 | 1.5 | 2.5 | 81 723 | 130 757 | 172 048 |
| Wheat–maize | Sprinkler | 0.5 | 1.7 | 2.6 | –10 080 | 79 648 | 146 944 |
| Cotton–maize | Sprinkler | 0.9 | 2.0 | 2.9 | 58 463 | 140 713 | 208 009 |
| Cotton–wheat | Sprinkler | 0.6 | 1.7 | 2.7 | 9 860 | 92 111 | 166 884 |

* Assumptions: 5% interest rate; 25 year technology life; 5% (sprinkler) and 8% (drip) yield increase; $300/ML temporary water trading price

## Carbon price

We considered two carbon price scenarios: $10/t $CO_2$-e and $30/t $CO_2$-e. The preliminary results indicated that, at a carbon price of $10/t $CO_2$-e, the costs of converting to a sprinkler irrigation system using electric motors would increase by $60/ha for cotton and by about $102/ha for lucerne.

The NPV of irrigation technology under different carbon prices is presented in Table 20. A $10/t $CO_2$-e carbon price reduced the NPV, although the results did not change much compared with the baseline economic evaluation. However, at $30/t $CO_2$-e, with average water savings achieved through adopting sprinkler irrigation, soybean was no longer an economically viable option.

Table 20: Net present value (NPV) of irrigation technology under various GHG emission tax

| *Crop* | *Irrigation technology* | *Avg. water saving (ML/ha)* | *Net present value (NPV)* ($)* | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | *Diesel ($/t $CO_2$-e)* | | | *Electric ($/t $CO_2$-e)* | | |
| | | | *0* | *10* | *30* | *0* | *10* | *30* |
| Maize (grain) | Sprinkler | 1.0 | 56 986 | 55 012 | 51 063 | 56 986 | 47 865 | 29 624 |
| Cotton | Sprinkler | 1.0 | 42 157 | 40 335 | 36 690 | 42 157 | 33 738 | 16 900 |
| Cotton | Drip | 1.5 | 40 580 | 39 567 | 37 542 | 40 580 | 35 971 | 26 754 |
| Wheat | Sprinkler | 0.6 | –45 180 | –45 696 | –46 729 | –45 180 | –47 565 | –52 336 |
| Soybean | Sprinkler | 0.7 | 10 001 | 8 574 | 5 719 | 10 001 | 3 406 | -9 784 |
| Lucerne | Sprinkler | 2.3 | 113 795 | 110 545 | 104 046 | 113 795 | 98 781 | 68 753 |
| Lucerne | Drip | 3.5 | 135 979 | 134 230 | 130 732 | 135 979 | 128 019 | 112 098 |
| Sorghum | Sprinkler | 0.7 | –31 051 | –31 993 | –33 876 | –31 051 | –35 401 | –44 100 |
| Barley | Sprinkler | 0.6 | –43 933 | –44 358 | –45 209 | –43 933 | –45 897 | –49 826 |
| Tomato† | Drip | 1.5 | 173 718 | 172 503 | 170 072 | 173 718 | 168 188 | 157 127 |
| Grape | Drip | 2.2 | 170 378 | 169 310 | 167 174 | 170 378 | 165 518 | 155 798 |
| Citrus | Drip | 1.5 | 130 757 | 129 527 | 127 307 | 130 757 | 125 637 | 14 437 |
| Wheat–maize | Sprinkler | 1.7 | 79 648 | 77 158 | 72 177 | 79 648 | 68 142 | 45 130 |
| Cotton–maize | Sprinkler | 2.0 | 140 713 | 136 917 | 129 324 | 140 713 | 123 173 | 88 094 |
| Cotton–wheat | Sprinkler | 1.7 | 92 111 | 89 772 | 85 095 | 92 111 | 81 307 | 59 698 |

* Assumptions: 5% interest rate; 25 year technology life; 5% (sprinkler) and 8% (drip) yield increase; $300/ML temporary water trading price

† Yield increased by 20% (DPI NSW 2010)

## Yield benefits

We applied the following yield benefits scenarios to current yield:

- S1—0% yield increase
- S2—5%(sprinkler) to 8% (drip) yield increase
- S3—15% yield increase.

The NPV under different levels of yield increase is presented in Table 21. Under S1, none of the new irrigation technologies showed economic potential. At a 15% yield increase (S3), both sprinkler and drip for most of the crops (except wheat and barley) showed economic potential.

Table 21: Net present value (NPV) of irrigation technology under various yield assumptions

| *Crop* | *Irrigation technology* | *Average water saving (ML/ha)* | *Net present value (NPV)* ($)* | | |
|---|---|---|---|---|---|
| | | | *0%* | *5–8%*† | *15%* |
| Maize (grain) | Sprinkler | 1.0 | –14 048 | 56,986 | 128 019 |
| Cotton | Sprinkler | 1.0 | –17 038 | 42,157 | 107 271 |
| Cotton | Drip | 1.5 | –54 132 | 40,580 | 70 177 |
| Wheat | Sprinkler | 0.6 | –73 227 | –45 180 | –30 903 |
| Soybean | Sprinkler | 0.7 | –44 162 | 10,001 | 37 230 |
| Lucerne | Sprinkler | 2.3 | –93 386 | 113 795 | 186 309 |
| Lucerne | Drip | 3.5 | –122 997 | 135,979 | 218 851 |
| Sorghum | Sprinkler | 0.7 | –51 177 | –31,051 | 9 202 |
| Barley | Sprinkler | 0.6 | –62 875 | –43,933 | –29 726 |
| Tomato‡ | Drip | 1.5 | –359 034 | 173,718 | 351 301 |
| Grape | Drip | 2.2 | –51 601 | 170 378 | 362 761 |
| Citrus | Drip | 1.5 | –38 729 | 130 757 | 321 429 |
| Wheat–maize | Sprinkler | 1.7 | –7 587 | 79 648 | 186 823 |
| Cotton–maize | Sprinkler | 2.0 | –5 095 | 140 713 | 301 476 |
| Cotton–wheat | Sprinkler | 1.7 | –12 602 | 92 111 | 158 623 |

* Assumptions: 5% interest rate; 25 year technology life; $300/ML temporary water trading price
† Yield modelling during basic economic analysis (sprinkler 5% and drip 8%)
‡ Yield increase by 20% (DPI NSW 2010)

## Technology life

We applied the following technology life scenarios:

- S1—30 years
- S2—25 years
- S3—20 years
- S4—15 years.

The NPV under technology life scenarios is presented in Table 22. Compared with the baseline technology life (25 years), technology life did not significantly change the results, although longer life made economic returns more attractive.

Table 22: Net present value (NPV) of irrigation technology under various yield assumptions

| *Crop* | *Irrigation technology* | *Average water saving (ML/ha)* | *Net present value (NPV)* ($)* | | | |
|---|---|---|---|---|---|---|
| | | | *30 years* | *25 years* | *20 years* | *15 years* |
| Maize (grain) | Sprinkler | 1.0 | 69 071 | 56 986 | 41 562 | 21 876 |
| Cotton | Sprinkler | 1.0 | 52 897 | 42 157 | 28 449 | 10 955 |
| Cotton | Drip | 1.5 | 54 542 | 40 580 | 22 760 | 180 |
| Wheat | Sprinkler | 0.6 | –42 286 | –45 180 | –48 713 | –53 313 |
| Soybean | Sprinkler | 0.7 | 17 824 | 10 001 | 16 | –12 727 |
| Lucerne | Sprinkler | 2.3 | 131 034 | 113 795 | 91 794 | 63 714 |
| Lucerne | Drip | 3.5 | 158 595 | 135 979 | 107 115 | 70 276 |
| Sorghum | Sprinkler | 0.7 | –26 951 | –31 051 | –36 282 | –42 960 |
| Barley | Sprinkler | 0.6 | –41 002 | –43 933 | –47 673 | –52 447 |
| Tomato | Drip | 1.5 | 199 757 | 73 718 | 140 484 | 98 069 |
| Grape | Drip | 2.2 | 196 115 | 170 378 | 137 532 | 95 610 |
| Citrus | Drip | 1.5 | 152 043 | 130 757 | 106 306 | 91 119 |
| Wheat–maize | Sprinkler | 1.7 | 92 895 | 79 648 | 62 741 | 52 255 |
| Cotton–maize | Sprinkler | 2.0 | 161 805 | 140 713 | 113 793 | 98 229 |
| Cotton–wheat | Sprinkler | 1.7 | 106 025 | 92 111 | 74 354 | 64 034 |

* Assumptions: 5% interest rate; 5% (sprinkler) and 8% (drip) yield increase; $300/ML temporary water trading price

## Interest rate

We applied the following interest rate scenarios:

- S1—10% interest rate
- S2—7% interest rate
- S3—5% interest rate
- S4—2% interest rate.

The NPV under various interest rates is presented in Table 23. Although lower interest rates (2%) made irrigation technology more attractive, adopting sprinkler irrigation technology for wheat and barley was not an economically viable option.

Table 23: Net present value (NPV) of irrigation technology under various interest rates

| *Crop* | *Irrigation technology* | *Average water saving (ML/ha)* | *Net present value (NPV) ($)* | | | |
|---|---|---|---|---|---|---|
| | | | *10% interest rate* | *7% interest rate* | *5% interest rate* | *2% interest rate* |
| Maize (grain) | Sprinkler | 1.0 | 13 649 | 36 016 | 56 986 | 103 036 |
| Cotton | Sprinkler | 1.0 | 3 643 | 23 521 | 42 157 | 83 081 |
| Cotton | Drip | 1.5 | –9 487 | 16 354 | 40 580 | 93 781 |
| Wheat | Sprinkler | 0.6 | –55 236 | –50 009 | –45 180 | –34 349 |
| Soybean | Sprinkler | 0.7 | –18 053 | –3 573 | 10 001 | 39 810 |
| Lucerne | Sprinkler | 2.3 | 51 978 | 83 884 | 113 795 | 179 483 |
| Lucerne | Drip | 3.5 | 54 879 | 96 737 | 135 979 | 222 156 |
| Sorghum | Sprinkler | 0.7 | –45 750 | –38 163 | –31 051 | –15 431 |
| Barley | Sprinkler | 0.6 | –54 442 | –49 018 | –43 933 | –32 766 |
| Tomato | Drip | 1.5 | 80 342 | 128 536 | 173 718 | 272 939 |
| Grape | Drip | 2.2 | 78 089 | 125 722 | 170 378 | 268 446 |
| Citrus | Drip | 1.5 | 63 795 | 98 760 | 130 757 | 198 555 |
| Wheat–maize | Sprinkler | 1.7 | 35 557 | 58 527 | 79 648 | 124 599 |
| Cotton–maize | Sprinkler | 2.0 | 77 273 | 110 437 | 140 713 | 204 721 |
| Cotton–wheat | Sprinkler | 1.7 | 44 071 | 69 121 | 92 111 | 140 950 |

* Assumptions: 5% interest rate; 5% (sprinkler) and 8% (drip) yield increase; $300/ML temporary water trading price

## 4.4 Farm level case studies

We undertook five case studies for detailed analysis over the full crop cycle to increase our understanding of the finer-scale farm-level variability of trade-offs between water savings and increased energy consumption (and GHG emissions). In the integrated analysis, the information on crop yield, energy use, prices received, input use, water and labour used and capital and operating costs for both systems was based on the farmer's records and accounts. To fill gaps in the data required for the analysis, information was collected through personal discussions with the local irrigation and industry people, and the technical staff involved in the project.

We assessed three cotton farms on the Darling Downs, a vegetable (lettuce) farm in the Lockyer Valley and a pasture–cropping (lucerne, oats) and vegetable (onion) farm on the southern Downs, all in southern Queensland. Irrigation technology transitions were from flood (furrow) to overhead sprinkler (lateral-move and/or centre-pivot), from flood (furrow) to drip (trickle), from overhead sprinkler (hand-shift) to drip (trickle), and from overhead sprinkler (roll-line) to improved overhead sprinkler (centre-pivot) systems.

### 4.4.1 Case study 1: Cotton farm, Darling Down, southern Queensland

#### Farm description and parameter estimation

This farm is a mixed farm with irrigated and dryland cotton and grain (wheat, corn) enterprises on the Darling Downs, southern Queensland. Cropping soil types are light dispersible clays (light box country) to heavy alluvial black cracking clays with high soil moisture-holding capacity. Irrigation water is sourced from overland flows (authorised water-harvesting) diverted from an unregulated watercourse. Harvested water is stored in onfarm storages or ‘ring tanks’ (authorised storage capacity) and distributed to irrigation paddocks by open channels. In a normal irrigation season, this farm relies on 2 ML/ha of irrigation water applied by lateral move sprinklers and 4 ML/ha applied by surface (furrow) irrigation.

#### *Property development*

The property was set up for surface irrigation when purchased. This area was expanded in 1996, and two lateral-move sprinkler systems were purchased in 2006. Currently, 453 ha are irrigated by furrow and 154 ha by lateral-move sprinkler irrigation. There are future plans to convert another 180 ha to lateral-move. Price is seen as a major barrier to the adoption of new irrigation technologies, but this is managed on a risk-management basis, with current investments paid off before additional systems are purchased. At the time of purchase, establishment costs for the lateral-move sprinkler system were approximately 155% above those for surface irrigation ($3250/ha and $1270/ha, respectively). The additional pumping cost is about $45/ML. Further barriers to adoption relate to the pre-existing shape or orientation of paddocks.

#### *Cropping system*

Farming is on a 4–5 year crop rotation with 2–3 crops of cotton (irrigated, dryland), followed by wheat (double-cropped, dryland), then corn (irrigated) if sufficient water is available (or fallow if insufficient water), then back into cotton. At any time, two-thirds of the irrigation area is planted to cotton and one-third to grain (corn, wheat) or fallow. This farming system is essentially opportunistic, with the area of irrigated cropping determined by water availability. Water savings achieved through the use of the lateral-move sprinkler systems (estimated at 2 ML/ha) allow an increased area of irrigated crop to be grown in any season, and carry-over that provides insurance in terms of available water for planting in the next season. This is critical as rainfall patterns in the region are highly variable and storages on this property are filled on average once every two years.

#### *Technology adoption*

Principal drivers for adoption of new irrigation technology were stated as increased productivity and terms of trade, rather than water savings. To quote: ’Adoption was about everything – greater flexibility, increased productivity, increased cropping intensity, reduced labour, fewer workings of paddocks and water saving’. Farming operations under sprinkler irrigation do not require furrow preparation, although furrows have been retained on this property to enable storm water control. Greater water savings are possible on the lighter country (15% savings for the same level of productivity); on heavier soils, there is a similar level of water use (i.e. little water saved), but better productivity is achieved.

The lateral-move sprinkler systems allow better control of moisture levels in the soil profile. Soil moisture levels and crop requirements are determined through monitoring, and a deficit irrigation protocol is followed. This is less easily controlled using flood irrigation, where crop stress needs to be anticipated due to the length of time taken to complete a water application. In addition, flooding provides a full profile of soil moisture, which is not always useful, and over-watering issues can arise when rain follows water application.

Drip irrigation has been considered on this farm but a number of issues make it less attractive, including damage from pests (mice and crickets), soil movement on self-mulching clay soils and the relatively short lifespan (15 years) of drip systems. Overhead irrigation has a much better lifespan and ‘can be taken away’ (i.e. value can be recouped). Drip irrigation is possibly a better option on sandy soil types.

Other technologies adopted include GPS technology (enabling straighter cultivation and less wear and tear on drivers) and licensed Bollgard and Roundup Ready GM crops, with associated benefits is terms of reduced paddock workings and herbicide use.

### *Crop production*

Production benefits are realised as increased yields and quality under the lateral-move system. In 2009, cotton grown under a lateral-move system yielded 2.6 t/ha (0.65 t/ML) while a crop grown on furrow irrigation (but also lighter soils) yielded 2.2 t/ha (0.37 t/ML). While some of this difference could be due to different soil types in the different paddocks, the landholder also reported greater corn production of 11.9 t/ha (4.0 t/ML) under lateral-move irrigation compared to 10.4 t/ha (2.9 t/ML) under flood irrigation on the same soil type. In these instances, yield improvement for cotton was 18% per ha but 77% per ML of water; for corn, this was 14% and 38%, respectively.

In addition, better cotton fibre quality (longer staple) was maintained when irrigation (and available soil moisture) could be extended over longer periods (i.e. under the lateral-move system), although this has not been measured. However, it was felt that increased productivity could not be attributed solely to lateral-moves; in reality, it was due to a combination of all growing conditions. Cotton staple is most likely to be affected when water is insufficient, often resulting in price discounts for cotton grown under dryland conditions.

### *Labour saving*

While new irrigation technologies can reduce labour requirements, they require more management and greater skill. Increased labour involves checking and maintenance (estimated at 20 hours/crop), and savings are not as evident at this scale except, for example, at the larger scale of Cubbie Station. Labour is usually subcontracted (mechanics, electricians, consultants etc), which means changing from flood irrigation to lateral-moves might save 20% labour (in hours) but could still incur similar labour costs due to the increased cost of skilled labour required to manage lateral-moves.

### *Crop inputs*

We expect that N application will increase in the longer term because of the increased frequency of cropping (fertilisers are applied on the basis of soil tests). Some fertiliser application has occurred through the lateral-move sprinkler system, which is expected to deliver greater efficiency of N use, but there are no data to support this. There has been no evidence of increased requirement or nutrient tie-ups in the lateral-move system—and no waterlogging—so denitrification would be minimised.

In recent years, more frequent long-fallow cropping has allowed a natural N build-up in the soil, and soil tests have indicated that less N fertiliser is needed. The standard level of N application is 200 kg N/ha; on fallow, this can be reduced to 100 kg N/ha. In the event of a crop failure, N is generally available for the next crop. There has been no evidence of denitrification except in areas where flood irrigation and rain has caused ponding, which is a limited problem as the farm has been laser-levelled. Anyway, this may not be a big issue on these soil types.

The application of crop sprays has been minimised under the lateral-move systems by planting genetically modified (GM) cotton (Bollgard, Roundup Ready Flex), although conventional cotton is still grown on the flood paddocks where crop spraying is easier (ease of turning boom sprays, etc). After Christmas, most spraying is done by aeroplane in both systems.

Herbicides are applied on a paddock-by-paddock basis. More weeds are germinating with additional watering, which can be an issue for some crops (e.g. corn) grown under the lateral-move system. However, this is not resulting in greater use of herbicides; instead, it is being managed through longer-term rotations, while herbicide can be applied when GM cotton is grown.

#### *Soil health*

Soil carbon content is likely to increase under the lateral-move system, due to minimum till (fewer cultivations with the lateral-move system) and the increased frequency of cropping (stubble from six crops in 3.5 years), although not all these are grown on full water (i.e. some are rainfed).

#### *Climate change*

Water savings are dependent on soil conditions and climate variables during the growing season, and future climate change is likely to increase the need for efficient water use. Climate change was seen as beneficial for irrigated cotton enterprises already set up to cope with ephemeral rains, with dams currently filling, on average, every two years. High intensity rain is better for overland flow harvesting; longer dry periods between rainfall events are also beneficial for cotton when deficit watering is possible.

#### *Water trading*

This landholder stated that he would not be interested in ‘giving saved water back’ through government water buy-back initiatives. While water savings are evident in the examples given above, there is no conclusive evidence that this is the case in every year nor that a predictable quantity of water can be saved. We need to account for other variables such as evaporative losses from storage dams (up to 20%) and seepage losses (around 3 mm/day). In any case, water in this location is not really tradeable; storage volumes would need to be separated from the land title to enable trading, and transfer of water volumes in storages situated away from the river is not physically possible now.

## Hydrological modelling

Detailed hydrological analysis was not performed in this case study because the water saving assessment (section 5.1, Table 6) was performed for the same region, soil types and environmental conditions. Instead, we used the farmer’s estimates of water savings and validated these against the water saving assessment derived through SWAP modelling. Based on the farmer’s assessment, water savings of 2.0 ML/ha (33%) and 1.2 ML/t (44%) were achieved for cotton grown under lateral-move irrigation compared to furrow irrigation. These estimates are within the upper limits of water savings estimated through SWAP modelling (Table 6). Similarly for corn, savings were 0.6 ML/ha (17%) and 0.09 ML/t (28%), respectively.

## Energy consumption and GHG estimation

#### *Use of fuels for farm operations for cotton crops*

The energy consumed and GHG emitted due to the use of fuels (diesel, aviation gas, electricity) for farm operations in the two different irrigation systems for cotton cropping is given in Table 24. The analysis shows that the amount of diesel used for farm machinery operation in furrow irrigation was higher than in lateral-move irrigation. This corresponds with a higher amount of diesel-related emissions (405.86 kg $CO_2$-e/ha) in furrow irrigation. This landholder used both electricity (225.0 kWh) and diesel (166.2 L/ha) for the lateral-move irrigation system, while only electricity (222.2 kWh) was used for the furrow irrigation system. Therefore, the irrigation energy-related emission in lateral-move (1236.71 kg $CO_2$-e/ha) was much higher than that from furrow irrigation (744.89 kg $CO_2$-e/ha). On aggregate, fuel-related emissions in the lateral-move system were 1.28 times the emissions from flood irrigation. However, this figure could increase if we considered GHG emission on a per ML basis, as sprinkler irrigation used 4 ML/ha of water whereas furrow used 6 ML/ha (discussed later).

Table 24: Energy consumption (MJ/ha) and greenhouse gas emissions (kg $CO_2$-e/ha) due to use of fuels in farm operations for cotton crops in case study 1, Darling Downs, southern Queensland

| *Farming operation* | *Sprinkler irrigation (lateral-move)* | | | | *Flood irrigation (furrow)* | | | |
|---|---|---|---|---|---|---|---|---|
| | *Diesel (L)* | *Electricity (kWh)* | *Energy used* | *Emissions (kg $CO_2$-e/ha)* | *Diesel (L)* | *Electricity (kWh)* | *Energy used* | *Emissions (kg $CO_2$-e/ha)* |
| Farm machinery operation | 79.61 | – | 3 072.95 | 231.09 | 139.82 | – | 5 397.05 | 405.86 |
| Aviation gas | 0.26 | – | 8.61 | 0.62 | 0.21 | – | 6.95 | 0.50 |
| Irrigation | 166.20 | 225 | 9 099.57 | 1236.71 | – | 222.2 | 2 650.85 | 744.89 |
| Total | – | – | 12 181.13 | 1468.42 | – | – | 8 054.85 | 1 151.25 |

Note: Sprinkler irrigation used 4 ML/ha of water and flood irrigation used 6 ML/ha

### *Use of agrochemicals for cotton crops*

In total, the production, packing, storage and transportation of agrochemicals used in the lateral-move and furrow irrigation systems released 749.1 kg $CO_2$-e/ha and 1209.4 kg $CO_2$-e/ha emissions, respectively (Table 25). Cotton farming under the lateral-move irrigation system used lower quantities of agrochemicals than the furrow irrigation. Major differences were in the use of urea and herbicides. Furrow irrigation used 1.8 times more urea (largely due to higher yield expectations) and more than 1.1 times the herbicides than the lateral-move sprinkler system. Higher GHG emissions from furrow irrigation were largely due to a much higher amount of urea used than in the sprinkler irrigation system (although this may be subject to annual variation in application rates).

Table 25: Energy consumption (MJ/ha) and greenhouse gas emissions (kg $CO_2$-e/ha) due to use of agrochemicals for cotton crops in case study 1, Darling Downs, southern Queensland

| *Agrochemicals* | *Sprinkler irrigation (lateral-move)* | | | *Flood irrigation (furrow)* | | |
|---|---|---|---|---|---|---|
| | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Urea | 250.0 | 16 535.0 | 548.6 | 450.0 | 29 763.0 | 987.4 |
| Focus Hi K | 7.0 | 3.9 | 1.5 | – | – | – |
| Insecticide | 6.4 | 1 280.0 | 29.9 | 6.4 | 1 280.0 | 29.9 |
| Herbicide | 14.2 | 3 416.9 | 164.4 | 16.0 | 3 840.0 | 184.8 |
| Fungicide | – | – | – | 0.3 | 23.0 | 0.9 |
| Plant regulator | 1.8 | 195.1 | 4.7 | 2.4 | 264.9 | 6.4 |
| Total | | 21 430.8 | 749.1 | | 35 170.9 | 1 209.4 |

### *Soil emissions of $N_2O$ due to N-fertiliser application*

In total, lateral-move irrigation and furrow irrigation in the cotton farming system emitted 1130 kg $CO_2$-e/ha and 2034 kg $CO_2$-e/ha, respectively, into the atmosphere simply from denitrification of applied N fertiliser (Table 26). This emission was directly related to N-fertiliser amounts; the higher the N fertiliser application, the greater the emissions of $N_2O$ (measured in $CO_2$-e). As urea contains 46% N and Focus Hi K contains no N, urea was the sole contributor to total N-related emissions. The case study farmer used more urea in furrow-irrigated cotton than in the lateral-move irrigated cotton. Therefore, 1.8 times more GHG emissions were emitted per ha by the furrow-irrigated cotton cropping system than the lateral-move-irrigated system.

#### *GHG emissions due to the production of farm machinery used in the cotton industry*

The amount of GHG emissions due to the use of farm machinery other than irrigation machinery was directly related to diesel-related emissions (to run farm machinery other than irrigation machinery). The furrow-irrigated cotton generated more machinery-related emissions (58.44 kg $CO_2$-e/ha) than the lateral-move irrigation (33.28 kg $CO_2$-e/ha) (Table 26).

Overall, the total GHG emissions from furrow irrigation cotton farming system (4452.89 kg $CO_2$-e/ha) were higher than the lateral-move system (3347.42 kg $CO_2$-e/ha; Table 26). These results are comparable to previous estimates of average emissions for irrigated cotton farming systems in the Darling Downs region (Maraseni et al. 2010a).

Table 26: GHG emissions (kg $CO_2$-e/ha) due to various farming inputs to the two cotton irrigation systems in case study 1, Darling Downs, southern Queensland

| *Sources of emissions* | *Sprinkler irrigation (lateral-move)* | | *Flood irrigation (furrow)* | |
|---|---|---|---|---|
| | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Fuels | 12 181.13 | 1 468.42 | 8 054.85 | 1 151.25 |
| Agrochemicals | 21 430.80 | 749.10 | 35 170.9 | 1 209.40 |
| Soil emissions due to N-fertiliser use | na | 1 129.90 | na | 2 033.80 |
| Farm machinery (except irrigation machinery) | na | 33.28 | na | 58.44 |
| Total emissions (kg $CO_2$-e/ha) | | 3 347.42 | | 4 452.89 |
| GHG emissions per kg of cotton (kg $CO_2$-e/kg) | | 1.30 | | 1.98 |
| GHG emissions per ML water (kg $CO_2$-e/ML) | | 836.86 | | 742.15 |

Note: Cotton yield was 2 566.24 kg/ha for lateral-move irrigation and 2 246.60 kg/ha for furrow irrigation. Total irrigation water was 4 ML/ha for lateral-move and 6 ML/ha for furrow irrigation. Compared to furrow irrigation, lateral-move produced more cotton with less water.

However, in terms of GHG emissions per ML of water, the lateral-move irrigation system is less efficient. This system emitted more GHGs (836.86 kg $CO_2$-e/ML) than furrow irrigation (742.15 kg $CO_2$-e/ML) due to the need to pump water twice, although this difference is relatively low. There are also other benefits (e.g. reduced urea requirements, higher yields and water savings) of using lateral-moves, which may outweigh the cost related to additional emissions.

There is a clear difference in the quantities of cotton yield per hectare between the two irrigated-cotton farming systems (Table 26). The lateral-move irrigated cotton system yielded more cotton (2566.24 kg/ha) than the furrow-irrigated system (2246.6 kg/ha). Conversely, GHG emissions per unit of production (t/ha) were higher in the furrow-irrigated system (1.98 kg $CO_2$-e/kg of cotton) than in the lateral-move system (1.3 kg $CO_2$-e/kg of cotton).

## Economic evaluations

We conducted an economic analysis of the costs and benefits of adopting sprinkler (lateral-move) irrigation technology on this cotton farm using the parameters described above. A cotton paddock of 23.4 ha, converted to sprinkler irrigation during 2005–06, was selected for detailed economic analysis.

### *Assumptions*

In addition to the assumptions discussed in section 5.3.3, some additional assumptions were used in the economic evaluations.

- The farmer's cropping schedule of 4–5 crops per rotation included 2–3 cotton crops, followed by rainfed wheat, and corn (when sufficient water is available) or fallow, then back into cotton. Only cotton was included in this analysis.
- All the saved water was used to increase the cotton area.
- Quality improvements, though reported in the case study, were ignored in the analysis.
- No water trading occurred at this property due to physical constraints, therefore no permanent or temporary water trading was considered in the analysis. In the sensitivity analysis, a 50/50 water sharing plan was considered.

The results of the economic analysis (see Table 27) indicate that, at the current level of water saving (2 ML/ha), sprinkler technology (lateral-move) is an economically viable option on this farm. The high rate of return was due to the high level of water saving and the increased crop yield. This farmer was achieving higher yield levels compared with average cotton yields. The BCR indicated that every dollar spent on the improved technology led to a $3.10 increase in income. The net benefit of adoption of the sprinkler irrigation system was about $437/ML/year. The estimated BE water saving for converting surface irrigation to sprinkler irrigation was 0.52 ML/ha with a payback period of about 3.1 years.

Table 27: Economic evaluation of sprinkler (lateral-move) irrigation technology adoption for cotton cropping in case study 1, Darling Downs, southern Queensland

| *Economic evaluation indexes* | *Unit* | *Base case scenario* |
|---|---|---|
| Net present value (NPV) | $ | 340 726.00 |
| Benefit–cost ratio (BCR) | | 3.72 |
| Internal rate of return (IRR) | % | 51.52 |
| Payback period | Years | 3.10 |
| Break-even (BE) water saving | ML/ha | 0.52 |
| Net benefit per ML of saved water | $ | 436.8 |

## Sensitivity analyses

We used sensitivity analysis to test the robustness of the economic analysis by changing the values of key benefit parameters. The details of the sensitivity parameters are discussed under section 4.3.5. For this case study, we considered a water-sharing scenario based on 50/50 water sharing instead of temporary water trading. The sensitivity analysis showed that all scenarios resulted in positive NPVs, making the investment in a sprinkler irrigation system for the case study farm viable and robust (Table 28).

Table 28: Sensitivity analysis of sprinkler (lateral-move) irrigation technology adoption for cotton cropping in case study 1, Darling Downs, southern Queensland

| *Scenario* | *Net present value ($)* | *Net benefit per ML saved ($)* |
|---|---|---|
| Base case scenario | 340 726 | 436.8 |
| 50% water saving | 164 787 | 202.18 |
| 0% labour saving | 319 949 | 365.66 |
| 0% yield increase | 83 434 | 142.62 |
| 50/50 water sharing @ $2500/ML | 242 904 | 311.4 |
| 50/50 water sharing @ $1500/ML | 227 304 | 291.41 |
| $10/t $CO_2$-e carbon price | 338 995 | 434.61 |
| $30/t $CO_2$-e carbon price | 335 532 | 430.17 |
| 30 year technology life | 379 300 | 486.28 |
| 15 year technology life | 228 663 | 293.16 |
| 10% interest rate | 202 403 | 259.49 |
| 2% interest rate | 487 709 | 625.27 |

The NPVs remained positive even if no yield or carbon prices were considered with the conversion due to the large values for water savings and crop yield. The sensitivity results showed that the investments were most sensitive to water savings.

In conclusion, the results show that investment in sprinkler (lateral-move) irrigation technology was an economically feasible option on this farm, provided that assumed water savings, yield increase and labour benefits were achieved.

## 4.4.2 Case study 2: cotton farm, Darling Downs, southern Queensland

### Farm description and parameter estimation

This farm is a 1700 ha mixed farm with irrigated cropping and riparian grazing enterprises on the Darling Downs, southern Queensland. The cropping component (1335 ha) produces cotton, lucerne and grains (wheat and sorghum). Cropping soil types are black cracking clays (Vertisols). Irrigation water sources on this farm are licensed streamflow harvesting from unregulated watercourses (nominal volumes, seasonally-adjusted allocations), diversion of overland flows (licensed volumetric limits) and groundwater (nominal volumetric entitlements, allocated volumes). Harvested water from all sources is stored in onfarm storages or ‘ring tanks’ (authorised storage capacity) and distributed to irrigation paddocks by open channels. In a normal irrigation season, this farm relies on 4 ML/ha of water applied by lateral-move and centre-pivot sprinklers and 5 ML/ha applied by flood (furrow) irrigation.

#### *Property development*

The property was originally set up for flood irrigation. Since 2002, parts of the flood-irrigated area have been converted to lateral-move (three systems; 503 ha in total) and centre-pivot sprinkler (one system; 60 ha in total) irrigation systems. Selection of paddocks for conversion to sprinkler systems was based on soil type (heavier soils) and paddock shape, particularly for the lateral-move systems, which require large rectangular paddocks. Remaining flood fields (772 ha) are generally more sloping, with ‘better’ (slightly lighter) soils. There are no immediate plans to convert further area to sprinkler systems in the future. Major barriers to the adoption of new irrigation technologies include price, the pre-existing paddock sizes and shapes, and lack of consistent water availability, hence the need to prioritise investments.

Total water storage capacity on this property is 4.6 GL. However, on average, storages are filled only once every 2–3 years. Rainfall and streamflow patterns in this area are highly variable, and water scarcity is a significant concern. Access to nominal in-stream harvesting volumes is subject to restrictions based on flow rate. In addition, local groundwater tables are declining and extraction restrictions (allocation is currently 60% of nominal entitlements) are increasing. Overland flow harvesting is a cheaper option, but only possible with storm rainfall run-off and subject to pumping restrictions. On average, stored water comprises 20% groundwater and 40% each from streamflow and overland flow diversions. Access to a range of water sources enables a degree of risk management, while mixing of water sources helps to avoid soil salinity issues associated with the continuous use of poorer quality groundwater.

The WUE associated with the sprinkler irrigation systems is assumed to be around 90%, but this is probably reduced to around 80% on a whole farm basis (due to evaporative and transmission losses). Up to 1.5 m/year is lost to evaporation or seepage from ring tanks.

#### *Cropping system*

Farming is on an opportunistic basis, with no set rotation. The area cropped and crop choice are determined by water availability and market prices. Water savings achieved through the use of the sprinkler systems (estimated at 1 ML/ha) allow an increased area of flood-irrigated crop to be grown in any one season, and enable carryover, which provides insurance in terms of available water for planting in the next season.

#### *Technology adoption*

Principle drivers for adoption of new irrigation technology were stated as more efficient management of available water and improved economics, or ‘more income with the same amount of water’. Water goes 30% further, enabling an increase in the cropping area each season, as well as improved productivity on sprinkler-irrigated crops. Other technologies adopted include licensed Bollgard and RoundUp Ready GM crops, which reduce paddock workings and pesticide use. The farmer uses soil capacitance probes and advice from consultants to monitor soil moisture for irrigation scheduling.

#### *Crop production*

Production benefits include increased yields and higher quality (price differential) under the lateral-move system. In an average year, cotton grown under sprinkler systems yields 10.0 round bales (227 kg each) per ha compared to 8.5–9.0 bales/ha for flood irrigation, and is less likely to suffer quality discounts. The equivalent productivity is 2.3 t/ha and 0.58 t/ML for sprinkler-irrigated cotton and 1.9–2.0t/ha and 0.39–0.41 t/ML for flood-irrigated cotton. Yield increases due to the adoption of sprinkler irrigation systems are estimated to be 15–21% per ha and 42–49% per ML of water in irrigated paddocks, with additional economic benefits due to the higher quality cotton fibre.

On average, the sprinkler systems can produce the same yield as flood systems on 30% less water, or at less than full water, yield will be 30% higher with overhead compared to flood for the same amount of water applied. However, on full water, flood irrigation on this property will out-yield the sprinkler systems and quality is maintained. In poorer years, the overhead systems allow water to be spread out to maintain the crop, while flood systems will suffer stress between watering. As a result, the sprinkler systems will produce double the yield of flood systems, which will suffer a 50% yield reduction, as well as quality discounts.

### *Labour savings*

The new irrigation technologies have reduced labour requirements on this property. The machines can be managed by the property owner, while the flood irrigation paddocks require two extra people.

### *Crop inputs*

Nitrogen inputs are reduced under the sprinkler systems. Each system (flood, sprinkler) receives 5 t/ha/year of animal manure from local feedlots, while urea or Big N® are applied at an average rate of 400kg/ha in the flood system and 300 kg/ha in the sprinkler-irrigated systems. The sprinkler systems offer significant benefits in terms of fertiliser application as they enable smaller, more frequent applications in line with crop requirements over the cropping season.

There is no difference in the application of crop sprays (pesticides, defoliants) in the flood and sprinkler-irrigated systems on this property, although overall requirements for herbicides and insecticides have been minimised by planting GM (Bollgard, Roundup Ready) cotton.

### *Climate change*

Increasing water scarcity will necessitate more efficient management of available water. Currently, the farmer notes climate forecasts and reduces planting areas if an El Niño year is predicted, and plans irrigation scheduling according to daily, weekly and 30-day forecasts (less water may be applied if rain is highly likely).

### *Water trading*

Water trading has not been considered, but price would be a factor influencing any decision to trade. If trading water could make a higher return, trading could be better than using the water to grow a crop. However, only temporary trades would be considered.

## Hydrological modelling

As in case study 1, we did not perform a detailed hydrological analysis of this case because the potential water saving assessment (section 5.1, Table 10) was performed for the same region, soil types and environmental conditions. Instead, the farmer's estimates of water savings were used and validated against the water saving assessment derived through SWAP modelling. Based on the farmer's assessment, water savings of 1.0 ML/ha (20%) and 0.82 ML/t (33%) were achieved for cotton grown under lateral-move irrigation compared to furrow irrigation. These estimates are within the average limits of water savings estimated through SWAP modelling (Table 10).

## Energy consumption and GHG estimation

### *Use of fuels for farm operations for cotton crops*

Fuel usage for farm machinery operations (other than irrigation machinery operations) in both the lateral-move and furrow irrigation systems was the same. In both irrigation systems, machinery operation-related emissions accounted for 238 kg $CO_2$-e/ha of GHGs. However, the lateral-move system used more irrigation-related fuels (diesel and electricity) than the furrow irrigation system (electricity only). Irrigation-related emissions for the lateral-move system were more than 1.15 times higher than for the furrow irrigation system (Table 29). Overall, the furrow irrigation system appeared better than the sprinkler systems in terms of energy use and GHG emissions from farming operations on a per ha basis.

Table 29: Energy consumption (MJ/ha) and greenhouse gas emissions (kg $CO_2$-e/ha) due to use of fuels in farm operations for cotton crops in case study 2, Darling Downs, southern Queensland

| *Farming operation* | *Sprinkler irrigation (lateral-move)* | | | | *Flood irrigation (furrow)* | | | |
|---|---|---|---|---|---|---|---|---|
| | *Diesel (L)* | *Electricity (kWh)* | *Energy used* | *Emission (kg $CO_2$-e/ha)* | *Diesel (L)* | *Electricity (kWh)* | *Energy used* | *Emission (kg $CO_2$-e/ha)* |
| Farm machinery operation | 82.0 | 0 | 3 165.2 | 238.0 | 82.0 | 0 | 3 165.2 | 238.0 |
| Aviation gas | 0.07 | 0 | 2.3 | 0.2 | 0.07 | 0 | 2.3 | 0.2 |
| Irrigation | 149.2 | 298.4 | 9 319.0 | 1 433.4 | 0.0 | 373.0 | 4 449.9 | 1 250.4 |
| Total | 231.27 | 298.4 | 12 486.5 | 1 671.6 | 82.07 | 373 | 7 617.4 | 1 488.6 |

Note: Sprinkler irrigation used 4 ML/ha of water and flood used 5 ML/ha.

### *Use of agrochemicals for cotton crops*

In total, the production, packing, storage and transportation of agrochemicals used in the lateral-move and furrow irrigation systems accounted for 722.5 kg $CO_2$-e/ha and 942 kg $CO_2$-e/ha of GHG emissions, respectively (Table 30). In both systems, the farmer used 5000 kg/ha of manure, which accounted for 37.5 kg $CO_2$-e/ha. There were no differences in the amount of agrochemicals used between the two irrigation systems, except urea. The farmer used 300 kg/ha of urea in the lateral-move system and 400 kg/ha in the furrow, which accounts for the differences in agrochemical-related emissions between the two systems.

### *Soil emissions of $N_2O$ due to N-fertiliser application*

In total, 1355.9 kg $CO_2$-e/ha and 1807.8 kg $CO_2$-e/ha of GHGs entered the atmosphere through denitrification of applied N fertiliser in soils from the lateral-move and furrow irrigated cotton farming systems, respectively (Table 31). As this emission is directly related to N-fertiliser amounts, the higher the N fertiliser use, the greater the emissions. As noted above, the farmer used more urea in furrow-irrigated cotton than in the lateral-move cotton. Therefore, 1.33 times more GHGs were emitted per ha by the furrow-irrigated cotton farming system than the lateral-move system.

Table 30: Energy consumption (MJ/ha) and greenhouse gas emissions (kg $CO_2$-e/ha) due to use of agrochemicals for cotton crops in case study 2, Darling Downs, southern Queensland

| *Agrochemicals* | *Sprinkler irrigation (lateral-move)* | | | *Flood irrigation (furrow)* | | |
|---|---|---|---|---|---|---|
| | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Urea | 300.0 | 19 842.0 | 658.3 | 400.0 | 26 456.0 | 877.7 |
| Manure | 5 000.0 | 1 515.5 | 37.5 | 5 000.0 | 1 515.5 | 37.5 |
| Insecticide | 0.5 | 100.0 | 2.3 | 0.5 | 100.0 | 2.3 |
| Herbicide | 4.0 | 960.0 | 46.2 | 4.0 | 960.0 | 46.2 |
| Fungicide | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Plant regulator | 6.0 | 654.0 | 15.8 | 6.0 | 654.0 | 15.8 |
| *Total* | | *23 071.5* | *760.0* | | *29 685.5* | *979.5* |

#### *GHG emissions due to the production of farm machinery used in the cotton industry*

GHG emissions due to farm machinery usage (other than irrigated-related machinery) are directly related to fossil fuel usage to operate the farm machinery. As both irrigation systems used equal amount of diesel to run the farm machinery, both irrigation systems had equal amounts of machinery-related emissions (34.3 kg $CO_2$-e/ha; Table 31).

Overall, higher total quantities of GHGs were emitted from the furrow-irrigated cotton farming system (4310.2 kg $CO_2$-e/ha) than from the lateral-move system (3821.8 kg $CO_2$-e/ha; Table 31). These results are lower than the previous estimates for cotton farming systems on the Darling Downs, Queensland (Maraseni et al. 2010a) because gravity is wisely used to assist irrigation and less GHG-intensive fertilisers and GHG-intensive manures are being used.

The clear difference in the quantities of GHG emissions per ha between the two cotton irrigation systems is mostly attributed to differences in amounts of fossil fuel used for irrigation and urea.

The lateral-move irrigation used 4 ML/ha of water and the furrow irrigation used 5 ML/ha. The GHG emissions per unit of water for furrow irrigated cotton was lower (862.1 kg $CO_2$-e/ML) than for the lateral-move system (955.5 kg $CO_2$-e/ML). GHG emissions per unit of yield were higher from the furrow system, as its cotton yield was lower (1986 kg/ha) than the lateral-move system (2270 kg/ha).

Table 31: Greenhouse emissions (kg $CO_2$-e/ha) due to various farming inputs to the two cotton irrigation systems in case study 2, Darling Downs, southern Queensland

| *Sources of emissions* | *Sprinkler irrigation (lateral-move)* | | *Flood irrigation (furrow)* | |
|---|---|---|---|---|
| | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Fuels | 12 486.5 | 1671.6 | 7 617.4 | 1 488.6 |
| Agrochemicals and manure | 23 071.5 | 760.0 | 29 685.5 | 979.5 |
| Emissions from soils due to N-fertiliser use | NA | 1 355.9 | NA | 1 807.8 |
| Farm machinery (except irrigation machinery) | NA | 34.3 | NA | 34.3 |
| Total emissions (kg $CO_2$-e/ha) | | 3 821.8 | | 4 310.2 |
| GHG emissions (kg $CO_2$-e/kg of cotton) | | 1.7 | | 2.2 |
| GHG emissions (kg $CO_2$-e/ML of water) | | 955.5 | | 862.1 |

Note: Cotton yield was 2270 kg/ha for lateral-move and 1986 kg/ha for furrow; total irrigation water was 4 ML/ha for lateral-move and 5 ML/ha for furrow irrigation. Compared to furrow irrigation, lateral-move produced more cotton with less water.

## Economic evaluation

We conducted an economic analysis of the costs and benefits of adopting sprinkler (lateral-move) irrigation technology on this cotton farm using the parameters described above. Of the three lateral-move systems on about 503 ha, one lateral-move system of about 165 ha was selected for detailed economic analysis.

### *Assumptions*

In addition to the assumptions discussed in section 5.3.3, we used some additional assumptions in the economic evaluations.

- The farmer's cropping schedule of 3–4 crops per rotation included 2–3 cotton crops, followed by rainfed wheat or sorghum, lucerne (when sufficient water is available) or fallow, then back into cotton. Only cotton was included in this analysis.
- All the saved water was used to increase the cotton area.
- Quality improvements, though reported in the case study, were ignored in the analysis.
- No water trading occurred at this property due to physical constraints, and permanent or temporary water trading was excluded from the analysis. In the sensitivity analysis, we considered a 50/50 water sharing plan.
- Water use efficiency was 90%.
- Labour saving was two full-time equivalents (FTEs).

The results of the economic analysis (Table 32) indicate that, at the current level of water savings (1 ML/ha), sprinkler technology (lateral-move) is an economically viable option on this farm. This was mainly attributed to an average level of water saving, increased crop yield and labour savings. When compared with case study 1, the economic viability was relatively weaker. The net benefit of adopting sprinkler irrigation was about $219.96/ML/year. The estimated BE water saving for converting surface irrigation to sprinkler irrigation was 0.71 ML/ha with a payback period of about 10.6 years. The BCR value indicates that every dollar spent on the improved technology leads to a $1.44 increase in income.

Table 32: Economic evaluation of sprinkler (lateral-move) irrigation technology adoption for cotton cropping in case study 2, Darling Downs, southern Queensland

| *Economic evaluation indexes* | *Unit* | *Base case scenario* |
|---|---|---|
| Net present value (NPV) | $ | 725 884 |
| Benefit–cost ratio (BCR) | | 1.44 |
| Internal rate of return (IRR) | % | 12.59 |
| Payback period | Years | 10.6 |
| Break–even (BE) water saving | ML/ha | 0.71 |
| Net benefit per ML of saved water | $ | 219.96 |

## Sensitivity analyses

We used sensitivity analysis to test the robustness of the economic analysis by changing the values of key benefit parameters. The details of the sensitivity parameters are discussed in section 5.3.5. For this case study, we considered a 50/50 water sharing scenario instead of temporary water trading. The sensitivity analysis showed that economic returns were sensitive to water savings and yield. The investments were not economically feasible at lower water savings and zero yield benefits (Table 33). However, investments were still viable with a carbon price, under water sharing plans, with reduced technology life and at higher interests rates, although higher interests rates made investments less attractive.

Table 33: Sensitivity analysis of sprinkler (lateral-move) irrigation technology adoption for cotton cropping in case study 2, Darling Downs, southern Queensland

| *Scenario* | *Net present value ($)* | *Net benefit/ML saved ($)* |
|---|---|---|
| Base case scenario | 725 884 | 219.96 |
| 50% water savings | –183 224 | –55.52 |
| 0% labour saving | 420 662 | 127.47 |
| 0% yield increase | –43 275 | –13.11 |
| 50/50 water sharing @ $2500/ML | 271 064 | 82.1 |
| 50/50 water sharing @ $1500/ML | 205 064 | 61.2 |
| $10/t $CO_2$-e carbon price | 713 675 | 216.26 |
| $30/t $CO_2$-e carbon price | 689 257 | 208.86 |
| 30 year technology life | 880 154 | 266.71 |
| 15 year technology life | 277 703 | 84.15 |
| 10% interest rate | 172 679 | 52.32 |
| 2% interest rate | 1 313 723 | 398.09 |

In conclusion, the conversion to lateral-move for the cotton farm in this case study farm will generate a reasonable return on the investment if the assumed yield benefits, water savings and labour savings occur for the crop.

### 4.4.3 Case study 3: cotton farm, Darling Downs, southern Queensland

## Farm description and parameter estimation

This farm is a 1011 ha mixed farm with irrigated and dryland grain–cotton cropping and pig enterprises on the Darling Downs, southern Queensland. Of the total area, 227 ha are irrigable and the remainder is dryland. Cropping soil types are Waco self-mulching black cracking clays (Vertisols). Irrigation water is sourced from diversion of overland flows (licensed volumetric limits) and groundwater extraction (nominal volumetric entitlements, allocated volumes). Harvested water from both sources is stored in onfarm storages (authorised storage capacity). Mixing of bore water and harvested overland flows is critical to maintaining water quality (bore water from the edge of the Condamine Alluvium is relatively poor quality) and makes distribution easier. In a normal irrigation season, this farm relies on 5 ML/ha of water applied by drip (trickle) irrigation and 6 ML/ha applied by flood (furrow) irrigation. Irrigation water is distributed to flood irrigation paddocks by open channels and to drip irrigation paddocks by pipe.

#### *Property development*

The property was originally set up for flood irrigation. In 2005, 37 ha were converted to a drip irrigation system to improve WUE and address water quality concerns ('less water means less salt, and the drip system keeps the water away from plants'). There are no immediate plans to convert further areas.

The total water storage capacity on this property is 0.58 GL, with a 60% reliability rating from RUSTIC (Runoff Storage and Irrigation Calculator), although the probability of filling is around 30–40% under current conditions. Rainfall patterns in this area are highly variable, and water scarcity is a significant concern. The local groundwater table fell significantly (about 20–80 m) in the decade following the commencement of irrigation in the local area in the early 1990s, but is currently stable. Groundwater allocations are currently 70% of nominal entitlements. The increased depth to groundwater has increased the cost of pumping; in addition, the recharge rate is reduced, so pumping is slower. Bores must be started earlier in the season to stockpile water in the dam for the coming irrigation season.

While drip irrigation was adopted to increase onfarm WUE, the WUE of this system is unknown. Drip irrigation reduces water use at planting (pre-watering and germination) by about 1 ML/ha, but once the crop is established, water use is about the same as flood. Additional water savings are achieved as there are no head ditches (or transmission losses) and there is less evaporation in the paddock. Trickle tape is buried at a depth of 100 mm, and water is applied close to the root zone of plants.

#### *Cropping system*

Farming is on an opportunistic basis, with no set rotation. The area cropped and crop choice are determined by water availability ('we farm moisture') and market prices. Water savings achieved through the use of the drip system (estimated at 1 ML/ha) allow an increased crop area to be grown in any one season, and reduces the risk for the current crop ('we are supplementary irrigators').

Cotton is planted on single skip 1.5 m rows for all farming systems (flood, drip and dryland) on this property. This enables the use of just one set of gear (cultivators etc), and the drip system can wet across this configuration. This effectively means that 66% of the area is actually planted, which is feasible as the Bollgard licence is based on green area planted. It also means that input costs are reduced by 33% compared with planting on a 1 m configuration.

#### *Technology adoption*

Principle drivers for adoption of drip irrigation technology were stated as increased crop productivity, reduced input costs and economic profit. It was felt that, with the trickle tape expected to last 10 years, the economic differential would be realised.

Major barriers to further adoption of new irrigation technologies include outlay costs ($1950/ha), water quality (limiting the conversion of dryland area to drip), and the efficiency of existing flood irrigation. The farmer expressed concerns about waste issues at the end of the

10 years, and the need to improve the labour efficiency of installation and removal. The main problems have been leaks due to rodents and mechanical damage, but these are readily spotted (wet spots in furrows and runs, and sprays).

Other technologies adopted include licensed Bollgard and Roundup Ready GM crops, which reduce paddock workings and pesticide use. The farmer uses neutron probes and advice from consultants to monitor soil moisture for irrigation scheduling.

#### *Crop production*

The trickle irrigation system realises production benefits such as increased yields and improved quality (price differential). In an average year, cotton grown on the drip system yields 1.11 bales/ha better (10.37 bales/aha) than flood irrigation (usually 9.26 bales/ha), and a 10% improvement in quality (longer staple). The equivalent per ha and per ML productivity is 2356 kg (2.4 t)/ha and 491 kg (0.5 t)/ML for trickle irrigated cotton and 2103 kg (2.1 t)/ha and 363 kg (0.4 t)/ML for flood irrigated cotton. On these values, yield increase due to the adoption of the trickle irrigation system is 12.0% per ha and 35.3% per ML of water compared with flood irrigation yields.

#### *Labour saving*

The new drip irrigation system has reduced labour requirements on this property by about 15% (1 FTE).

#### *Crop inputs*

Each system (flood, drip) receives 10 t/ha/year of animal manure (pig effluent or slurry) from the onfarm piggery, as well as 200 kg/ha of anhydrous ammonia. Nitrogen inputs are not reduced on the drip system, but can be applied over time in line with crop requirements over the cropping season. Generally, 70% is applied upfront and the rest as required.

There is no difference in the application of crop sprays (pesticides, defoliants) in the flood and drip irrigation systems on this property. Overall requirements for herbicides and insecticides have been minimised by planting GM cotton (Bollgard, Roundup Ready). Gypsum has been applied (5 t/ha every four years) to counteract the effects of the saline bore water. The only difference is that the rodenticide Mouseoff (0.5 kg/ha) is applied between crops on the drip cropping systems to minimise damage to the trickle tape.

#### *Climate change*

Increasing water scarcity will necessitate more efficient management of available water. Climate forecasts (SOI) are not used, but irrigation is held off if rain is forecast to avoid overwatering.

#### *Water trading*

Water trading has not been considered, nor would price be a factor influencing any decision to trade. On this property, trading is not physically possible for disconnected water resources.

## Hydrological modelling

As in case studies 1 and 2, a detailed hydrological analysis was not performed because the potential water saving assessment (Section 5.1, Table 10) had been performed for the same region, soil types and environmental conditions. Instead, the farmer's estimates of water savings were used and validated against the water saving assessment derived through SWAP modelling. Based on the farmer's assessment, water savings of 1.0 ML/ha (17.2%)

and 0.82 ML/t (28%) were achieved for cotton grown under drip and furrow irrigation, respectively. These estimates indicate relatively low levels of water savings at about the lower limits estimated through SWAP modelling (Table 6). The farmer said that he only achieved water savings at planting (pre-watering and germination), and once the crop was established, water use was about the same as furrow.

## Energy consumption and GHG estimation

### *Use of fuels for farm operations for cotton crops*

The emission of GHGs due to the production and consumption of fuels used for farm machinery operation (other than irrigation machinery operations) in flood irrigation is almost 1.2 times higher than in trickle irrigation on this farm. On the other hand, while both irrigation systems used electricity for pumping water, the trickle system used much more electricity than the flood system. Overall, irrigation-related emissions for the trickle irrigation system were more than 6.9 times higher than for the flood system (Table 34). On a per ha basis, the flood irrigation system appears to emit less GHGs than the trickle irrigation system.

Table 34: Energy consumption (MJ/ha) and greenhouse gas emissions (kg $CO_2$-e/ha) due to use of fuels in farm operations for cotton crops in case study 3, Darling Downs, southern Queensland

| *Farming operation* | *Trickle irrigation* | | | | *Flood irrigation* | | | |
|---|---|---|---|---|---|---|---|---|
| | *Diesel (L)* | *Electricity (kWh)* | *Energy used* | *Emissions (kg $CO_2$-e/ha)* | *Diesel (L)* | *Electricity (kWh)* | *Energy used* | *Emissions (kg $CO_2$-e/ha)* |
| Farm machinery operation | 78.50 | 0 | 3 030.1 | 227.9 | 93.5 | | 3 609.1 | 271.4 |
| Aviation gas | 0.07 | 0 | 2.3 | 0.2 | 0.07 | 0 | 2.3 | 0.2 |
| Irrigation | 0.00 | 1 409.7 | 16 817.7 | 4 725.8 | 0.00 | 202.5 | 2 415.8 | 678.8 |
| Total | | | 19 850.1 | 4 953.9 | | | 6 027.2 | 950.4 |

### *Use of agrochemicals for cotton crops*

The total GHG emissions due to production, packing, storage and transportation of agrochemicals used in the trickle and flood irrigation systems on this farm are similar, at approximately 1365 kg $CO_2$-e/ha (Table 35). Both irrigation systems used the same amounts of all agrochemicals except rodenticide, which makes only a small difference between the GHG emissions from the two systems. Both systems also used equal amounts of manure, which accounted for 75 kg $CO_2$-e of GHG emissions.

### *Soil emissions of $N_2O$ due to N-fertiliser application*

Emissions of $N_2O$ from the soil due to N-fertiliser application is the same (1611.3 kg $CO_2$-e/ha) for both irrigation systems, as both systems used the same amount of N fertiliser (Table 35).

Table 35: Energy consumption (MJ/ha) and greenhouse gas emissions (kg $CO_2$-e/ha) due to use of agrochemicals for cotton crops in case study 3, Darling Downs, southern Queensland

| *Agrochemicals* | *Trickle irrigation* | | | *Flood irrigation* | | |
|---|---|---|---|---|---|---|
| | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Anhydrous ammonia | 200.0 | 13 228.0 | 782.3 | 200.0 | 13 228.0 | 782.3 |
| Gypsum | 1 250.0 | 6 250.0 | 462.5 | 1 250.0 | 6 250.0 | 462.5 |
| Manure | 10 000.0 | 3 031.0 | 75.0 | 10 000.0 | 3 031.0 | 75.0 |
| Insecticide | 1.0 | 200.0 | 4.7 | 1.0 | 200.0 | 4.7 |
| Herbicide | 9.0 | 2 160.0 | 104.0 | 9.0 | 2 160.0 | 104.0 |
| Fungicide | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Plant regulator | 4.4 | 479.6 | 11.6 | 3.9 | 425.1 | 10.2 |
| Total | | 25 348.6 | 1 440.0 | | 25 294.1 | 1438.6 |

### *GHG emissions due to the production of farm machinery used in the cotton industry*

Flood irrigation used 93.5 L/ha of diesel for farm machinery (other than irrigated related machinery) operations, whereas trickle irrigation used 78.5 L/ha. Similarly, GHG emissions due to farm machinery usage in the flood irrigation system (39.1 kg $CO_2$-e/ha) were higher than from the trickle system (32.8 kg $CO_2$-e/ha; Table 36). The higher amount of fuel used (and thus GHG emissions) in flood irrigation system is mainly due to the preparation and maintenance of furrows.

Table 36: Greenhouse emissions (kg $CO_2$-e/ha) due to various farming inputs to the two cotton irrigation systems in case study 3, Darling Downs, southern Queensland

| *Sources of emissions* | *Trickle irrigation* | | *Flood irrigation* | |
|---|---|---|---|---|
| | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Fuels | 19 850.1 | 4 953.9 | 6 027.2 | 950.4 |
| Agrochemicals | 25 348.6 | 1 440.0 | 25 294.1 | 1 438.6 |
| Emissions from soils due to N-fertiliser use | na | 1 611.3 | na | 1 611.3 |
| Farm machinery (except irrigation machinery) | na | 32.8 | na | 39.1 |
| Total emissions (kg $CO_2$-e/ha) | | 8 038.0 | | 4 039.4 |
| GHG emissions per kg (kg $CO_2$-e/kg of cotton) | | 3.4 | | 1.9 |
| GHG emissions per ML water (kg $CO_2$-e/ML) | | 1 674.6 | | 696.4 |

Note: Cotton yield was 4.2 bales/ac (2356 kg/ha) for trickle and 3.75 bales/ac (2103 kg/ha) for flood; total irrigation water was 4.8 ML/ha for trickle and 5.8 ML/ha for flood. Compared to furrow irrigation, lateral-move produced more cotton with less water.

Overall analysis shows a significant difference in GHG emissions due to the application of primary farm inputs in the two irrigation systems. Higher total GHGs were emitted from the trickle irrigation cotton farming system (8038.0 kg $CO_2$-e/ha) than from the flood system (4039.4 kg $CO_2$-e/ha; Table 36). Higher GHG emissions in trickle irrigation were mostly associated with more farm machinery and irrigation-related energy use.

The GHG emissions for trickle irrigation were slightly higher than the results from other case studies, and previous estimates for cotton farming systems on the Darling Downs (Maraseni et al. 2010a). This was mainly due to the use of electricity (100%) for irrigation purposes, as electricity emits more GHGs than diesel.

Trickle irrigation used 4.8 ML/ha of water whereas flood irrigation used 5.8 ML/ha. However, the GHG emissions per unit of water from flood-irrigated cotton (696.4 kg $CO_2$-e/ML) was still much lower than from trickle-irrigated cotton (1674.6 kg $CO_2$-e/ML). The cotton yield for the flood irrigation system (2103 kg/ha) was lower than the trickle system (2356 kg/ha). Comparing the GHG emissions for a unit of yield, the trickle system (3.4 kg $CO_2$-e/kg) emitted more GHG emissions than the flood system (1.9 kg $CO_2$-e/kg).

## Economic evaluations

We conducted an economic analysis of the costs and benefits of adopting drip (trickle) irrigation technology on this cotton farm for a 37 ha paddock, which was converted to drip irrigation in 2005 to improve WUE and yield, and to address water quality concerns.

### *Assumptions*

In addition to the assumptions discussed in section 5.3.3, some additional assumptions were used in the economic evaluations.

- The farmer's cropping schedule of 3–4 crops per rotation included 2–3 cotton crops, followed by rainfed wheat or sorghum, and lucerne (when sufficient water is available) or fallow, then back into cotton. Only cotton was included in this analysis.
- All the saved water was used to increase the cotton area.
- Quality improvements, though reported in the case study, were ignored in the analysis.
- No water trading occurred at this property due to physical constraints, therefore no permanent or temporary water trading was considered in the analysis. However, in the sensitivity analysis, a 50/50 water sharing plan was considered.
- Water use efficiency was 90%.
- The labour saving was 15%.

The results of the economic analysis (Table 37) indicated weaker economic returns at the current level of water saving (1 ML/ha), although the drip irrigation technology was still an economically viable option at this farm. The parameters contributing to economic returns included increased crop yield, labour savings and water savings. The net benefit of adopting the drip irrigation system was about $114.38/ML/year. The BCR indicated that every dollar spent on the improved technology led to a $1.28 increase in income. The estimated BE water saving for converting surface irrigation to sprinkler irrigation was 0.83 ML/ha with a payback period of about 13 years.

## Sensitivity analyses

We used sensitivity analysis to validate the robustness of the economic analysis by changing the values of key benefit parameters. However, for this case study, we considered a 50/50 water sharing scenario instead of temporary water sharing. The sensitivity analysis showed that economic returns were sensitive to water savings, yield and a water-sharing plan. The investments were not economically feasible at lower water savings (1 ML/ha), zero yield benefits or with the 50/50 water-sharing plan (Table 38). However, investments were still viable with a carbon price, so lower rates made investments more attractive.

Table 37: Economic evaluation of drip irrigation technology adoption for cotton cropping in case study 3, Darling Downs, southern Queensland

| *Economic evaluation indexes* | *Unit* | *Base case scenario* |
|---|---|---|
| Net present value (NPV) | $ | 87 501 |
| Benefit–cost ratio (BCR) | | 1.28 |
| Internal rate of return (IRR) | % | 10.20 |
| Payback period | Years | 13.0 |
| Break-even (BE) water saving | ML/ha | 0.83 |
| Net benefit per ML of saved water | $ | 114.38 |

Table 38: Sensitivity analysis of sprinkler (lateral-move) irrigation technology adoption for cotton cropping in case study 3, Darling Downs, southern Queensland

| *Scenario* | *Net present value ($)* | *Net benefit/ML saved ($)* |
|---|---|---|
| Base case scenario | 87 501 | 114.38 |
| 50% water savings | –88 769 | –116.04 |
| 0% labour saving | 32 568 | 42.57 |
| 0% yield increase | –110 342 | –144.23 |
| 50/50 water sharing @ $2 500/ML | –4 185 | –5.47 |
| 50/50 water sharing @ $1 500/ML | –21 815 | –28.51 |
| $10/t $CO_2$-e carbon price | 83 120 | 108.65 |
| $30/t $CO_2$-e carbon price | 74 360 | 97.202 |
| 30 year technology life | 111 233 | 145.40 |
| 15 year technology life | 18 555 | 24.25 |
| 10% interest rate | 2 399 | 3.13 |
| 2% interest rate | 177 930 | 232.58 |

From this assessment, the conversion to a drip irrigation cotton farming system for the case study farm would generate a reasonable return on the investment if the assumed yield benefits, water savings and labour savings occurred for the crop.

### 4.4.4 Case study 4: vegetable (lettuce) farm, Lockyer Valley, south-eastern Queensland

#### Farm description and parameter estimation

This 80 ha farm in the Lockyer Valley, south-eastern Queensland, grows irrigated seasonal vegetables (lettuce, broccoli, cauliflower) through winter and rainfed cover crops (barley, wheat, oats) through summer. The soil type is a sandy loam, and the irrigation water source is groundwater only, with the aquifer fed by the adjacent creek. Access to groundwater depends on availability, and there is no allocation on quantity. Water use in the local area is metered and charged by volume of usage. Drip (trickle) irrigation is distributed to paddocks by pipe. In a normal irrigation season (two vegetable crops), the farm relies on 1.2–2.5 ML/ha of water per irrigated crop, with annual usage of about 5 ML/ha for vegetables.

*Property development*

This farm was originally irrigated by overhead sprinklers (manual shift). Since 2004, the entire property has been converted, in 2 ha blocks, to a drip irrigation system. The change from overhead to trickle was driven by water scarcity and the need to improve WUE, but water savings have not been the only benefit. Improved soil and crop health, increased yields, easier management and economies of scale were all listed as advantages of the new irrigation system.

Rainfall patterns in this area can be highly variable, and water scarcity is a significant concern. Groundwater access has become progressively worse with recurrent droughts since 1990 (at times, down to around 5% of total water availability, or around 22.5 ML/hour). Pumping water when potential supply is limited incurs additional costs; pumps need to be adjusted down and run less efficiently, and may need to run 24 hours a day. In addition, low pumping pressures under these conditions mean that water must be pumped into a dam, then re-pumped to deliver water at the pressure required (90 ML/hour) for the drip system.

The adoption of the trickle system has enabled this farm to irrigate 20 ha using the same amount of water previously needed to irrigate 8 ha with overhead. Water savings are dependent on soil type; this property has achieved approximately 50% water savings but this has not been replicated on other (leased) properties (e.g. on the eastern Darling Downs) where soil types are heavier.

#### *Cropping system*

The land is farmed on an annual rotational basis, with winter vegetable crops and summer cover crops, as described above. Harvesting is determined by demand and market prices.

Vegetables are planted and irrigated in 2 ha blocks, with permanent traffic 'marks'. Permanent tracking means a 10% loss of soil but this reduces soil compaction and benefits soil health. Trickle tape is retrieved after each crop and reused up to five times ('with experience, we are getting better at it all the time') within a cropping season, but replaced each year.

#### *Technology adoption*

Principal drivers for adoption of drip irrigation technology were stated as increased WUE, improved crop and soil health, increased yields, easier management and increased profit. Barriers to adoption were seen as cost—with an initial outlay of $10 000 per 2 ha block ($5000/ha) and annual replacement costs of $50 000 ($625/ha)—and the limits of the technology (can only pump around 130 m before losing pressure). No significant problems have been encountered with the use of this technology. The drip system on this farm is fully automated and centrally controlled.

EnviroSCAN probes (Sentek Sensor Technologies) help to provide an understanding of how quickly water moves through the soil profile. These are used predominantly as a learning and planning tool, rather than for day-to-day irrigation scheduling; with up to 20 plantings at one time, it would be expensive to install a probe in every block, as well as time-consuming to interpret all the information.

#### *Crop production*

Production benefits under the trickle irrigation system are increased yields and improved crop quality. Increased productivity is difficult to quantify as harvesting is based on market demand, and quantified on a per head basis. However, further investigation and discussion with Dr Craig Henderson from DEEDI indicated that this farm yields about 3775 cartons (12 heads/carton, with an average weight of about 825 g/head). In addition to yield benefits, the quality benefits are potentially significant. In overhead systems, mildews can reduce yield by up to 60% in wet weather due to a high level of residual mildews present in the crop. Under drip irrigation, there is generally very little leaf wetness, hence fewer mildews present in the crop, and yield reduction in wet weather may be closer to 10%.

### *Labour saving*

The old hand shift sprinkler system required 5–6 FTEs to operate. When the drip system was installed, labour was reduced to 2 FTEs (required to operate taps in each irrigation block), but this has been further reduced now that the system is fully automated and centrally controlled. In addition, the complexity of many tasks has been reduced, for example through fertigation.

### *Crop inputs*

The drip system allows significant flexibility and multitasking. With the completely automated system, each 2 ha block is watered for 1.5 hours/week, and the entire farm can be watered in a single day. This allows the flexibility to wait if rain is predicted, but to water as required if rain doesn't eventuate. With the old hand shift system, watering was continuous as the system had to be kept moving around the farm.

Regular soil testing is conducted on average once every three years. Fertiliser use has increased under the drip system, but with changes in fertiliser technology over time, it was expected that use would also have increased under the old sprinkler systems. Despite this, fertiliser efficiency is greater with trickle than with sprinkler irrigation systems. Fertigation in regular quantities is adjusted to temporal crop requirements; the old sprinkler system required the application of granular fertilisers, usually in two applications, which resulted in more leaching over time.

Herbicide and insecticide use has remained unchanged. Crops are checked twice a week and decisions about insecticides and fungicides are made as required.

Cultivation has been reduced under the new system, but fuel usage is not recorded because it is a relatively low proportion of enterprise costs. It was expected that energy use would be reduced under the trickle system, with less water applied and also lower pressure required for application than the former sprinkler system.

### *Soil health*

Significant soil health benefits (in terms of limited compaction) are associated with the permanent tracking system adopted in conjunction with the drip irrigation system.

### *Climate change*

With increasing water scarcity, the value of water can only increase, necessitating more efficient management of available water.

### *Water trading*

Water trading is not conducted on the case study farm, but it is on other leased farms. The landlords have purchased water from neighbouring farms on the temporary transfer market. This was viewed as a poor system from a vegetable growing perspective, where 100% water security is needed; permanent transfers would be preferred.

## Hydrological modelling

Water saving estimates had not previously been conducted for lettuce, so we applied the SWAP model to estimate the potential water savings. The farmer's estimates were used to validate the water savings obtained through the SWAP model.

This farm harvests two lettuce crops (autumn and winter) during the cropping year but we only estimated water savings for winter lettuce. Winter lettuce is transplanted early August and harvest starts in early October (about 55–60 days after transplantation). Lettuce is grown on a wide range of soil types ranging from light sandy to heavy clay loams in the Lockyer Valley (Amjed 2010). For the SWAP model, we used sandy loam, the main soil type at this farm. Lettuce is a shallow-rooted crop and 85% of water uptake occurs from the top 20 cm of the soil profile, making the plant susceptible to water stress. This implies that uniform distribution of irrigation water is necessary to ensure the crop is not over or under irrigated.

We used Bureau of Meteorology climatic data from Gatton weather station in the SWAP model. The average annual rainfall is 770 mm, with a large variation in annual rainfall distribution. The mean maximum and minimum temperatures during the cropping period are 25°C and 9.8°C, respectively. The potential evapotranspiration (ETo) during the growing season ranges from 3.2–5.5 mm/day. The timing of irrigation applications throughout the season were determined by the grower using visual observations of the crop and soil, his past experience and EnviroSCAN probes. Approximately 25 mm of water was applied in each irrigation event. The SWAP model was simulated for the period from January 1980 to December 2009 using three irrigation practices.

The results showed that an average of 1.6 ML/ha of water savings was possible—with a range of 1.4–2.0 ML/ha for winter lettuce—when converting from overhead sprinklers (manual shift) to drip irrigation systems. Based on the farmer's assessment, water savings of 1.96 ML/ha (52.4%) were achieved for lettuce grown under drip irrigation compared to overhead sprinklers, indicating that the farmer was achieving at the higher level of water savings indicated through SWAP modelling.

## Energy consumption and GHG estimation

### *Use of fuels for farm operations for lettuce crops*

The energy consumption and GHG emissions due to the use of fuel (diesel and electricity) for lettuce farming operations in two different irrigation systems is given in Table 39. Overall, fuel-related GHG emissions in trickle and hand shift irrigation systems were 3133.5 kg $CO_2$-e/ha and 4967.7 kg $CO_2$-e/ha, respectively. Both the farm machinery operation and irrigation-related emissions were higher in the hand shift irrigation system, which used more diesel and electricity. Farm machinery operation-related emissions in the hand shift system were 1.3 times the emissions from trickle irrigation, and irrigation-related emissions were double. Farm machinery-related emissions in the lettuce crop were higher than many other crops analysed in this research. This was expected, as pre-planting and harvesting operations for a lettuce crop require more machinery operations and use more fuel.

Table 39: Energy consumption (MJ/ha) and greenhouse gas emissions (kg$CO_2$-e/ha) due to use of fuels in lettuce farming operations in case study 4, Lockyer Valley, south-eastern Queensland

| *Farming operation* | *Drip (trickle)* | | | | *Sprinkler (hand shift)* | | | |
|---|---|---|---|---|---|---|---|---|
| | *Diesel (L)* | *Electricity (kWh)* | *Energy used* | *Emissions (kg $CO_2$-e/ha)* | *Diesel (L)* | *Electricity (kWh)* | *Energy used* | *Emissions (kg $CO_2$-e/ha)* |
| Farm machinery operation | 635.6 | – | 24 533.9 | 1 844.9 | 823.6 | – | 31 790.3 | 2 390.6 |
| Irrigation | – | 384.4 | 4 585.6 | 1 288.6 | – | 768.8 | 9 171.2 | 2 577.1 |
| Total | | | 29 119.5 | 3 133.5 | | | 40 961.5 | 4 967.7 |

### *Use of agrochemicals for lettuce crops*

In total, the production, packing, storage and transportation of agrochemicals used in the trickle and hand shift irrigation systems emitted 1209.8 kg $CO_2$-e/ha and 677.3 kg $CO_2$-e/ha, respectively (Table 40). Lettuce farming under the hand shift irrigation system used more Crop King (NPK) fertiliser than trickle irrigation. The hand shift system used 200 kg of sulfate of ammonia but did not require potassium nitrate and calcium nitrate. Lettuce farming under trickle irrigation did not require sulfate of ammonia but required 800 kg/ha of calcium nitrate and 200 kg/ha of potassium nitrate. However, much of this difference can be attributed to changes in fertilisation practices over recent years and to the farmer's experience in precision farming rather than differences in irrigation systems.

Table 40: Energy consumption (MJ/ha) and greenhouse gas emissions (kg $CO_2$-e/ha) due to use of agrochemicals for lettuce crops in case study 4, Lockyer Valley, south-eastern Queensland

| *Agrochemicals* | *Drip (trickle)* | | | *Sprinkler (hand shift)* | | |
|---|---|---|---|---|---|---|
| | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Crop King 77S | 300.0 | 3 466.7 | 239.2 | 400.0 | 4 622.2 | 318.9 |
| Sulfate of ammonia | – | – | – | 200.0 | 3 014.9 | 217.9 |
| Calcium nitrate | 800.0 | 9 667.3 | 657.8 | – | – | – |
| Potassium nitrate | 200.0 | 2 700.8 | 172.4 | – | – | – |
| Insecticide | 7.7 | 1 540.0 | 36.0 | 7.7 | 1 540.0 | 36.0 |
| Herbicide | 7.5 | 1 800.0 | 86.6 | 7.5 | 1 800.0 | 86.6 |
| Fungicide | 5.0 | 460.0 | 17.9 | 5.0 | 460.0 | 17.9 |
| Total | | 19 634.8 | 1 209.8 | | 11 437.1 | 677.3 |

### *Soil emissions of $N_2O$ due to N-fertiliser application*

Trickle and hand shift irrigation in the lettuce crops emitted around 1826.5 kg $CO_2$-e/ha and 935.3 kg $CO_2$-e/ha, respectively, into the atmosphere simply from denitrification of applied N fertiliser (Table 41). Emissions were directly related to N fertiliser quantities: the higher the N fertiliser application, the greater the emissions of $N_2O$ ($CO_2$-e). All fertilisers used for lettuce crops in both irrigation systems contained some amount of nitrogen. However, more fertilisers were used in the present-day trickle irrigation system. The GHG emissions per hectare from the trickle-irrigated lettuce crop was almost double those of the former hand shift irrigated lettuce cropping system.

#### *GHG emissions due to the production of farm machinery used in the lettuce cropping*

As noted, operation of lettuce farm machinery (other than irrigation machinery) in the hand-shift irrigation system required more diesel than the trickle irrigation system. As the GHG emissions due to the use of farm machinery were directly related to diesel-related emissions, the hand shift irrigation system had greater machinery-related emissions (344.25 kg $CO_2$-e/ha) than the trickle system (265.67 kg $CO_2$-e/ha) (Table 42).

Table 41: Soil emissions of $N_2O$ (kg $CO_2$-e/ha) due to N-fertiliser application in case study 4, Lockyer Valley, south-eastern Queensland

| *N fertilisers* | *Drip (trickle)* | | *Sprinkler (hand shift)* | |
|---|---|---|---|---|
| | *Amount (kg/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Amount (kg/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Crop King 77S NPK | 300 | 392.0 | 400.0 | 522.7 |
| Sulfate of ammonia | 0 | 0.0 | 200.0 | 412.7 |
| Calcium nitrate | 800 | 1 179.0 | 0.0 | 0.0 |
| Potassium nitrate | 200 | 255.5 | 0.0 | 0.0 |
| Total | | 1 826.5 | | 935.3 |

Table 42: Greenhouse gas emissions (kg $CO_2$-e/ha) due to various farming inputs to the two lettuce irrigation systems in case study 4, Lockyer Valley, south-eastern Queensland

| *Sources of emissions* | *Drip (trickle)* | | *Sprinkler (hand shift)* | |
|---|---|---|---|---|
| | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Fuel | 29 119.5 | 3 133.50 | 40 961.5 | 4 967.70 |
| Agrochemicals | 19 634.8 | 1 209.80 | 11 437.1 | 677.30 |
| N fertilisers | na | 1 826.50 | na | 935.30 |
| Farm machinery (except irrigation machinery) | na | 265.67 | na | 344.25 |
| Total emissions (kg $CO_2$-e/ha) | na | 6 435.47 | na | 6 924.60 |
| GHG emissions (kg $CO_2$-e/ML of water) | na | 3 605.30 | na | 1 846.56 |
| GHG emissions (kg $CO_2$-e/kg of lettuce) | na | 0.17 | na | 0.22 |

Note: Lettuce yield was 37 372 kg/ha for drip and 31 766 kg/ha for hand shift; total water used was 1.79 ML/ha for drip (trickle) and 3.75 ML/ha for sprinkler (hand shift).

Overall, more GHGs were emitted from the hand shift system (6924.6 kg $CO_2$-e/ha) than from the trickle system (6435.47 kg $CO_2$-e/ha; Table 42). These results are a little lower than the previous estimate of average national-level emissions for lettuce farming systems in Australia (8750 kg$CO_2$-e/ha; Maraseni et al. 2010b). This variation is inevitable as farms operate under different climatic, topographic and edaphic conditions.

The GHG emissions per hectare are clearly different between the two lettuce farming irrigation systems (Table 42). Major differences were noted in fuel and agrochemical-related emissions. Trickle irrigation released more agrochemical-related emissions but less fuel-related emissions.

Trickle irrigation used 1.79 ML/ha whereas hand shift used 3.75 ML/ha. GHG emissions per unit of water were higher in the trickle system (3605.3 kg $CO_2$-e/ML) than the hand shift system (1846.56 kg $CO_2$-e/ML). The lettuce yields for drip and hand shift irrigation were 37 125 kg/ha and 31 556 kg/ha, respectively. The GHG emissions per unit of yield in drip irrigation were 1.3 times lower than from hand shift irrigation.

## Economic evaluation

The economic analysis of conversion from overhead sprinklers (manual shift) to the drip irrigation system was conducted for this 80 ha farm, which was converted to a drip irrigation system in after 2004 to improve WUE, yield, quality and labour efficiency. The farm consists of multiple 2 ha blocks, and we used one 2 ha block for economic analysis.

### *Assumptions that underlie the base case scenario*

In addition to the assumptions previously discussed in section 5.3.3, some additional assumptions were used in the economic evaluations.

- The farmer's cropping pattern included mainly autumn and winter lettuce, replaced by broccoli and cauliflower, depending on the market conditions. We used two autumn and winter lettuce crops in the analysis. The barley, wheat and oats grown during summer were mainly rainfed, and not included in the analysis.
- All the saved water was used to increase the cropping area.
- Quality improvements were modelled through higher market prices. Based on the farmer's assessment and lettuce grown, using drip irrigation increased market prices by 10%.
- No water trading occurred at this property due to physical constraints, so we did not consider permanent or temporary water trading in the analysis. In the sensitivity analysis, we considered a 50/50 water sharing plan.
- Water use efficiency was 92%.
- The labour saving was 20%.

The results of the economic analysis (Table 43) indicated a stronger economic return at the current level of water savings (1.96 ML/ha); however, drip irrigation technology was still an economically viable option for this farm. The parameters contributing to economic returns included increased crop yield, labour savings and water savings. The net benefit of adopting the drip irrigation system was about $4613/ML/year. The BCR indicates that every dollar spent on the improved technology led to a $13.12 increase in income. The increase in the yield and labour savings were sufficient to recover costs within the first year of investment.

Table 43: Economic evaluation of drip irrigation technology adoption for lettuce in case study 4, Lockyer Valley, south-eastern Queensland

| *Economic evaluation indexes* | *Unit* | *Base case scenario* |
|---|---|---|
| Net present value (NPV) | $ | 453 257 |
| Benefit–cost ratio (BCR) | | 13.12 |
| Internal rate of return (IRR) | % | na |
| Payback period | Years | Less than a year |
| Break–even (BE) water saving | ML/ha | 0* |
| Net benefit per ML of saved water | $ | 4 613.0 |

* Increase in yield and labour saving is more than enough to justify investment.

## Sensitivity analyses

The sensitivity analysis showed that all scenarios resulted in positive NPVs, making investments in converting the hand shift sprinkler irrigation system to drip irrigation viable and robust (Table 44). This was mainly due to higher yield and quality benefits, and significant water and labour savings.

The conversion to a drip irrigation system for the case study farm will generate a very high return on the investment if the assumed yield benefits, water savings and labour savings occur for lettuce farming.

Table 44: Sensitivity analysis of drip irrigation technology adoption for lettuce in case study 4, Lockyer Valley, south-eastern Queensland

| *Scenario* | *Net present value ($)* | *Net benefit per ML saved ($)* |
|---|---|---|
| Base case scenario | 453 257 | 4 613.00 |
| 50% water saving | 182 200 | 3 680.80 |
| 0% labour benefits | 422 180 | 4 296.90 |
| 0% yield increase | 121 291 | 1 234.51 |
| 50/50 water sharing @ $2 500/ML | 262 069 | 2 667.36 |
| 50/50 water sharing @ $1 500/ML | 260 119 | 2 647.52 |
| $10/t $CO_2$-e carbon price | 453 507 | 4 615.80 |
| $30/t $CO_2$-e carbon price | 454 007 | 4 620.90 |
| 30 year technology life | 496 958 | 5 058.09 |
| 15 year technology life | 326 300 | 3 321.12 |
| 10% interest rate | 296 549 | 3 018.31 |
| 2% interest rate | 619 777 | 6 308.16 |

### 4.4.5 Case study 5: pasture–cropping (lucerne, oats), southern Darling Downs, southern Queensland

## Farm description and parameter estimation

This farm is a 708 ha mixed farm with irrigated and dryland lucerne–grain cropping and feedlot enterprises on the eastern Darling Downs, southern Queensland, with part of the cropping area leased to a horticultural enterprise (onions). Of the total cropped area, 263 ha is irrigable and 40 ha is dryland. Cropping soil types are black alluvium (creek flats) and sandy loam (ridges). Irrigation water is sourced from harvested streamflow (nominal volumetric entitlements, allocated volumes) and overland flows (licensed volumetric limits), and groundwater extraction (nominal volumetric entitlements, allocated volumes), although little groundwater (40% of allocation) is used due to diminishing quality. Harvested overland flow water is stored in onfarm storages (authorised storage capacity). The farm relies on 8–16 ML/ha/year of irrigation water applied by sprinkler (centre-pivot, roll-line) irrigation systems. Water is distributed to irrigation paddocks by pipe.

*Property development*

Irrigation on this property commenced 12–14 years ago with the installation of roll-line sprinkler systems, but has been progressively converted to centre-pivots over the past 10 years. There are currently 251 ha under five centre-pivot systems and 12 ha under roll-line sprinkler systems. Further areas on the lighter (sandy loam) ridge country are currently being developed for another three centre-pivot systems to expand the leased horticultural area.

Water reliability is viewed as a serious problem, and water security has been a high priority ('you need to invest in things that are in short supply'). The irrigation farming system on this property is currently designed to cope with the worst-case scenario in terms of water availability, based on analysis of 120 years of climate records from the Hermitage Research Station near Warwick, Queensland. Total off-stream water storage capacity on this property is 1.0 GL, and the instream weir ponds up to 1.7 GL. Sprinkler irrigation systems were adopted to increase the onfarm WUE, although their actual WUE is unknown. Water savings have enabled an increase in the irrigated cropping area on this farm. Centre-pivot systems can apply approximately 55 mm/week at peak evaporation, and use approximately 50% of the water used by the older roll-line sprinkler system.

#### *Cropping system*

To some extent, farming is on a set rotation, with lucerne grown for three years, followed by either a grain (maize, sorghum, wheat) or pasture crop (oats). Lucerne is cut for hay or grazed if the crop is poor. On the lighter country, onions are grown on a two-year rotation, followed by two years of forage crop. The cropping program is effectively based on the quantity of water in storage ('we farm the water'), and commercial judgments are made on that basis.

#### *Technology adoption*

Principal drivers for adoption of centre-pivot sprinkler irrigation technology were stated as labour savings, increased efficiency, lower cost of application and maintenance, greater reliability and easier management. Full-circle centre-pivot systems were preferred; earlier lateral-move and part-circle centre-pivot systems used were found to be problematic, as they needed to be 'walked back' and the timing caused problems when a crop required water. While irrigation is on the circle, planting is still generally done on the square with planting rates adjusted by GPS (tractors are all GPS auto-steer).

Barriers to adoption of new irrigation technologies include time, outlay costs (e.g. $80 000–90 000 per centre-pivot, and $2470–3700/ha installed) and lack of water plan security. ('Each new policy initiative, from the WAMP [water allocation management plan] to the proposed federal Murray–Darling [Basin] Plan, has involved cuts to water allocations and security'). Permanent drip irrigation is not seen as a feasible option on the black soils because of their self-mulching characteristics; however temporary tape is considered an option that could be easily installed, if needed, on the horticulture pivots on the lighter country.

Electronic probes and manual soil probes are used to monitor soil moisture, enabling deficit irrigation (application of water at the best time based on the soil water profile). This is critical on the heavier black soil types ('need to deficit irrigate or waste it'), but if well managed, it is possible to achieve a 30% better crop with 30% less water ('the 30% rule'). Even greater efficiencies can be achieved on lighter soil types where deficit irrigation can increase profits by 60–80%.

The farm is highly monitored ('if you can't measure it, you can't manage it') and increasingly automated. All creek pumps and pivots have onsite meters, and it's planned to monitor and operate these remotely, although this is currently limited by the technology (e.g. low speed broadband) that's currently available at an economic rate. 'Farming in water-poor regions is generational, with incremental long-term gains.'

#### *Crop production*

Lucerne is the most profitable crop grown, but it is a high water user. The crop is cut for hay, producing around 6.5 t/ha/cut (about three cuts per year) under centre-pivot sprinkler irrigation; this is 1.5–2.0 t/cut more than when it was grown under the older roll-line irrigation system. The equivalent water productivity for these systems is 2.44 t/ML for the centre-pivot system and 0.93 t/ML for the roll-line system; centre-pivot water use is 8 ML/ha compared to 16 ML/ha for the roll-line system. On these values, yield improvement due to the adoption of the centre-pivot irrigation system is approximately 45% per ha and 170% per ML of water compared with yields for the roll-line irrigation system. Gross margins on lucerne grown under the centre-pivot system and cut for hay are estimated at $4940/ha and about $620/ML.

Benefits in terms of horticultural productivity are more difficult to measure, as these are essentially market-driven. While profits can be significant, the level of financial risk is also high. For example, in two consecutive years, 40.5 ha of irrigated onions yielded 49 400 kg/ha on 3.3 ML/ha and 4.3 ML/ha of water (i.e. 15.0 and 11.5 t/ML, respectively). However, price variation meant that gross margins ranged from $54 340/ha to $19 760/ha (i.e. $1.10/kg to $0.40/kg or $16 467/ML to $4595/ML)

#### *Labour savings*

The new irrigation technologies have reduced labour requirements on this property by about 100 person-days/year. However, concern was expressed about issues associated with retaining trained staff who, once they were competent in the use of high-tech equipment such as GPS auto-steer tractors, have moved on to employment in the mines.

In terms of labour costs, comparison was provided for the different irrigation systems under horticulture:

- hand-shift sprinkler systems: $121–200/ha/crop
- drip-tape trickle systems: $121/ha/crop ($40 to lay, $40 to retrieve)
- pivot sprinkler systems: $40/ha/crop (maximum).

#### *Crop inputs*

Each irrigation and cropping system receives small inputs of effluent (estimated at 10 ML/year) from the onfarm feedlot that runs into the storage dam from which irrigation water is drawn for distribution around the farm. No additional fertiliser is applied, although lucerne provides 2–3 years benefit in terms of N input (‘land is something to stand the crop on’ and ‘centre-pivot is broadacre hydroponics: sunlight plus water equals profits’). Both systems receive 2.5 t/ha of gypsum every six years.

The application of crop sprays (herbicides) for the two irrigation systems used on this farm are the same, and overall requirements for herbicides are minimal (1 L/ha pre-planting, and 0.2 L/ha three times a year over the life of the crop). The owner describes himself as a percentage farmer (‘90% is good enough’), using temporary fencing, farming by contract where possible and not too concerned about weeds. Lucerne is grown because herbicides can be used to control grass weeds, and because GM crops (e.g. corn) cannot be grown. This system requires minimal crop cultivation and management (‘we only manage if there’s a problem’).

There was concern expressed about the quantity of energy used on the farm, largely associated with the irrigated cropping components (‘everyone is currently focused on volumetric issues in terms of water use. However, this focus will change in the next 10–20 years; the energy factor will be critical into the future.’). Energy use has been reduced by an estimated 15% with the adoption of the centre-pivot irrigation system and conversion to electric pumps. Reduced water requirements, and hence pumping, also enabled a change to pumping at night and on weekends when tariffs were lower (from $0.15/kW down to $0.11/kW).

### *Climate change*

Increasing water scarcity will necessitate more efficient management of available water. On this farm, climate forecasts (SOI) are noted as these indicate the probability of water harvesting events. Commercial decisions are based on both water availability and climate forecasts (the probability of rain). The property is essentially set up for climate change. It was felt that there might be little change in the overall amount of rainfall, but that rainfall distribution and intensity might change. This property is set up to enable the maximum-allowable capture and storage of high-intensity rain.

### *Water trading*

Water trading is not considered an attractive option for this enterprise ('never sell your best asset; you need to use it to create additional income'). Concern was expressed about the one-size-fits-all approach of the current water-trading market. It was felt that there should be greater appreciation of the value of water associated with where it sits in the catchment ('1 ML here is not the same everywhere'). For example, a volume of water transferred from the eastern Downs, where pan evaporation is 1.4 m, would be significantly diminished in value if it were transferred to an area such as Cubby, where pan evaporation is greater than 2.4 m. In addition, 1 ML water on the eastern Downs has higher value than 1 ML water further from markets.

## Hydrological modelling

We did not perform a detailed hydrological analysis for this case study because the potential water saving assessment (section 5.1, Table 10) was performed for the same region, soil types and environmental conditions. Instead, we used the farmer's estimates of water saving and validated these against the water saving assessment derived through SWAP modelling. According to the farmer's assessment, 50% (8 ML/ha) water savings were achieved for lucerne under centre-pivot irrigation compared with the older roll-line sprinkler irrigation system. These water savings are relatively high when compared with the SWAP model assessment (Table 10). The farmer monitors soil moisture using electronic probes and manual soil probes and applies deficit irrigation practices on the centre-pivot irrigation systems, which would account for up to 30% of the reported water savings. Overall, the centre-pivot irrigation system and deficit irrigation practice enabled the farmer to realise about 50% water savings.

## Energy consumption and GHG estimation

### *Use of fuels for farm operations for lucerne crops*

The amount of fuel used for farm machinery operations (other than irrigation machinery operations) in both the centre-pivot and roll-line irrigation systems was the same. In both irrigation systems, GHG emissions related to machinery operations accounted for 83.7 kg $CO_2$-e/ha. Both the centre-pivot and roll-line systems only used electricity for irrigation, but the roll-line system used twice as much. GHG emissions related to irrigation in the roll-line system were therefore two times higher than those from the centre-pivot system (Table 45). Overall, over three years, the centre-pivot system emitted 22 611.4 kg $CO_2$-e/ha whereas roll-line system emitted 45 139.0 kg $CO_2$-e/ha.

Table 45: Energy consumption (MJ/ha) and greenhouse gas emissions (kg $CO_2$-e/ha) due to use of fuel in lucerne crop operations in case study 5, Darling Downs, southern Queensland

| *Farming operation* | *Centre-pivot* | | | | *Roll-line* | | | |
|---|---|---|---|---|---|---|---|---|
| | Diesel (L) | Electricity (kWh) | Energy used | Emissions (kg $CO_2$-e/ha) | Diesel (L) | Electricity (kWh) | Energy used | Emissions (kg $CO_2$-e/ha) |
| Farm machinery operation | 28.9 | – | 1 113.6 | 83.7 | 28.9 | – | 1 113.6 | 83.7 |
| Irrigation | – | 6720 | 80 169.6 | 22 527.7 | – | 13 440.0 | 160 339.2 | 45 055.3 |
| Total | 28.90 | 6720 | 81 283.2 | 22 611.4 | 28.9 | 13 440.0 | 161 452.8 | 45 139.0 |

Note: Lucerne crop is perennial three-year crop. All data are for three years.

### *Use of agrochemicals for lucerne crops*

No fertilisers, insecticides, fungicides or plant regulators were used in either the centre-pivot or roll-line irrigation systems on this farm. Gypsum and herbicides were used, at the same rate, in both irrigation systems. Lucerne is a legume crop that fixes N and makes it available to a companion crop or the next crop, thus saving synthetic N-fertiliser use and reducing GHG emissions. In addition, legume cropping systems have a number of other benefits: they serve to regenerate soil fertility; help to maintain manageable pest populations and retard pest evolution (Crews and Peoples 2004); reduce weed seed banks and crop loss from insects and diseases (Liebman and Dyck 1993); increase soil carbon levels (Paul et al. 2002); and can prevent N leaching by producing nitrification inhibitors (Subbarao et al. 2007). These are some of the possible reasons why few agrochemicals were used on this farm.

In both irrigation systems, the farmer used 1240 kg/ha of gypsum and 2.8 L/ha of herbicides. In total, the production, packing, storage and transportation of gypsum and herbicides in each irrigation system accounted for 491.1 kg $CO_2$-e/ha of GHG emissions (Table 46).

Table 46: Energy consumption (MJ/ha) and greenhouse gas emissions (kg $CO_2$-e/ha) due to use of agrochemicals for lucerne crops in case study 5, Darling Downs, southern Queensland

| *Agrochemicals* | *Centre-pivot* | | | *Roll-line* | | |
|---|---|---|---|---|---|---|
| | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Amount (kg or L/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Gypsum | 1 240.0 | 6 200.0 | 458.8 | 1 240.0 | 6 200.0 | 458.8 |
| Herbicide | 2.8 | 672.0 | 32.3 | 2.8 | 672.0 | 32.3 |
| Total | | 6 872.0 | 491.1 | | 6 872.0 | 491.1 |

Note: Lucerne crop is a perennial three-year crop. All data are for three years.

### *Soil emissions of $N_2O$ due to biologically fixed N*

Both applied synthetic N fertiliser and biologically fixed N emit $N_2O$ into the atmosphere from the soil but the scientific community debates whether emissions from biologically fixed N are as much as from N fertiliser. Dalal et al. (2003) suggested that the $N_2O$ emissions from legume crops exceeded those from N fertiliser due to frequent wetting and drying cycles over a longer period. Crews and Peoples (2004) argued that the biologically fixed N was ultimately derived from solar energy while N fertiliser requires significant amounts of fossil fuels, thus legumes should have a lower impact. Despite this debate, IPCC (2001) considers the $N_2O$ emissions factors for all inorganic N fertiliser and biologically fixed N to be equal at 1.25% (of total N).

Nitrogen fixation by legumes depends upon soil nitrate conditions, the legume species and cultivar, soil moisture, crop and soil management practices and whether the legume was inoculated with rhizobium (Peoples et al. 1992; Rochester et al. 1998). Many Australian studies have estimated the amount of N fixation by legume crops (see Henzell et al. 1967; Peoples et al. 1992; Bell et al. 1994; Rochester et al. 1998; Armstrong et al. 1999; Peoples and Griffiths 2009) but we cannot readily apply these studies to our sites and crop species due to the variation described above. We know that a large amount of $N_2O$ will be emitted from N biologically fixed by lucerne as its biomass and yield is very high.

### *GHG emissions due to the production of farm machinery*

GHG emissions due to farm machinery usage (other than irrigation-related machinery) are directly related to fossil fuels used to operate the machinery. As both irrigation systems used equal amounts of diesel to run farm machinery, both irrigation systems had equal amounts of machinery-related emissions (12.1 kg $CO_2$-e/ha; Table 47).

Table 47: Greenhouse gas emissions (kg $CO_2$-e/ha) due to various farming inputs to the two lucerne irrigation systems in case study 5, Darling Downs, southern Queensland

| *Sources of emissions* | *Centre-pivot* | | *Roll-line* | |
|---|---|---|---|---|
| | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* | *Energy (MJ/ha)* | *Emissions (kg $CO_2$-e/ha)* |
| Fuel | 81 283.2 | 22 611.4 | 161 452.8 | 45 139.0 |
| Agrochemicals | 6 872.0 | 491.1 | 6 872.0 | 491.1 |
| Farm machinery (except irrigation machinery) | na | 12.1 | na | 12.1 |
| Total emissions (kg $CO_2$-e/ha) | | 23 114.6 | | 45 642.2 |
| GHG emissions (kg $CO_2$-e/kg of lucerne) | | 3.6 | | 9.6 |
| GHG emissions (kg $CO_2$-e/ML) | | 963.1 | | 950.9 |

Notes: Lucerne crop is a perennial three-year crop. All data are for three years. Lucerne yield was 6500 kg/ha for centre-pivot and 4750 kg/ha for roll-line (average of 4500–5000 kg/ha); over three years, total irrigation water was 24 ML/ha for centre-pivot and 48 ML/ha for roll-line irrigation. Compared to furrow irrigation, lateral-move produced more lucerne with less water.

Lucerne is a perennial crop grown over a three-year period. Over three years, more GHGs were emitted from the roll-line irrigation system (45 642.2 kg $CO_2$-e/ha) than from the centre-pivot system (23 114.4 kg $CO_2$-e/ha; Table 47). This difference was associated with the differing amounts of electricity used for irrigation. These results are higher than the results from other case studies because more irrigation water was used and electricity was the only energy source.

Over the three-year cropping period, the centre-pivot irrigation systems used 24 ML/ha of water whereas roll-line irrigation used 48 ML/ha. However, there was little difference in the GHGs emitted per unit of water between the centre-pivot (963.1 kg $CO_2$-e/ML) and roll-line (950.9 kg $CO_2$-e/ML). These values are comparable with the values in other case studies.

The yield of lucerne for the roll-line irrigation system (4750 kg/ha) was lower than that from the centre-pivot system (6500 kg/ha). Therefore, GHG emissions per unit of yield frmo the roll-line system were more than 2.6 times the emissions from the centre-pivot system.

## Economic evaluation

We conducted an economic analysis of conversion from a roll-line sprinkler system to a centre-pivot sprinkler system for 251 ha of cropping area on this farm, with conversion to the centre-pivot system based on the need to achieve labour and water savings, increased efficiency, lower cost of application and maintenance, greater reliability and easier management. As this farm had five centre-pivots that were used on five paddocks, a single paddock area of 50 ha was used for this analysis.

### *Assumptions that underlie the base case scenario*

In addition to the assumptions discussed in section 5.3.3, some additional assumptions were used in the economic evaluations.

- The farmer is following a rotation with lucerne grown for three years, following by grain that is usually rainfed. (Onions are grown on lighter soils, however this land is leased to external onion growers, therefore only lucerne was used in the economic analysis.)
- All the saved water was used to increase the lucerne area.
- Quality improvements were not reported and therefore not included in the analysis.
- Gross margins were prepared for cut lucerne (hay) with three cuts per year (about 6.5 t/cut).
- The labour saving was 20 person-days (about 2.5 days/ha).
- The farmer was not trading water at this property, therefore no permanent or temporary water trading was considered in the analysis. In the sensitivity analysis, a 50/50 water-sharing plan was considered.
- Water use efficiency was 90%.

### *Results of the economic analysis*

The results of the economic analysis indicated that, at the current level of water saving (8 ML/ha), centre-pivot irrigation technology is a highly economically viable option. The parameters contributing to the very high economic returns included large volumes of water savings (including about 30% of water savings from deficit irrigation), higher yields and labour savings. The net benefit of adopting centre-pivot system was about $414.20/ML/year. The BCR indicated that every dollar spent on the improved technology led to an $8.86 increase in income. The estimated BE water saving for converting from roll-line irrigation to centre-pivot irrigation was close to zero (0.05 ML/ha), and yield increases and labour savings were sufficient to recover the investment. The farmer was expecting to recover his capital investment in less than a year.

Since total water savings included 30% of water savings achieved through deficit irrigation, a separate economic analysis was conducted on water savings achieved without deficit irrigation practices. The results showed that the centre-pivot was still an economically viable option with high NPV ($913 019), a BCR (3.28) greater than 1, IRR (132%) higher than the discount rate, and a payback period of about two years. Similarly, the net benefit adopting centre-pivot system was about $285/ML/year.

Table 48: Economic evaluation of centre-pivot irrigation technology adoption for lucerne crops in case study 5 Darling Downs, southern Queensland

| *Economic evaluation indexes* | *Unit* | *Base case scenario* |
|---|---|---|
| Net present value (NPV) | $ | 2 071 074 |
| Benefit–cost ratio (BCR) | | 8.86 |
| Internal rate of return (IRR) | % | NA |
| Payback period | Years | Less than a year |
| Break–even (BE) water saving | ML/ha | 0.05* |
| Net benefit per ML of saved water | $ | 414.20 |

*Yield increases and labour savings were more than enough to justify investment.

## Sensitivity analyses

The sensitivity analysis was conducted on total water savings, including deficit irrigation. The sensitivity analysis showed that all scenarios resulted in a positive NPV, therefore investments in converting the roll-line irrigation system to a centre-pivot sprinkler irrigation system were viable and robust (Table 49). This was mainly due to higher yields and significant water and labour savings.

Table 49: Sensitivity analysis of centre-pivot irrigation technology adoption for lucerne crops in case study 5 Darling Downs, southern Queensland

| *Scenario* | *Net present value ($)* | *Net benefit/ML saved ($)* |
|---|---|---|
| Base case scenario | 2 071 074 | 414.20 |
| 50% water savings | 1 106 028 | 294.00 |
| 0% labour saving | 1 886 091 | 377.21 |
| 0% yield increase | 1 081 045 | 216.20 |
| 50/50 water sharing @ $2500/ML | 1 966 371 | 393.27 |
| 50/50 water sharing @ $1500/ML | 1 865 571 | 373.11 |
| $10/t $CO_2$-e carbon price | 2 015 579 | 403.31 |
| $30/t $CO_2$-e carbon price | 1 904 589 | 380.91 |
| 30 year technology life | 2 270 078 | 454.01 |
| 15 year technology life | 1 492 933 | 298.58 |
| 10% interest rate | 1 357 455 | 271.49 |
| 2% interest rate | 2 829 371 | 565.87 |

For the lucerne crop, conversion from a roll-line irrigation system to centre-pivot generated a very high return on the investment. This has enabled the farmer to plan for further investment in three additional centre-pivot systems to enable more land to be leased for horticultural production.

# 4.5 Integrated analysis trade-off matrix

Possible conflicts between adaptation and mitigation might arise as a result of new irrigation technology, but at this point, we do not have a complete insight into the practicality, consequences or unintended consequences of adopting this new irrigation technology. We have explored possible conflicts by creating a trade-off matrix (Table 50), which quantifies the relationships between water savings, economics and GHG emissions.

Based on the five case studies, the trade-off matrix shows that the adoption of new irrigation technologies generates economic benefits and saves water. Although new irrigation technologies require additional energy and, subsequently increase GHG emissions, changes in farm level machinery and input uses can offset these.

Table 50: Trade-off matrix of converting surface irrigation to drip and sprinkler irrigation systems based on five Australian farm case studies

| *Case study* | *Irrigation technology conversion* | *Crop* | *Water saving (ML/ha/year)* | *Estimated net present value ($/ha/year)* | *Emissions (kg $CO_2$-e/ha/year* | |
|---|---|---|---|---|---|---|
| | | | | | *New irrigation technology* | *Crop-level inputs* |
| 1 | Flood (furrow) to sprinkler (lateral-move) | Cotton | 2.00 | 582.4 | 491.8 | –1 105.5 |
| 2 | Flood (furrow) to sprinkler (centre-pivot) | Cotton | 1.00 | 176.0 | 183.0 | –488.4 |
| 3 | Flood (furrow) to drip | Cotton | 1.00 | 95.0 | 4 047.0 | 4 000.4 |
| 4 | Sprinkler (hand shift) to drip | Lettuce | 1.96 | 9 065.0 | –1 288.5 | –489.1 |
| 5 | Sprinkler (roll-line) to sprinkler (centre-pivot) | Lucerne | 8.00 | 1 657.0 | –7 509.2 | –7 509.2 |

Conversion of older, inefficient and energy-intensive sprinkler irrigation systems (hand shift and roll-line) to drip and efficient sprinkler irrigation technologies saves considerable energy and reduces GHG emissions due to farming operations. This creates a win–win situation; water savings and emission reductions can both be achieved as a result of technology adoption and farm-level input.

The trade-off analysis raises a critical point, indicating that both mitigation and adaptation have to be evaluated simultaneously to optimise economic investments in irrigation technologies while managing climate change.

## 4.6 Irrigation technology transformation scenarios

To evaluate the irrigation industry-wide trade-offs between water savings, energy consumption (and GHG emissions), and economic returns associated with irrigation technology transformation, we tested three scenarios. We used the integrated framework (section 3.1) along with the following assumptions.

- Use of farm-level inputs, such as farm operation and fertilisers, may ameliorate or exacerbate energy consumption (and GHG emissions). In three of our five case studies, a reduction in machinery operations and inputs essentially neutralised GHG emissions associated with the adoption of energy-intensive new irrigation technologies. We only considered energy consumption and GHG emissions as a result of new irrigation technologies in the analysis.
- In some instances, flood irrigation systems may consume energy, and therefore emit GHGs, but for these scenarios, we did not consider energy consumption and GHG emissions in flood irrigation.

- Both electric and diesel pumps are used on Australian farms. We used electric pumps in the analysis because they are used more frequently.

### 4.6.1 Scenario 1

***Reducing the total area of surface irrigation systems from 44% during 2008–09 to 25%, and replacing them with drip irrigation (40%) and sprinkler irrigation systems (60%)***

Nationally, the area under surface irrigation systems such as furrow, border check and flood irrigation during 2008–09 was approximately 804 000 ha, which accounted for almost 44% of the total irrigated area. Under this scenario, the area under surface irrigation was reduced by 43% from 804 000 ha to 456 250 ha, and 40% (139 100 ha) was replaced with drip irrigation and 60% (208 650 ha) with sprinkler irrigation systems.

The results of the scenario are presented as a trade-off matrix in terms of water savings, economic returns, energy required and GHG emissions (Table 51). The amount of water saved depends on soil, climate and crop types. The total estimated water savings from replacing surface irrigation with drip and sprinkler irrigation was around 373 GL/year in the low water saving scenario, 553 GL/year in the average water saving scenario and 869 GL/year in the high water saving scenario (Table 51). Economic returns largely depended on water savings, yield increases and labour savings. Under low water savings, cereal crops showed a negative NPV. While new irrigation technologies save water, an additional 6188 TJ of energy would be required to realise water savings from them under average water use condition. These estimates do not include any change in farm-level machinery and inputs, which might increase or decrease energy consumption. As a result of increased energy consumption, GHG emissions would be likely to increase. Under average water savings, GHG emissions would be about 1 737 000 t $CO_2$-e/year.

An alternative way of explaining the trade-off could be, for example, 120 GL of water savings through conversion of surface irrigation systems to drip irrigation for a cotton crop would increase energy consumption by 889 TJ and GHG emissions by 250 000 t $CO_2$-e. An ETS with a carbon price of \$20/t $CO_2$-e would cost around \$5 million extra nationally per year. Nevertheless, this is trivial as the benefits of water savings and productivity of new technology would outweigh the additional GHG costs.

### 4.6.2 Scenario 2

***Reducing the total irrigation area under 'portable irrigators sprinkler irrigation system' and 'hose irrigators sprinkler system' from 16 to 8% during 2008–09, and replacing them with a drip irrigation system (50%) and an efficient sprinkler (lateral-move and centre-pivot) irrigation system (50%).***

The national area of portable irrigator sprinkler irrigation systems (81 000 ha) and hose irrigator sprinkler systems (214 000 ha) was roughly about 16% of the total irrigation area during 2008–09. Under this scenario, the area of portable irrigator and hose irrigator sprinkler systems was reduced by 49% from 299 000 ha to 146 000 ha, and 50% (76 500 ha) was replaced with drip irrigation and 50% (76 500 ha) with efficient sprinkler irrigation.

The results of the scenario are presented as a trade-off matrix in terms of water savings, economic returns, energy required and GHG emissions (Table 52). Under an average water saving scenario, the conversion of portable and hose sprinkler irrigation systems to drip and efficient sprinkler irrigation systems would save over 226 GL of water. Since portable and hose sprinkler irrigation are energy-intensive and labour-intensive systems, their replacement would be likely to result in energy savings, especially when they are replaced with drip irrigation systems. As a result, GHG emissions would be likely to decrease. Under average water savings, GHG emissions would decrease by about 306 000 t $CO_2$-e. With a \$20/t $CO_2$-e carbon price, this would result in \$6.1 million of GHG avoidance benefits. Given increasing concerns about GHG reduction and water savings, this could be an efficient means of saving water and reducing GHG footprints. The economic viability however would be questionable when savings were at the lower end of the water-saving scale; but for high water savings, the installation of drip and efficient sprinkler irrigations systems are economically viable options.

Table 51: Scenario 1: Trade-off matrix of converting surface irrigation to drip and sprinkler irrigation systems

| *Onfarm technology* | *Area replaced ('000 ha)* | *Irrigation technology* | *Range of water savings under irrigation (GL)* | | | *Estimated net present value (millions $)* | | | *Energy consumption (GJ)* | | | *Emissions ('000 t $CO_2$-e)* | | | *Estimated value of emissions* ('000 $)* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *Low* | *Avg.* | *High* | *Low* | *Avg.* | *High* | *Low* | *Avg.* | *High* | *Low* | *Avg.* | *High* | *Low* | *Avg.* | *High* |
| Pasture for grazing* | 105 | Sprinkler | 105 | 126 | 210 | 59 | 115 | 342 | 2 486 | 2 663 | 2 983 | 698 | 748 | 838 | 13 970 | 14 968 | 16 764 |
| Pasture for hay | 59 | Drip | 148 | 207 | 266 | 19 | 401 | 784 | 1132 | 1 132 | 1 251 | 318 | 318 | 352 | 6 362 | 6 362 | 7 031 |
| Pasture for silage | 9 | Sprinkler | 9 | 14 | 23 | 3 | 18 | 52 | 198 | 225 | 274 | 56 | 63 | 77 | 1 112 | 1 266 | 1 540 |
| Pasture for seed production | 10 | Sprinkler | 10 | 15 | 25 | 4 | 17 | 58 | 220 | 250 | 304 | 62 | 70 | 86 | 1 235 | 1 406 | 1 711 |
| Cereal crops for hay | 6 | Sprinkler | 2 | 5 | 8 | –16 | –2 | 11 | 41 | 73 | 103 | 12 | 20 | 29 | 231 | 408 | 579 |
| Cereal crops for grain or seed | 73 | Sprinkler | 18 | 62 | 91 | –200 | –20 | 136 | 500 | 883 | 1 253 | 140 | 248 | 352 | 2 810 | 4 960 | 7 041 |
| Cereal crops (not grain, seed or hay) | 6 | Sprinkler | 2 | 5 | 8 | –16 | –2 | 11 | 41 | 73 | 103 | 12 | 20 | 29 | 231 | 408 | 579 |
| Cotton | 80 | Drip | 80 | 120 | 240 | –97 | 162 | 1 132 | 808 | 889 | 808 | 227 | 250 | 227 | 4 540 | 4 994 | 4 540 |
| Total | 348 | – | 373 | 553 | 869 | –246 | 690 | 2 526 | 5 425 | 6 187 | 7 079 | 1 525 | 1 739 | 1 989 | 30 490 | 3 4771 | 39 784 |

* At $20/t $CO_2$-e carbon price

Note: for simplicity, we only used average values of energy consumption and greenhouse gas emissions for all irrigation technologies.

Table 52: Scenario 2: Trade-off matrix of converting a portable irrigators sprinkler irrigation system and a hose irrigators sprinkler system to drip and sprinkler irrigation systems

| *Onfarm technology* | *Area replaced ('000 ha)* | *Irrigation technology* | *Range of water savings under irrigation (GL)* | | | *Estimated net present value (millions $)* | | | *Energy consumption (GJ)* | | | *Emissions ('000 t $CO_2$-e)* | | | *Estimated value of emissions* ('000 $)* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Low | Avg. | High | Low | Avg. | High | Low | Avg. | High | Low | Avg. | High | Low | Avg. | High |
| Cotton | 21 | Sprinkler | 17 | 25 | 34 | 0 | 40 | 152 | 8 | –11 | –31 | 3 | –3 | –8 | 56 | –50 | –156 |
| Cotton | 21 | Drip | 27 | 36 | 65 | 0 | 38 | 268 | –171 | –204 | –280 | –47 | –57 | –78 | –948 | –1 134 | –1 559 |
| Lucerne | 15 | Sprinkler | 5 | 15 | 44 | 14 | 77 | 171 | 64 | 35 | –42 | 19 | 11 | –11 | 374 | 213 | –214 |
| Lucerne | 15 | Drip | 20 | 33 | 59 | 4 | 92 | 179 | –181 | –220 | –307 | –50 | –61 | –85 | –1 002 | –1 220 | –1 705 |
| Tomato | 30 | Drip | 17 | 45 | 90 | 147 | 235 | 259 | –175 | –233 | –297 | –48 | –64 | –82 | –965 | –1 289 | –1 642 |
| Grapes | 52 | Drip | 52 | 73 | 109 | 247 | 399 | 641 | –391 | –474 | –589 | –108 | –132 | –163 | –2 169 | –2 631 | –3 270 |
| Total | 154 | – | 137 | 226 | 400 | 413 | 880 | 1670 | –846 | –1 108 | –1 545 | –233 | –306 | –427 | –4 654 | –6 112 | –8 546 |

* At $20/t $CO_2$-e carbon price

Note: for simplicity, we only used average value of energy consumption and greenhouse gas emission for all irrigation technologies.

### 4.6.3 Scenario 3

***Increasing the drip irrigation area on horticultural crops from 13.3 to 20% of the total irrigated area during 2008–09***

Nationally, the area under drip irrigation (surface and subsurface systems) during 2008–09 was approximately 243 000 ha, approximately 13.3% of the total irrigated area. The main crops under drip irrigation systems were horticultural crops, mostly grapes, citrus and other fruits, and vegetables. Under this scenario, the area under drip irrigation was increased by approximately 6.7% from 243 000 to 365 000 ha.

Grapes, citrus and tomato crops were selected to represent horticultural and vegetable crops. The trade-off matrix of increasing drip irrigation technology on horticultural crops is shown in Table 53. Overall, a 6.7% increase in drip irrigation area would save around 154 GL/year in the low water saving scenario, 216 GL/year in the average water saving scenario and 311 GL/year in the high water saving scenario. The NPV indicated that increasing the area under drip irrigation for horticultural crops would be an economically feasible option. This was due to the relatively high level of water savings (even in a low water saving scenario), increased productivity and labour savings. The NPV was $593 million for the low water saving scenario, $952 million for the average water saving scenario and $1 328 million for the high water saving scenario. The additional energy required for these conversions under the average water saving scenario was about 1700 TJ. This increase in energy consumption would generate an additional 478 000 t $CO_2$-e per year. These estimates were based on replacing surface irrigation systems with drip irrigation. Replacing older, inefficient and labour-intensive sprinkler irrigation systems, such as portable irrigators, with drip irrigation would result in long-term operational energy savings and a reduction in GHGs, as shown under scenario 2.

Table 53: Scenario 3: Trade-off matrix of replacing surface irrigation with drip irrigation technology on horticultural crops

| *Onfarm technology* | *Area replaced ('000 ha)* | *Irrigation technology* | *Range of water savings under irrigation (GL)* | | | *Estimated net present value (millions $)* | | | *Energy consumption (GJ)* | | | *Carbon equivalent emissions ('000 t $CO_2$-e)* | | | *Estimated value of GHG emissions* ('000 $)* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Low | Avg. | High | Low | Avg. | High | Low | Avg. | High | Low | Avg. | High | Low | Avg. | High |
| Grapevines | 52 | Drip | 78 | 114 | 156 | 274 | 443 | 713 | 578 | 609 | 630 | 162 | 171 | 177 | 3 246 | 3 423 | 3 541 |
| Vegetables for human consumption (Tomato) | 30 | Drip | 30 | 45 | 60 | 163 | 261 | 288 | 333 | 400 | 485 | 94 | 112 | 136 | 1 873 | 2 247 | 2 724 |
| Fruit trees, nut trees, plantation or berry fruits (Citrus) | 38 | Drip | 46 | 57 | 95 | 155 | 248 | 327 | 599 | 691 | 729 | 168 | 194 | 205 | 3 364 | 3 882 | 4 097 |
| Total | 120 | | 154 | 216 | 311 | 593 | 952 | 1328 | 1 509 | 1 700 | 1 844 | 424 | 478 | 518 | 8 483 | 9 552 | 10 363 |

* At $20/t $CO_2$-e carbon price

# 5. Discussion—the effects and consequences of technological change

Climate change will affect both the demand for and availability of water in Australian catchments. Altered hydrological regimes due to climate change are predicted to lead to changes in the amount and timing of streamflow and groundwater recharge, with important implications for the performance and sustainability of the irrigation industry, our single largest water user. On the other hand, with higher atmospheric temperatures and evapotranspiration, crops will generally require more water to maintain healthy growth. In addition to the threat of climate change, climate variability, ongoing drought and water for environmental purposes underscore the importance of making the best use of our water resources.

The imperative for more efficient water use is clear. The goals of the Australian Government's Water for the Future initiative are taking action on climate change, using water wisely, securing water supply and supporting healthy rivers. A large focus of the program is the Murray–Darling Basin, which is where most of Australia's irrigation occurs, and where the irrigation industry is under pressure to reduce its water use through realising higher WUEs. As part of the initiative, the Sustainable Rural Water Use and Infrastructure Program supports irrigation investments of about $5.8 billion over 10 years to modernise irrigation infrastructure both on- and off-farm to save water and increase WUE. Modern irrigation technology leads to more efficient, productive and profitable use of water with a view to maintaining the value of irrigated production in the face of declining water availability, and is a key component of adaptation to climate change.

On the other hand, the Australian Government is committed to reducing Australia's GHG emissions and has proposed a carbon price as the most effective way for Australia to meet its target of a 5–25% reduction by 2020 compared to 2000 levels. Even if agriculture were excluded from an ETS, the irrigation industry would still be affected by changes in energy costs.

Ideally, climate change mitigation and adaptation strategies should complement each other in order to manage climate change risks. However, the relationship within the water sector is a reciprocal one (IPCC 2008). Mitigation measures can influence water resources and their management, but water management policies and measures can influence GHG emissions. As a result, interventions in the water system might be counterproductive when evaluated in terms of climate change mitigation. This study explored the trade-offs and synergies between water savings, economics, energy consumption and GHG emissions.

The study showed that the level of water savings achieved when converting from surface (flood and furrow) irrigation to drip and sprinkler irrigations systems affected the economic viability of the conversion. For example, it was shown to be uneconomic to install drip and sprinkler irrigation systems for lower value crops when water savings were at the lower end of the scale; for these crops, economic viability was dependent on a high level of water savings per ha. Conversely, for high value horticultural crops, the installation of drip and sprinkler irrigation systems was economic at any level of water savings. It was also found that conversion to drip and efficient sprinkler irrigation systems for crops with the potential for a high range of water savings, such as lucerne, was economically viable.

While the level of water savings can be substantial and the conversions can be economically feasible, the energy costs associated with these conversions are considerable. This has implications for production costs, as well as infrastructure requirements, depending on the spatial distribution of energy demand. Irrigators will also bear increased costs of pumping, particularly in surface water regions where irrigation water would previously have been applied in a relatively energy-free way, with little or no cost for application. According to the results of this study, costs could vary from $120–1000/ha for drip and sprinkler irrigations systems, depending on crop water use, irrigation method and fuel source, among other factors. This is an option that would need to be carefully considered by both farmers and policy-makers.

The most common fuel sources for irrigation operating energy in Australia are diesel and electricity. Both energy sources have associated GHG emissions and environmental consequences in terms of potentially increasing GHG emissions with the introduction of pressurised irrigation systems. The level of emissions depends on the quantity of energy used and the fuel source. In Australia, electricity has higher emissions than diesel fuel in all states except Tasmania (DCC 2008). The CPRS will have direct and indirect effects on irrigators who increase energy use through the use of pressurised systems. Directly, irrigators may be required to mitigate or pay a penalty for extra emissions. Indirectly, increased fuel costs arising from the introduction of the CPRS will change the prices and costs faced by irrigators. Higher diesel and electricity prices are to be expected from the inception of the scheme, regardless of whether agriculture is included or not.

## 5.1 Policy-level implications

The outcomes of the United Nations Climate Change Conference 2009 (COP15) in Copenhagen, Denmark, brought two major changes, one in carbon price and another in agricultural policy. For example, carbon prices in Europe dropped to a six-month low after the Copenhagen meeting (BBC News, 21 December 2009). This was mainly as a result of the lack of a globally binding target, thus the European Union was unwilling to increase its emissions reduction target to 30% by 2020. If the REDD (reduced emissions from deforestation and forests degradation) mechanism, the most favoured policy for many countries, is accepted in the post-Kyoto policy, the carbon price may continue to fall.

Similarly, after COP15, all developed countries except New Zealand have excluded agriculture from their proposed ETSs. Australia has followed the same line, but this may not be an efficient outcome. As mentioned earlier, when energy and transport inputs in agricultural production are included, the Australian agricultural sector accounts for 23% of national GHG emissions (Hatfield-Dodds et al. 2007). From 1990 to 2005, Australia's emissions from agriculture increased by 1.5% (DCC 2009a). If emissions from agriculture are left unchecked, they are likely to increase in the future. It has been asserted that if agriculture is not included in the proposed CPRS, then the Australian Government's previously stated emissions reduction target for 2050 (60% reduction below 2000 levels by 2050) cannot be met (Maraseni 2009; Maraseni et al. 2009a). Therefore, agriculture should be in the emissions reduction equations to some extent, as outlined in Maraseni (2009) and Maraseni et al. (2009a). Including agriculture in an ETS is also becoming less complicated, as recent studies (e.g. Maraseni 2009; Maraseni et al. 2009a,b) have developed cost-effective monitoring and verification methodologies.

Although agriculture is currently excluded from the proposed ETS, two common tendencies are increasing in all developed countries. The first is proposed offset schemes to encourage emissions abatement from the agriculture sector, and the second is development of policies for voluntary carbon markets and changing behaviour of farmers through these markets. The Australian Government has followed suit by excluding agricultural emissions from the proposed CPRS but allowing participation in a voluntary carbon market for offsets. With this amendment to the CPRS policy proposal, the Government expects agriculture to contribute to Australia's unconditional target of a 5% reduction in GHG emissions by 2020, relative to 2000 levels (Calford et al. 2010). Three provisions are allowed within the amended CPRS settings: Kyoto-compliant CPRS offsets, non-CPRS voluntary market offsets and a CPRS opt-in.

Kyoto-compliant CPRS offsets are counted toward Australia's international commitments. Non-CPRS voluntary offsets do not contribute to meeting Australia's international commitments but can be sold into voluntary markets, which would involve a price that could be significantly lower than that for Kyoto-compliant offsets. The CPRS opt-in would cover carbon credits from reforestation, forest regrowth and increased soil carbon on deforested land (Calford et al. 2010).

Irrigation technologies have some affect on fertiliser and water use, thus energy consumption and GHG emissions, but changes in irrigation technology do not make any difference in many of the proposed CPRS activities (Table 4 in Calford et al. [2010] for proposed activities). Therefore, the CPRS policy may have little affect on irrigation technology. Setting aside the issues of the proposed CPRS policy, this study compares energy use and GHG emissions due to the use of different irrigation technologies, and provides advice to policy-makers with valuable insights and data about where and how well different irrigation technologies are positioned in relation to GHG emissions.

We have estimated the differences in GHG emissions due to changing one irrigation system to another (Table 54). These differences can be used for setting emissions factors for conversion of irrigation systems. This may have policy implications if an ETS is provided to farmers on the basis of emissions factors. For example, a farmer using an electric pump 1000 ML/year of irrigation water wants to change technology from flood to a drip irrigation system. The farmer may receive 568 free carbon permits (one permit is equal to 1000 kg $CO_2$-e) because the emissions factor for changing from flood to drip irrigation would be 568 t $CO_2$/1000 ML water. Queensland uses significant quantities of coal to generate electricity, making its emissions factor for electricity generation very high. If Queensland growers could use renewable energy then these emissions factors (carbon permits) could be reduced.

Table 54: Average greenhouse gas (GHG) emissions in different irrigation systems with electric pumps

| *Description* | *Electric* | | |
|---|---|---|---|
| | *Centre-pivot* | *Lateral-move* | *Drip* |
| GHG emissions (kg $CO_2$-e/ML) | 906 | 995 | 568 |
| GHG emissions (t $CO_2$-e/1000 ML) | 906 | 995 | 568 |
| Number of free carbon permits for changing irrigation system | 906 | 995 | 568 |

Note: All figures are average, taken average of maximum and minimum from Table 12.

There is a significance difference in energy consumption and GHG emissions between diesel-based and electricity-based water pumping systems, mainly due to differences in emissions factors per unit of energy. The detailed discussion on the GHG emissions factors for diesel and electricity is given in Table 6 and section 3.1.2, and lifecycle (pumping, installation, maintenance and decommissioning) energy consumption and GHG emissions for irrigating 1 ML of water for diesel and electricity-based irrigation systems is given in Table 20 and section 5.2. If the same farmer from the example given above uses a diesel pump instead of an electric pump, he will only get 125 free carbon permits. Here it seems that government policy would encourage electric pump users rather than diesel pump users, which would be a perverse outcome for climate change mitigation efforts, as diesel pumps generate less GHG emissions than electric pumps. There are several reasons why farmers want to use an electric pump, wherever possible, and we believe that in the long run, most pumps will be electric. A diesel pump is better for GHG emissions but there are several additional costs associated with the use of diesel. For example, the working life of a diesel pump is 7000–15 000 hours but for an electric pump, it is almost infinite; the maintenance cost for a diesel pump is almost double that of an electric pump; and diesel pumps are labour intensive (you need to go to the field to operate it), while electric pumps can be operated from a computer or home.

With the case studies analysis, it was generally found that the GHG emissions due to the use of farm machinery operation and agrochemicals decline with new irrigation technology. However, reduction in agrochemical-related emissions may not be solely due to new irrigation technologies; it may result in part from new experience with precision agriculture. Moreover, it is also realised that the comparison of energy and water consumption of various irrigation technologies could not give a complete picture without analysing both energy and water consumption data for a complete rotation of crops. In one season or crop cycle, one irrigation technology could consume less energy or water but it may consume more in a different year. Similarly, the use of farm inputs (fuels, agrochemicals, machinery) and thus the energy consumption and GHG emissions due to production, consumption and use of those farm inputs, could vary significantly between irrigation types. However, due to limited funding, this study could not provide a more complete picture.

Similarly, $N_2O$ soil emissions due to the use of N fertiliser and soil carbon sequestration rates in various irrigation systems could vary significantly. However, since there is no research on emissions factors for different irrigation technologies, we used the same $N_2O$ emissions factors were used for all irrigation systems for the same crop. For the same reason, soil C sequestration amounts for different irrigation systems were not considered.

There is a clear research gap in this area. Efforts are going into minimising $N_2O$ soil emissions due to applied N fertilisers by maintaining water-filled pore space at less than 40%, reducing soil compaction to increase oxygen diffusion in soils, reducing the readily available carbon supply that increases microbial proliferation, and removing residual nitrate from the soil by growing cover crops (Dalal et al. 2003). In the future, we might expect lower $N_2O$ emissions than we have estimated in this study.

New irrigation technologies reduce soil disturbance, so we may assume that the amount of soil carbon sequestration would be higher. This is in line with the belief that conservation tillage, compared to conventional tillage, increases soil carbon sequestration. There is no study comparing the amount of soil organic carbon (SOC) under different irrigation systems but several studies compare SOC between conventional and conservation tillage systems. In most of those studies, soils were only sampled to a depth of 30 cm or less, and the results are consistent with the general perception (Baker et al. 2007). In cases where sampling extended deeper than 30 cm, the story is completely different, with higher concentrations of SOC realised near the surface in conservation tillage and higher concentrations in deeper layers under conventional tillage (Baker et al. 2007). To some extent, this conclusion is supported by a review in Canada (VandenBygaart et al. 2003) and research at Hermitage Research Station, near Warwick, Australia (Wang et al. 2004). At this stage, we cannot accurately pinpoint which irrigation systems could have more SOC.

# 6. Conclusion and recommendations

## 6.1 Key conclusions

- Modern irrigation technologies are capable of saving volumes of water. The water savings generally depend on climatic conditions, soil types and management. The SWAP modelling results show that, on average, 15–25% water savings are possible. Among all the pressurised systems, drip irrigation systems achieved the highest levels of water savings.
- With proper design and better management of irrigation and pumping systems, higher levels of water savings are possible. This was evident from the case studies where farmers saved amounts at the higher end of modelled water savings.
- Compared to surface gravity-based irrigation systems, all pressurised (sprinkler, drip) irrigation systems consume more energy and emit more GHGs. Among the three irrigation systems investigated (drip, lateral-move sprinkler, centre-pivot sprinkler), drip irrigation systems were considered the most efficient in terms of energy consumption and GHG emissions. Results showed a general trend of increasing energy consumption with increasing water use.
- This study provides an indication of the comparative energy and GHG consequences of adopting a particular irrigation system over another. There is little apparent difference in energy consumption and GHG emissions between the centre-pivot and lateral-move sprinkler systems, but a relatively large difference between these and the more energy-efficient drip irrigation systems. Thus, when energy use and GHG emission-related expenses are factored into choices between irrigation systems, drip irrigation system may be the most attractive alternative.
- From the five case studies conducted, it was found that GHG emissions resulting from the use of farm machinery in farming operations either declined or remained constant with the adoption of new irrigation technologies. A similar trend was observed in terms of agrochemical-related emissions (fertilisers, pesticides), with the exception of case study 4 (an intensive horticultural farming enterprise). However, even in this case, due to higher productivity under the more efficient drip irrigation system, GHG emissions per kg of yield were lower than those under the less efficient hand shift sprinkler system. Additional advantages in cropping-related emissions were also evident as a result of the associated adoption of precision-farming techniques (GPS-guided tractors, soil moisture monitoring and improved irrigation scheduling) and reduced pesticide (and associated fuel) use with the planting of GM cotton.
- Results from the case study farms showed large variations in resource use across farms for water and energy use at the field level. On one hand, irrigation-related GHG emissions increased significantly with the adoption of new irrigation technologies. While the new irrigation technologies used less water per ha of crop, emissions per ML of water and per ha increased considerably. On the other hand, due to increased production, emissions per kg of crop yield fell in all cases except case study 3. In this instance, the new drip irrigation system used much more electricity than the old flood irrigation system, and the irrigation-related emissions for the trickle irrigation system were 1.8 times higher per kg of crop yield than for the flood irrigation system.

- Overall, these analyses indicated significant variation in GHG emissions across the different irrigation technologies, and with different crop types, farming systems and locations (water source, soil type, climatic factors). Indications are that a range of management decisions in addition to the adoption of efficient irrigation technologies will influence water savings, as well as irrigation-related energy use, GHG emissions and associated costs.
- The economic modelling showed that if only the lower end of water savings were achieved, conversion to more water efficient irrigation technologies was not economically viable, especially for grain crops. However, irrigation technology was economically viable for horticultural crops even at the lower end of water savings because of increased productivity and labour benefits. In terms of economic returns, there was little difference between drip and sprinkler irrigation systems. However, since drip irrigation is mostly adopted for horticultural crops, it generally shows better economic returns.
- All five case studies generated positive economic returns to investments, mainly due to water savings, increased productivity and labour savings. Among others, case study 4 (the lettuce farm) showed a considerably high rate of return owing to double crop plantings, water savings and yield increases.
- The sensitivity analysis showed that, among the parameters tested, economic returns were most sensitive to water savings, yield increases and labour savings. The sensitivity analysis for 50/50 water sharing, using permanent water trading pricing as a substitute, showed that farmers were better off using water savings on their land rather than trading water.
- Under circumstances where the CPRS becomes a reality, the CPRS covers the entire agricultural industry without any benchmarking, there is no emissions-intensive trade-exposed industry support, and there is no fuel credits support as proposed in the CPRS, then this study indicates that, if the carbon price is set at $10/t $CO_2$-e, a drip irrigation system with electric pumps will bear an additional financial burden of $5.70/ML of water pumped, whereas centre-pivot and lateral-move sprinkler systems will carry additional costs of $9.10/ML and $10.00/ML, respectively.
- In all irrigation systems, using diesel rather than electric pumps has significant energy and GHG benefits. Pumping 1 ML of water with a diesel pump emits 4.5 times less GHGs than pumping the same amount of water using electricity, and an irrigator using diesel pumps will pay 4.5 times less per ML than one using electric pumps under a carbon pricing scenario. Nevertheless, whenever possible, farmers are more inclined to opt for electric pumps due to their longer working life, lower maintenance costs and relative ease of use. Therefore, in the absence of the CPRS or any similar mechanism that would infer a significant price advantage for the use of diesel pumps, the use of electric pumps is likely to increase.
- Possible disagreement between adaptation and mitigation might arise as a result of new irrigation technology. The trade-off analysis indicates that the adoption of new irrigation technologies saves water and thus generates economic benefits. Although new irrigation technologies require additional energy and consequently increase GHG emissions, changes in farm level machinery use and inputs can offset increases in GHG emissions.

- The trade-off analysis raised a critical point that both mitigation and adaptation have to be evaluated simultaneously to optimise investments in irrigation technologies while managing for climate change. Four of the five case studies showed that, overall, the adoption of new irrigation technology reduced GHG emissions. This was mainly due to reduced levels of inputs. In addition, the conversion of older inefficient and energy-intensive sprinkler irrigation systems (hand shift and roll-line) to drip and efficient sprinkler irrigation technologies saves considerable energy (and GHG emissions). This creates a win–win situation, where water savings and GHG reductions can be achieved both as a result of technology adoption and farm-level input.
- Irrigation technology transformation scenarios also showed trade-offs. Two out of three scenarios showed that water savings associated with conversion to new irrigation technologies would increase GHG emissions. However, these scenarios were simulated without incorporation of changes in the farm machinery and input uses; including farm-level changes may yield different results. More research is needed to understand the finer-scale implications of inputs and machinery uses as a result of new irrigation technology adoptions.

## 6.2 Key recommendations

- The use of pressurised systems can result in significant benefits in terms of savings and economic returns. However, the risk of increasing energy consumption and GHG emissions should be carefully considered. A more targeted approach that achieves balance between improvement in water use and the potential increase in energy consumption is required. Without this, a focus on improving IE to create water savings could subject irrigation enterprises to unexpected increases in energy consumption and escalating costs.
- Priority should be given to replacing older, inefficient and energy-intensive sprinkler irrigation systems, such as hand shift and roll-line. This will not only save water but also save considerable energy in addition to GHG reductions due to improved farming operations. This creates a win–win situation where water savings and GHG reductions can be achieved both as a result of technology adoption and farm-level input.
- The results from the case studies showed that high-end water savings were possible with skilful management and proper design of the irrigation system. This also has implications for energy use (and GHG emissions). Therefore emphasis should be given to management of the new irrigation systems along with the proper design of the systems.
- The current snapshot comparison of energy and water consumption of various irrigation technologies is unable to provide a complete picture because of the significant inter-annual variation inherent in farming systems within eastern Australia, and southern Queensland in particular. Similarly, even within the same irrigation technologies, the level of farm inputs (fuels, agrochemicals, machinery)—and thus the energy consumption and GHG emissions due to production, consumption and use of those farm inputs—could vary significantly between the crops in a rotation. A farmer may use more agrochemicals in a first crop with the intention to use less in the following crop. Therefore, a comprehensive study of water consumption and GHG emissions across full cropping rotations is necessary.
- $N_2O$ soil emissions due to the use of N fertilisers could vary significantly between irrigation technologies, but has been little researched. Research that investigates and quantifies the $N_2O$ emissions factors for a number of crops with different irrigation technologies is crucial.

- Soil carbon sequestration amounts for different irrigation systems may also vary significantly. There is currently no research into soil carbon between different irrigation systems. However, there is a widespread assumption that an irrigated cropping system that involves less soil disturbance will retain more soil carbon in the upper soil layer. While soil carbon sequestration in the top layer could increase with new irrigation technologies, it has been suggested that this may also mean lower amounts of soil carbon in deeper soils. Research that investigates soil carbon levels through the soil profile under different irrigation technologies is required.
- For water savings and emissions reduction policies, several factors need to be taken into consideration in terms of the adoption of new irrigation technologies:
  - Firstly, climate change is a global problem and requires a global solution. Australia accounts for only 1.5% of global emissions. If Australia achieves its previously-stated emissions reduction target (60% below 2000 levels by 2050), it would have reduced its GHG emissions by 300 Mt $CO_2$-e/year at the end of 2050. This is only 0.7% of current annual global emissions and 0.01% of the current atmospheric stock. Therefore, without a global effort, Australia's efforts in emissions reduction will be meaningless. With the background of current climate change negotiations following COP15, there is significant uncertainty as to whether a global agreement will be reached at COP16 (United Nations Climate Change Conference 2010, Cancun, Mexico).
  - Secondly, climate change is already happening, with effects being felt year by year. Even if all countries committed today to severely cut emissions, the effects will only be seen after a long period of time. Australia, and Australian agriculture, is particularly vulnerable, with climate change projections of decreased water availability for much of the country, as well as increased climate variability.
  - Thirdly, GHGs are a public good and also a global problem, whereas water is largely treated as private property and is a local problem within Australia.
  - Fourthly, in dollar terms, the economic benefit of saving 1 ML of water through using irrigation technologies is far greater than the estimated additional cost incurred due to being charged a carbon price under a CPRS-style ETS.

Against this background, we make two policy recommendations:

- that policy should be in place to encourage adoption of technologies that lead to the more efficient use of water by irrigators
- that climate change adaptation should be given a higher priority in policy considerations.

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# Appendix A—Types of irrigation systems

| *Irrigation system* | *Description* |
|---|---|
| Furrow systems | This system comprises a series of small, shallow channels used to guide water down a slope across a paddock. Furrows are generally straight but may also be curved to follow the contour of the land, especially on steeply sloping land. Row crops are typically grown on the ridge or bed between the furrows, spaced from 1 m apart. |
| Flood or border check systems | These systems divide the paddock into bays separated by parallel ridges/border checks. Water flows down the paddock's slope as a sheet guided by ridges. On steeply sloping lands, ridges are more closely spaced and may be curved to follow the contour of the land. Border systems are suited to orchards and vineyards, and for pastures and grain crops. |
| Level basin systems | These systems differ from traditional border check or flood systems in that the slope of the land is level and the area's ends are closed. Water is applied at high volumes to achieve an even, rapid ponding of the desired application depth within basins. |
| Centre-pivot sprinkler systems | A centre-pivot sprinkler is a self-propelled system in which a single pipeline supported by a row of mobile towers is suspended 2–4 m above ground. Water is pumped into the central pipe and as the towers rotate slowly around the pivot point, a large circular area is irrigated. Sprinkler nozzles mounted on or suspended from the pipeline distribute water under pressure as the pipeline rotates. The nozzles are graduated small to large so that the faster moving outer circle receives the same amount of water as the slower moving inner circle. |
| Hand move sprinkler systems | Hand move sprinkler systems are a series of lightweight pipeline sections that are moved manually for successive irrigations. Lateral pipelines are connected to a mainline, which may be portable or buried. Hand move systems are often used for small, irregular areas. Hand move systems are not suited to tall-growing field crops due to difficulty in repositioning laterals. Labour requirements are higher than for all other sprinklers. |
| Solid set/fixed sprinkler systems | Solid set/fixed refer to a stationary sprinkler system. Water-supply pipelines are generally fixed (usually below the soil surface) and sprinkler nozzles are elevated above the surface. Solid-set systems are commonly used in orchards and vineyards for frost protection and crop cooling. Solid-set systems are also widely used on turf and in landscaping. |
| Travelling gun sprinkler systems | Travelling gun systems use a large sprinkler mounted on a wheel or trailer, fed by a flexible rubber hose. The sprinkler is self-propelled while applying water, travelling in a lane guided by a cable. The system requires high operating pressures, with 100 psi not uncommon. |
| Side-roll wheel-move systems | Side-roll wheel-move systems have large-diameter wheels mounted on a pipeline, enabling the line to be rolled as a unit to successive positions across the field. Crop type is an important consideration for this system because the pipeline is roughly 1 m above ground. |
| Linear or lateral-move systems | Linear or lateral-move systems are similar to centre-pivot systems, except that the lateral line and towers move in a continuous straight path across a rectangular field. Water may be supplied by a flexible hose or pressurised from a concrete-lined ditch along the field's edge. |

Source: DPI Vic (2010): Irrigation system description. Available online at: *new.dpi.vic.gov.au/agriculture/soil-water/irrigation* (accessed 4 Oct 2010)

# Appendix B—Questionnaire

## Water and energy use efficiency study

***All information provided by the farmers in this survey will be kept strictly confidential. Only aggregate data will be used for research purposes.***

*General*

1. Total farm area (ha): ______________________________________________

2. Total irrigated area (ha): __________ Total rainfed/dryland area (ha): __________

3. What soil types are cropped on your farm (e.g., Sandy Loam, Clay Loam etc)?

______________________________________________________________

4. Crop rotation pattern: ______________________________________________

______________________________________________________________

______________________________________________________________

5. Total water allocation - medium security (ML): ________ high security (ML): ________

6. What proportion of your total irrigation water use is from:

streamflow __________ groundwater _________ harvested overland flow_____________

7. What is the condition of the water table in last 10 years (risen, fallen, stable)? ________

Change in water level (m): ___________________________________________

8. Has the changing watertable affected your pumping costs? ________ Y ______ N ______

If so, how? ______________________________________________________

9. What are the important factors responsible for any increase in pumping costs?

______________________________________________________________

______________________________________________________________

______________________________________________________________

10. Has the changing watertable affected your irrigation practices? Y ______ N ______

If so, how? ______________________________________________________

*Onfarm technology*

11. What type of irrigation system do you use on your land and how much area is under each irrigation system?

Flood (ha): __________ Centre-pivot (ha): ___________ Lateral-move (ha): ___________

Drip (ha): ___________ Other (ha): __________ Type: ________________________________

12. Why did you select this particular irrigation method?

________________________________________________________________________________

________________________________________________________________________________

13. How much water (ML or % per ha) do you save by using new irrigation technology?

________________________________________________________________________________

________________________________________________________________________________

14. How do you use the additional saved water (e.g., increased cropped area, water trading)

________________________________________________________________________________

________________________________________________________________________________

15. When was it installed?

________________________________________________________________________________

16. What was the cost of installation? _______________________________________________

17. What are the usual maintenance costs over one year? _____________________________

18. What is the onfarm water use efficiency of your current system (%) __________________

19. What type of irrigation technology would you use if you were to replace your existing system?

Centre-pivot (ha): ___________ Lateral-move (ha): ___________ Drip (ha):______________

Other (ha): ___________ Type: ____________________________________________________

Other (ha): ___________ Type: ____________________________________________________

20. What do you believe are the most appropriate irrigation technologies for your situation considering the following points, and why?

* Economic aspects – crop productivity, economic profit:

________________________________________________________________________________

________________________________________________________________________________

* Future effects of climate change – water scarcity, warmer climate:

________________________________________________________________________________

________________________________________________________________________________

21. What are the present barriers to your adoption of these technologies?

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

22. Do you monitor soil moisture to determine irrigation needs? _______ Y ______ N ______

If so, how? ______________________________________________________________

23. Do you use climate forecasts (e.g. SOI) to plan irrigation needs? ___ Y ______ N ______

If so, how? ____________________________________________________________
________________________________________________________________________
________________________________________________________________________

24. Is water trading an option for any water 'saved' due to water use efficiency technologies or measures for your enterprise? Y ______ N _____

If yes, would the price of water be a major factor in your decision to trade? Y ____ N____

If not price, what would be the major factor(s) in your decision not to trade? ___________
_______________________________________________________________________
________________________________________________________________________

25. Please provide details of the machinery and implements you use per irrigation type/crop/rotation:

Old: ______________________ ___________New: _______________________________

Irrigation type: _________________________ Rotation: ________________________

Crop: _________________________

| Process | Practices | Frequency | Size (hp or PTO hp) | Fuel use (L/ha) | ~Weight (t) | | MFD co. | Cost ($/ha) |
|---|---|---|---|---|---|---|---|---|
| | | | | | Machine | Accessory | | |
| Prep | Discing | | | | | | | |
| | Regrade (annual cost in every –yr) | | | | | | | |
| | Deep ripping | | | | | | | |
| | Lister-bed forming (N-application) | | | | | | | |
| | Spraying (herbicides)-raptor | | | | | | | |
| | Other (type:) | | | | | | | |
| Planting | Planter | | | | | | | |
| | Aerial spray (herbicides) | | | | | | | |
| | Chains | | | | | | | |
| | Other (type:) | | | | | | | |
| In season | Inter-row cultivation (clean furrow) | | | | | | | |
| | Shielding spray (herbicides) | | | | | | | |
| | Aerial spray (defoliator) | | | | | | | |
| | Other (type:) | | | | | | | |
| Harvest | Harvester | | | | | | | |
| | Module builder | | | | | | | |
| | Other (type) | | | | | | | |
| Post harvest | Transportation (distance and Mode) | | | | | | | |
| | Slashing | | | | | | | |
| | Stalk pulling | | | | | | | |
| | Mulcher | | | | | | | |
| | Other (type:) | | | | | | | |

Irrigation volume (ML): ___________________________________________

Number of applications: ___________________________________________

Labour (# employed): ___________________________________________

26. Please provide the following information regarding agrochemical use:

Irrigation type: ________________ Rotation: ________________ Crop: ________________

| Fertilisers | Kg or L/ha | Cost ($/ha) |
|---|---|---|
| Type: | | |
| | | |
| | | |
| Lime/Sulfur | | |
| Gypsum | | |
| Herbicides | | |
| Type: | | |
| | | |
| | | |
| Insecticides | | |
| Type: | | |
| | | |
| | | |
| Fungicides | | |
| Type: | | |
| | | |
| | | |
| Plant regulators | | |
| Type: | | |
| | | |
| | | |
| Rodenticides | | |
| Type: | | |
| | | |
| Other | | |
| Type: | | |
| | | |

27. Please provide information related to irrigation equipment and accessories:

Irrigation type: ________________ Rotation: ________________ Crop: ________________

| Machine/implements | Size (hp or PTO hp) | Fuel use (L/ha) | Weight or $m^2$ | MFD company | Cost |
|---|---|---|---|---|---|
| Pump | | | | | |
| Motor | | | | | |
| Spans | | | | | |
| PVC main water | | | | | |
| Polythene pipes | | | | | |
| Concrete weight/area | | | | | |
| Shed used for irrigation instruments (area) | | | | | |
| | | | | | |

28. Please provide the following characteristics of pumping operations:

Bore depth (m): ____________________

Capital cost ($): ____________________

Maintenance per year ($): ____________________

Bore entitlement ($): ____________________

Bore yield (ML): ____________________

Pump type (diesel/electric/other): ____________________

Suction head (m): ____________________

Pressure head (m): ____________________

Pump efficiency (%): ____________________

Flow rate ($m^3$/sec): ____________________

Energy use per ML pumped - electricity (kW/hour): ____diesel (litres/hour): ____

Pumping cost ($/ML): ____________________

29. Crop yields (tonne/ha): ____________________

30.Did crop productivity improve as a result of new irrigation technology? (please circle): Y / N

If Yes, by how much: __________ % or __________ tonne/ha

31. _ Did the new irrigation technology improve the quality of the crop? (please circle): Y / N

If Yes, by how much: ____________ % Comment:

__________________________________________________________________

__________________________________________________________________

__________________________________________________________________

32. Did you save labour as a result of new irrigation technology? (please circle): ___ Y / N

If Yes, by how much: _______ % or __________ hrs

33. Compared with your old irrigation technologies, has there been a change in energy use as a result of new irrigation technology (please circle): increased / decreased

Change in energy used: __________ % or __________ kW

## Water and energy use efficiency study

***Questions for formal and informal discussions with irrigation auditors, experts, and dealers related to irrigation instruments***

(1) Potential of water savings under different irrigation technology (%):

(a) Centre-pivot: ____________________

(b) Lateral-move: ____________________

(c) Drip: ____________________

(2) Cost of irrigation technology, including installation costs ($/ha)

(a) Centre-pivot: ____________________

(b) Lateral-move: ____________________

(c) Drip: ____________________

(3) Usual average maintenance costs over one year ($/ha)

(a) Centre-pivot: ____________________

(b) Lateral-move: ____________________

(c) Drip: ____________________

(4) Average energy use per ML water pumped or hour pumped (litre/kilowatt):

(a) Centre-pivot: ____________________

(b) Lateral-move: ____________________

(c) Drip: ____________________

(5) Average pumping efficiency of irrigation system (%)

(a) Centre-pivot: ____________________

(b) Lateral-move: ____________________

(c) Drip: ____________________

(6) Range and mode (most common) of suction head in Australia:

____________________

____________________

(7) Range and mode of pressure head in Australia:

____________________

____________________

(8) Range and mode of flow rate in Australia:

(9) Range and mode of pump efficiency in Australia:

(10) Most popular irrigation machines and accessories in Australia, and their size/power:

(11) Weights of different types of machines and accessory (for example galvanised steel spans in centre-pivot, PVC water mains, polythene pipes etc) used in different irrigation systems:

(12) Information about structure (for example weight of concrete structure, concrete to support pivot system, area of shed etc) for different irrigation methods:

(13) Installation, maintenance, and decommissioning energy required for these structures: