Design and demonstration of precision agriculture irrigation applied to different vegetable crops

Dr Susan Lambert
University of Tasmania

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Final Report for Project VG08029

(July 2012)

Design and demonstration of precision agriculture irrigation applied to different vegetable crops

Investigators: Dr Susan Lambert[A], Dr. Frank Hay[A],

Dr. Bill Cotching[A] and Prof. Tony Norton[A]

[A] Tasmanian Institute of Agriculture (TIA), University of Tasmania Cradle Coast campus, 16-20 Mooreville Road, Burnie, Tasmania, Australia 7320.

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Contact details for project leader:

Dr. Susan Lambert

TIA, University of Tasmania Cradle Coast campus 16-20 Mooreville Road, P.O. Box 3523,
Burnie, Tasmania, Australia 7008

Purpose of the project

The aim of this project was to develop and investigate two retro-fit irrigation technology systems to improve water and energy consumption during vegetable production, with trials conducted over three growing seasons (2010-2012). The first retro-fit irrigation system was fitted to a travelling gun irrigator to improve both energy and water efficiency. In addition, the project aimed to develop and demonstrate a retro-fit variable rate irrigation system for a linear move irrigator that enabled communication with a network of soil moisture sensors across the field (provided by CSIRO ICT). The overall aim of the project was to provide growers with options which will allow them to improve water use efficiency, reduce energy costs and reduce environmental impact.

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Media summary

Modification of new and existing technology in agriculture is required to ensure productivity growth and to address issues of climate change and natural resource sustainability. Two key challenges faced by the irrigated agriculture community are (i) competition for increasingly limited water resources and (ii) increases in energy costs. In this project the potential of two retro-fit systems were assessed over three seasons (2010-2012) and included: i) a pressure control system for a travelling gun irrigator; and ii) a variable rate irrigation (VRI) system for a linear move irrigator. Travelling gun irrigators are commonly used in horticulture due to their low capital cost and practicality of use on undulating topography. Modifications to improve the performance of a travelling gun irrigator were under taken as part of a collaborative project between the Tasmanian Institute of Agriculture (TIA) and Seattle Services Pty. Ltd. The retro-fit of telemetry devices and modified irrigation components to a travelling gun irrigator in this project enabled a constant set pressure to be maintained at the gun regardless of slope or length of the irrigation run. Comparisons between modified and conventional travelling gun irrigation were conducted and included monitoring energy and water use, yield, quality and disease assessments in a carrot crop. In 2011 there was a 17-21.8% and 5-10% reduction in energy and water use respectively between the modified and conventional irrigator, with a 10% increase in yield of carrots for the modified irrigator.

In addition a collaborative project was conducted between the Tasmanian Institute of Agriculture (TIA), Seattle Services Pty. Ltd. and CSIRO ICT. The aim was to use soil moisture measurements collected in real-time from a wireless sensor network (WSN) provided by the CSIRO ICT, to schedule irrigation events, develop a VRI (developed by Seattle Services Pty Ltd.), and develop a decision support system to enable closed loop site-specific irrigation to meet plant water requirements. The two components (VRI and WSN) were independently assessed. The WSN soil moisture system provided data during the second season (2011), however, problems with calibration remained unresolved. The variable rate system operated with water savings of 10-15% over the three cropping seasons. However, high rainfall resulted in reduced irrigation events during the growing seasons and limited the ability to monitor equipment in this trial. The retro-fitted component technology developed in this project demonstrate an innovative approach to address issues of sustainable natural resources management, adapting to climate change challenges and responding to increases in energy costs.

Technical summary

Two key challenges in the vegetable industry are water and energy use efficiency. Limitations to water availability are expected to intensify under climate change scenarios, while energy costs will increase under pricing strategies, including those to limit carbon emissions. Tasmanian irrigated vegetables for human consumption and seed production gross value in 2008/2009 was $217.3 million (ABS 2011). Irrigation requirements range between 2.5 to 5.5 megalitres (ML) per hectare for vegetable crops during the Tasmanian summer, with a net economic benefits typically between $700-$1200 per ML (O'Donnell 2006). There is increasing pressure on the irrigated agriculture sector to reduce water and energy consumption to enhance the competitive position of irrigated agriculture. This project developed and investigated the potential of two retro-fit systems (one for a travelling gun irrigator and the other for a linear move irrigator) to improve water and energy use. This study investigated the ability to improve irrigation efficiency in different vegetable crops through retro-fit irrigation technology.

Travelling gun irrigators are commonly used in vegetable production, and also other industry sectors including the dairy and sugar industry, due to portability and low capital cost. However, travelling gun irrigators are generally considered inefficient with regard to energy and water use. Uniformity of water distribution is also of concern with this type of irrigator. As part of collaborative project between the Tasmanian Institute of Agriculture and Seattle Services Pty. Ltd., components of a retro-fit pressure control system for travelling gun irrigators were developed to improve energy and water efficiency. The pressure control system consisted of telemetry and irrigation components including a solar panel, microprocessor, radio and controller in conjunction with a commercial variable speed drive. Trials were conducted over three consecutive vegetable growing seasons (2010-2012) with two treatments, modified travelling gun irrigator run and conventional travelling gun irrigator run. In the first season (2010), limited data was collected due to a breakdown in the soft hose irrigator. However, results suggested a 15% and 10% saving of energy and water, respectively, for the modified treatment compared the conventional treatment. In 2011, a hardhose irrigator retro-fit with telemetry was modified and resulted in energy savings of 17-21.8% and water savings of 5-10% with the modified equipment. Due to frequent rain events in the third season (2012), only three irrigation events occurred and resulted in 10% saving in water. Yield results for 2010 (green bean marketable pod yield), 2011 (carrot) and 2012 (green bean marketable pod yield) was significantly higher in modified compared to conventional traveller gun irrigation treatment, with increased yields of 14.6%, 10.0% and 14.8%, respectively.

Retro-fit variable rate irrigation equipment was assessed over three consecutive seasons (2010-2012) to investigate water and energy saving potential. One span of a two span linear move irrigator was retro-fit with a custom built variable rate irrigation (VRI) system; the other span consisted of conventional irrigation with water applied uniformly across the field. In addition a real time soil moisture wireless sensor network (WSN) was assessed, with the intent of integrating the VRI, WSN and a decision support system to improve water use efficiency in irrigated vegetable production. The VRI system was established as a test bed to ensure any changes to the system function that may be required during the season could be addressed in a timely manner to ensure successful operation during each of the three seasons. The VRI operated successfully in 2011 and 2012, with only minor interruption to functionality. The WSN was operational in 2011 and 2012 season. Data received was assessed against rain and irrigation events, but some problems with calibration were encountered.

The irrigation system was used on a green bean crop (2010), carrot crop (2011) and green bean crop (2012). In 2010, 2011 and 2012 water saving of 10.5%, 10.7% and 20.0%, respectively, were reported for VRI treatments compared to conventional irrigation treatments. However frequent, and in some seasons high, rainfall events occurred which may have impacted on results. In 2010 the marketable pod yield of green bean was significantly (2.8t/ha, 14.8%) greater in the VRI treatment than in the conventional treatment. In 2011, there was no difference between treatments in the yield of carrots in different size categories, viz ‘below small’ (<25mm diameter), ‘medium’ (25 to 30mm) or ‘large’ (30 to 40mm). However, carrot yield of the ‘large’ category boarded on statistical significance. The total yield (weight) of ‘small’, ‘medium’ and ‘large’ (no. 1 grade) carrot was significantly higher in VRI treatment than in conventional treatment. In 2012 there was no significant different between variable rate irrigation treatment compared to conventional treatment in marketable pod yield of green bean crop. Frequent rain events occurred during the season which may have prevented a good comparison of irrigation types.

The retro-fitted component technology developed in this project demonstrate an innovative approach to address issues of sustainable natural resources management, adapting to climate change challenges and responding to increases in energy costs.

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1. Introduction

Increasingly irrigators are faced with economic, environmental and social challenges. Economic pressures resulting from fluctuating and increasing energy prices drive a preference for increased productivity through reduced input of water and/or energy. Sustainable management of natural resources is required to maintain and increase future food production to met increasing global demand. Socially, irrigators are also under increasing pressure from other sectors to be more efficient and reduce the use of limited resources to enable redistribution of natural resources to other sectors, for example urban use (Cooley et al. 2007). A projected 55% increase in global demand for water between 2000 and 2050 has been suggested by the Organisation for Economic Co-operation and Development (OECD, a global policy development group), with future demand mainly from the domestic, manufacturing and electrical sectors (Leflaive et al. 2012). Future water demands will ensure further competition between irrigators and other water users (Leflaive et al. 2012). Therefore, it seems unlikely in the future any additional water would be available for irrigators (Leflaive et al. 2012), only increased pressure to produce more with fewer inputs. Irrigation technology that can be retro-fit to existing technology may provide an adaptive solution to reducing water and energy use in the vegetable industry. This introduction centres around irrigated agriculture with a particular focus on two types of irrigators including the travelling gun irrigator and the linear move irrigator (with the exception of centre pivots irrigators) and are discussed below. Also discussed below are irrigation scheduling, precision irrigation, soil moisture sensors and wireless sensor networks and decision support systems.

Significant contributions are made to the Australian economy by the irrigation industry. The largest water user in Australia is irrigated agriculture, which in 2009/2010 used 6,600 GL (50% of total Australian water usage). Irrigated vegetable production in Australia was valued at $2.6 billion in 2009/10, with 80% of vegetable producers in Australia using some type of irrigation (ABS 2011). The average application rate in the Australian vegetable industry in 2009/2010 was 4.0 ML/ha, totalling 420,000 ML (ABS 2011). The gross values of the Tasmanian irrigated vegetables for human consumption and seed production in 2008/09 was $217m, from 115,000 ha, 99% of which received some form of irrigation (ABS 2011). The annual volume applied in 2009/10 in Tasmania was 44,300 ML, averaging 3.0 ML/ha. Irrigation requirements for Tasmanian summer vegetable crops ranging between 2.5 to 5.5

ML per hectare (O’Donnell, 2006). On the northwest coast of Tasmania the typical rainfall is between 900-1200mm annually. In Tasmania the average rainfall is 345 mm during the major vegetable cropping months (October to March), with average evaporation of 910 mm. Thus irrigation is required at 40-50 mm replacement per week for crops such as carrot, brassica, potato and poppy (O’Donnell 2006). As competition for natural resources increases, irrigators will require innovative solutions to adapt.

Travelling gun irrigators are also referred to as rain guns and big guns. A travelling gun irrigator consists of a cart mounted with a sprinkler (gun) and either a cable or supply hose that can be used to tow the cart through the field (Smith et al. 2008). Nationally, travelling gun irrigators are used in the horticulture, dairy and sugar industries, with an estimated 5,933 farms using travelling gun irrigators covering 219,000 ha (ABS 2006; Smith et al. 2008). Travelling gun irrigators are popular in the vegetable industry due to their low cost and portability. High pressure and high volume are characteristics of travelling gun irrigators, due to high application rate set by advance speed, water pressure and sprinkler design. Typically poor uniformity is associated with these systems (Burt et al. 1999 cited in Christen et al. 2006). Recent research that has been under taken to improve the performance of travelling gun irrigators includes the developed of a decision support tool for travelling gun irrigators called the TRAVGUN (a computer model) (Smith et al. 2008). The TRAVGUN enables irrigation application to be simulated under various wind conditions to identify information on optimal machine performance for evaluation and design of systems (Smith et al. 2008). Additional improvements are required to enhance the energy and water use of the travelling gun irrigator.

Centre Pivot and Lateral Move (CPLM) irrigators are large mobile sprinkler systems that were developed in the 1940s in the US. In the 1950s the first CPLM machine became commercially available and remains popular with irrigators (Foley 2004). A review by Foley (2004) covers the history of CPLM irrigators. Sprinklers mounted in a row along one or more span(s) are propelled by one or more gear box and operate in a rectangular field (linear move irrigator) or in a circle (centre pivot irrigator) (Heermanand Kohl 1981 cited in Christen et al. 2006). Early CPLM machines were high pressure (at the centre of the machine approximately 80 pounds per square inch (psi)). However, in the 1970s machines were modified to low pressure units (<40 psi), as results of the 1970s energy crisis (Foley 2004). These systems tend to be low pressure compared to travelling gun irrigators. CPLM have been available for, as mentioned, a number of decades and enable improved water application (Wigginton 2007). Uniformity in the direction of travel is conferred with the continuous movement of this irrigation type. Spray patterns overlap with closely spaced nozzles to manage the sprinkler over-lap for water application perpendicular to the direction of the irrigator. Dursun and Ozden (2011), Smith et al. (2009, 2010), King et al. (2009), Hedley and Yule (2009), Evans et al. (2010), Kranz (2009) and Dejonge et al. (2007) suggest there is great potential for this type of machine to enable spatially varied application as a result of adaptive control and also for uniform application, compared with other systems. However, previous study results regarding CPLM uniformity applications have been mixed (Hills and Barragan 1998, Smith 1995 cited in Smith 2009). The appeal of a variable rate irrigation system is the ease at which a system can be reto-fit to existing linear move or centre pivot irrigators (Perry and Pocknee 2003).

Determining irrigation requirements for a crop during the growing season can be achieved with one (or more) of the following methods: i) visual observation; ii) evapotranspiration loss calculations; and iii) monitoring of soil moisture (Greenwood et al. 2009; Cardenas-Lailhacar and Dukes 2010). A traditional and common method used by growers to assess soil moisture to determine appropriate irrigation applications is conducted by the grower assessing the appearance and feel of the soil (Leopold 2008). This is a low cost method of soil moisture assessment and enables growers to i) determine when to irrigate, ii) required amount of irrigation water, iii) penetration depth of irrigation water, and iv) determine available root zone water prior to irrigation event or planting. Assessment of compaction issues, insect pressure, weeds and nutrient deficiencies can also be conducted during soil sample collection to assess soil moisture. To assess soil moisture growers will be required to determine soil texture and type, and of each layer sampled the available water holding capacity will need to be assessed (Risinger et al. 1985 cited in Leopold 2008). Soil texture is dependent on the amounts of silt, clay and sand in the soil, soil texture determines the soil water holding capacity (Klocke and Fischbach 1998 cited in Leopold 2008). Weather based scheduling is also used to aid irrigation decisions, using daily evaporation data and weather forecast readily available on the internet. Soil moisture monitoring for irrigation scheduling is used by approximately 21% of Tasmanian farmers (O’Donnell 2006). Soil moisture monitoring generally consists of granular matrix blocks or capacitance probes. Granular matrix blocks such as Watermark^{TM} sensors are linked to a data logger (e.g. MEA (GBug), Hanson^{TM} or Irrometer^{TM} data loggers) (O'Donnell 2006). Capacitance probes (e.g. Adcon^{TM} and EnviroSCAN^{TM}) are more sophisticated and more expensive (O'Donnell 2006).

Until recently irrigation was rarely referred to with a precision agricultural perspective, possibly due to the assumption that spatial variability that is trying to be addressed by the variable rate is less than the variations between and within seasons (temporal variations) (Smith et al. 2009). However, variable rate irrigation aims to apply precise water applications of different amounts to different parts of the field, when and where it is needed, rather than a blanket water application (Wigginton (2007). A recent review on precision irrigation by Smith et al. (2010) provides a current overview of the topic. Details relevant to this report are briefly outlined below. Precision agriculture is used in dry-land agriculture and includes the use of yield mapping and variable rate technologies. In addition to yield and variable rate technologies the most common precision agricultural tools adopted in Australia also include vehicle navigation systems and soil apparent electrical conductivity (ECa) mapping (Whelan 2007). Variable rate, spatially variable, site specific and prescription are all terms that have been used to described precision farming (Smith et al. 2009), and are generally accepted as having the same meaning. Traditionally irrigation has aimed to provide each plant with the same quantity of water, a uniform application. Traditional assumptions have been held that lower efficiencies and potential yield losses may occur if water is not applied uniformly. However, spatial differences such as soil fertility and hydraulic properties are not taken into consideration with the assumption that each plant requires the same water application. Traditionally water is applied in larger amounts to overcome potential variability across the field and results in decreased water use efficiencies (Smith et al. 2009; Thompson et al. 2007). However, this irrigation approach can result in an increase in production costs and detrimental effects on the environment (e.g. increased fertiliser leaching) (Ali and Talukder 2008). Of particular importance to managing spatial variability of crop and soil properties in a field is the following two responses: i) temporally separate response and ii) automatic response. Temporally separate response refers to occurrence of an appropriate action occurring after the recording or measurement, possibly the following season (Schueller 1997 cited in Smith et al. 2009). Automatic response refers to an immediate real time response (Schueller 1997 cited in Smith et al. 2009). Four fundamental steps have been identified in the technology and process for managing spatially variability in soil and crop properties and include: i) acquisition of data; ii) interpretation; iii) control, and iv) evaluation (Kitchen et al.

1996 cited in Smith et al. 2009; Smith et al. 2010). For further information refer to review by Smith et al. 2010.

Research on variably applying water across the field has focused on CPLM due to the complexity of adapting either drip systems (controllers would be required to operate individual emitters) or surface irrigation in which it is not possible to apply different amounts of water when and where required across the field (Wigginton 2007). US research has focused on two main issues and include: i) applying irrigation in the field to meet the different plant requirements across a field and thus addressing accurate crop water requirements; and ii) addressing issues of areas of the field that do not require water especially where CPLM operate over different crops, roads and non-cropped areas (Wigginton 2007). To achieve this, several methods of altering water application supplied by CPLM have been investigated. One method (Dr John Sadler and Dr Carl Crump, USDA-ARS, South Carolina) developed to achieve different flow rates along the machine used a series of underslung pipes along the machine, with a series of separate manifolds along each span which enabled areas to be irrigated individually (approx. 6 m wide) (Wigginton 2007). However, as a result this system applied water constantly, although different application rates can be applied along the machine. The second method pioneered by researchers at the University of Georgia (Tifton, USA) used solenoids fitted to sprinklers (outlets) which enabled water application control by shutting off one or more solenoid valves (pulsing on and off) to achieve the desired amount of water application across the field (Wigginton 2007). This also enabled entire regions of the machine to be turned off, which is advantageous for example over a road or non-cropped area. Research published to date on modifications of CPLM systems is provided in a review by Smith et al. (2009). Common features between research systems included: i) water application controlled by a GPS from predetermined soil type maps; ii) area ranging from 40-100 m^2 for each differential irrigation regime; iii) main focus on machine modification for control and design to provide water applications that are spatially varied (Smith et al. 2009). Efficiency of crop inputs can increase with managed zones in a field (Moore and Wolcott 2000 cited in Smith et al. 2009). Management zones may be delineated by either real-time sensors or historical map-based approaches (Smith et al. 2009).

Real-time sensors provide an opportunity for appropriate prescriptions of water application (Stewart et al. 2005 cited in Smith et al. 2009; Kim and Evans 2009). Current research of on-the-go sensors include sensors for soil moisture, crop response and crop water (soil-crop-atmosphere). Alternatively, infra-red thermometers fitted at intervals along the length of the machine have been used (Camp et al. 1998), to measure variation in canopy and soil temperature over the field before irrigation. Smith et al. (2009) suggest none of these sensors have been adopted in irrigation for real time control. A number of Australia researchers are currently working on plant based sensors (e.g. Dr Simon White, National Centre for Engineering in Agriculture, Toowoomba) to determine irrigation regimes and monitoring crop characteristics (Cheryl McCarthy, National Centre for Engineering in Agriculture, Toowoomba) in real-time to develop irrigation regimes based on growth (Wigginton 2007). In addition Dr. Troy Peters & Dr Paul Colaizzi (USDA-ARS, Bushland) use on-the-go mounted infrared thermocouples (IRT) to estimate crop water stress by measuring temperature in the crop canopy. Fully automatic sections of the pivot enabled varied irrigation application depending on information collected on canopy temperature. However, this may be more appropriate for the cotton industry where cotton is generally grown in arid regions (Wigginton 2007) and less suitable for the vegetable industry in cool temperate climates.

Initially decision making tools were defined for site-specific irrigation and used in the early 1980s (Kraz 2009). Control systems were generally either open–loop or closed-loop control systems. Open-loop systems adjust control parameters by knowledge of process input and output relationships, but do not include output process monitoring. Close-loop controllers utilise the difference between measured outputs and input (Smith et al. 2009). Kim et al. (2009) developed a closed-loop control system by integrating a controllable irrigation system and an in-field wireless sensor network to enable automated variable rate irrigation. All components were individually tested and deemed functional prior to any integration of the real-time wireless communication between variable rate irrigation, base station and the in-field sensing station (Kim et al. 2009). Further evaluation was required to test this technology on a grower’s field.

2. Materials and methods

The objective of this research was to evaluate two retro-fit irrigation systems with respect to water and energy use, and crop production under, i) retro-fit travelling gun irrigator and ii) VRI retro-fit linear move irrigator. The pressure control system was designed for a travelling gun irrigator and the variable rate irrigation system was developed for a linear move irrigator, both systems are outlined below. Trials were conducted over three growing seasons in one field with trials adjacent to one another. Description of retro-fit equipment, trial site, field trials undertaken including yield, quality and disease assessments, water and energy monitoring and cost benefit analysis are given below.

2.1 Telemetry and irrigation technology for travelling gun irrigators

Telemetry and irrigation components were retro-fitted to a travelling gun irrigator prior to commencement of the first trial season. Telemetry components developed by Seattle Services Pty Ltd. in collaboration with the Tasmanian Institute of Agriculture (TIA) consisted of a microprocessor pressure control system, solar panel, battery, microprocessor unit, radio and water pressure sensor. Additional components were installed at the pump shed and included a microprocessor pressure control system connected to a commercially available variable speed drive (VSD) (ABB ACS550), and an external radio antenna mounted to the pump shed. Components fitted to the irrigation equipment work in conjunction with the VSD to maintain a constant water pressure at the gun via a real-time feedback loop, regardless of slope or length of the irrigation run. In 2011, a prototype data logger was fitted to the controller to monitor energy consumption, enabling comparisons between the modified and conventional irrigator runs. The data logger recorded i) data, ii) time, iii) energy (kW) consumed, iv) pressure (kPa) at the gun, v) and pump speed (rpm), at 5 minute intervals and was manually downloaded to a personal computer (PC) for further analysis. The travelling gun irrigator was set to operate in a 270° sector angle for all three seasons (2010, 2011 and 2012) to minimise the overlap in irrigation of plots located on the inside of the treatment runs. Travelling gun machine speed was 39 m h^{-1}. Irrigation events were conducted over night.

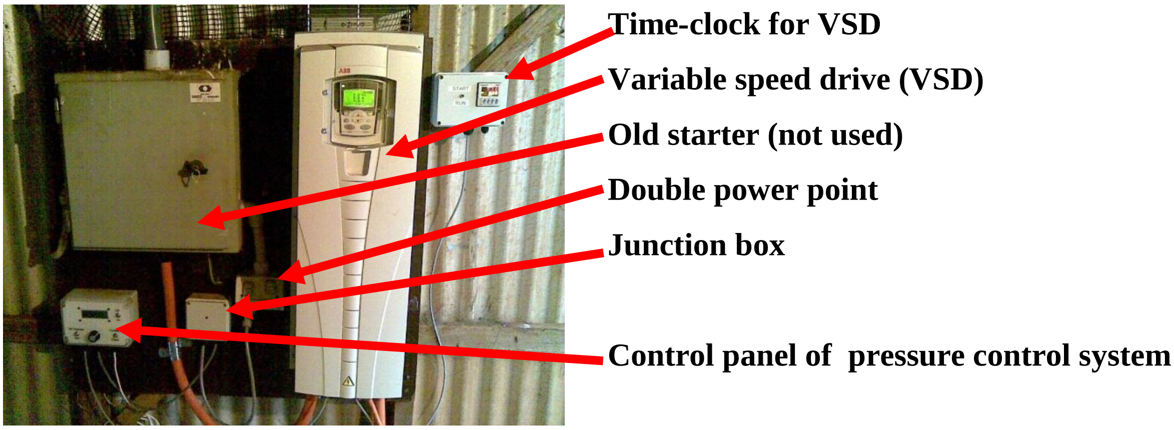


Figure 2.1. Photo showing pump control equipment components of the pressure control system including variable speed drive (VSD) and control panel of pressure control system.

Prior to the first trial season (2010), telemetry and irrigation components were retro-fitted to a second-hand soft hose travelling gun irrigator (Southern Cross TCE 3000). However, due to ongoing maintenance issues of the twenty year old soft hose irrigation machine during the first season, the pressure control system was retro-fit to a near-new hard hose travelling gun irrigator (Idrofoglia 110G-340) to mitigate the risk of irrigation machine failure during subsequent irrigation trials. Although the irrigation machinery break downs were not associated with the pressure control system, a beta prototype pressure control system was retro-fitted to the hard hose gun irrigator. Improvements to the beta prototype included a more compact design with easier access to retro-fit components.

a) **b)**

Figure 2.2. Pressure control system: a) prototype fitted to the soft hose irrigator (2010 season) and b) beta prototype fitted to a hard hose irrigator used in 2011 and 2012 season.

The control unit enabled a desired (target) pressure to be set using a dial up pressure control panel. The digital screen of the control panel provided a real-time display of actual and target pressure (psi displayed) at the gun during the irrigation run. Prior to the commencement of the third season (2012) an issue with the radio was identified and new radios were fitted to provide reliable data capture during 2012.

2.2 Retro-fit variable rate irrigation technology

This component of the project aimed to develop and investigate retrofit variable rate irrigation technology to improve water and energy consumption during vegetable production. The conceptual components of the VRI system included three main components: i) a variable rate irrigation system, ii) a real time soil moisture wireless sensor network (WSN), and iii) a basic decision support system (Figure 2.3).

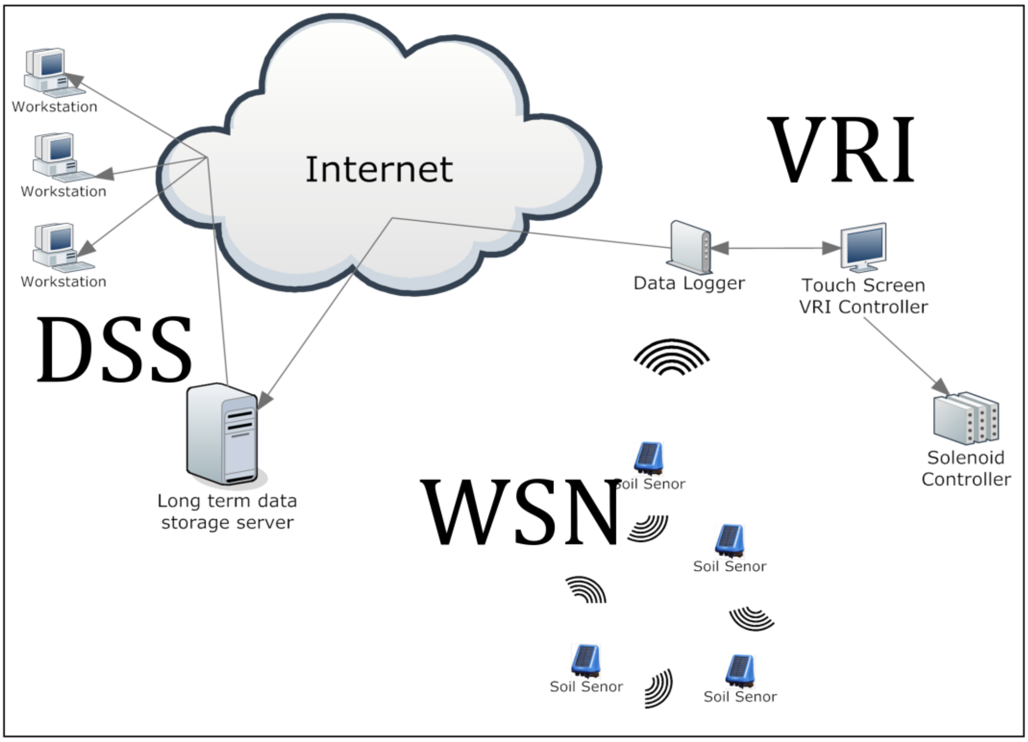


Figure 2.3. Conceptual diagram of variable rate irrigation (VRI) system including VRI system, wireless sensor network (developed by CSIRO Information & Communication Technology (ICT) Centre) and a decision support system (DSS).

The variable rate irrigation system was developed as part of this project as a test bed that is a commercially independent system (not reliant on third party, in-house system) to enable full scope of experimental modification to specifically assist the vegetable industry. This enabled

TIA researchers and project collaborators to change requirements and alter system functionality in swift response to unforseen issues. Also, this ensured that commercial crops grown under the retrofit irrigator would not be jeopardised through use of prototype technology. Figure 2.3 shows the conceptual components of our VRI system. The VRI system included a touch screen VRI controller, which controlled solenoid operation of banks of sprinklers on the linear move irrigator. Information from the network of soil moisture sensors could then be used to schedule irrigation in different plots of the field. Soil moisture data was available in real time on a work station via the internet, with one or more workstations able to access the data from the storage server. The technical objective for the first season (2010) was to design and implement the control computer system for the irrigator VRI, deploy soil moisture sensors in the field and obtain regular readings to aid in irrigation scheduling. The system was to be a rapidly developed proto-type only, suitable to test the concepts and methodology of system implementation.

In December 2009 the VRI technology developed by Seattle Services Pty. Ltd. in collaboration with TIA was retrofitted to a two span linear move irrigator (Reinke E2 Maxigator). Modification of the linear move irrigator included fitting of hydraulic valves and electrically operated solenoids. In addition a computer control system developed by Seattle Services Pty. Ltd. was mounted on the linear move irrigator with custom software, GPS and control box to enable variable rate irrigation to defined areas of the field. The VRI control module was implemented and attached to one span of a two span linear move irrigator. Two banks or groups of eight sprinklers were configured to provide zones that were consistent with plot placement under the linear move irrigator enabling multiple control zones. Details of the VRI system are outlined below.

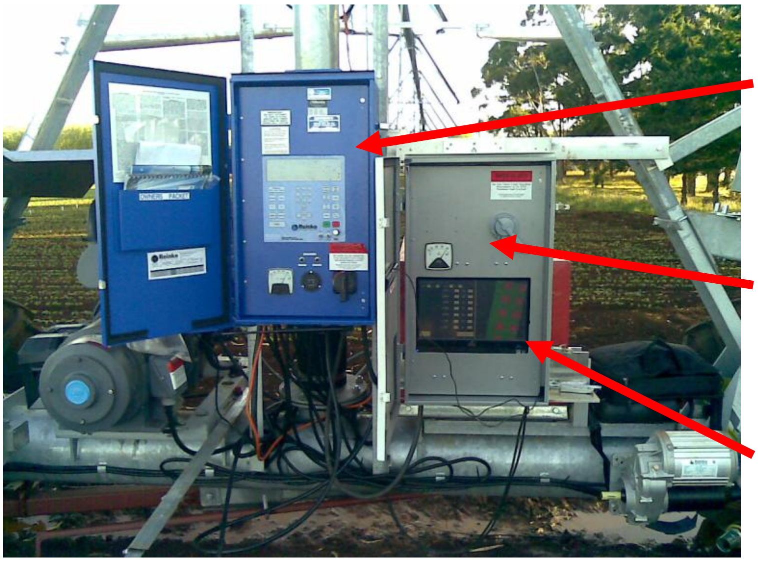
The variable control system comprised of three parts including the GPS reader, valve control box (VCB) and central computer system (CCS). For the GPS reader an inexpensive GPS (Garmin GPS 18x) was selected as it was a robust unit built for rugged outdoor installation with no user interface. The unit has only a USB interface. The GPS had an accuracy of + or – 15 meters. The accuracy was improved by taking periodic readings over a set interval and averaging them for a reading that the irrigation controller acted upon. The VCB enabled the computer to switch banks of water valves on and off using a RS232 serial interface. The VCB was custom built for the irrigator and provided the interface between the computer and the valves. As part of the CCS, a low touch screen PC running Microsoft Windows XP® was selected as the central controller system for the irrigator as speed of implementation was a high priority. The project accepted that there was possible risk with using the equipment as a PC, as it was not constructed for outdoor use and operational environment temperature was limited to 0°C to 40°C. The cost of ruggedized equipment for outdoor use was prohibitive and was not manufactured in a suitable form.

The VRI system was built on the following assumptions:

- The linear irrigator would travel in a straight line and each side would travel at the same speed.
- The area covered by the irrigation movement was rectangular and did not contain any curves.
- GPS readings did not need to be adjusted for curvature of Earth.
- The speed of the irrigator would not exceed 3km per hour.
- The areas to be irrigated at different water quantities would be irregular polygons (referred to as plots) and there may be areas that are not assigned to crop production.
- Plot corners and various initial set up GPS readings required by the system would be accurate to 20cm.
- The initial settings required by controller software are set in an XML settings file, with no user interface required.

Operation of the CCS is briefly outlined below. The CCS is comprised of two computer programs. The first program was a Windows® service program that obtained the GPS readings, calculated the irrigator location and determined the instructions to issue to the VCB to control the flow of water from the valves. The service also produced a picture of the irrigation area, the plots, and irrigator and nozzle location over the plots. The system also logged all actions, errors and alerts. The second computer program was a Windows® graphical user interface that enabled a user of the system to set water flow rates for the different plots, view the service log and view the status picture produced by the service.

Power to the irrigator computer was initially supplied by the irrigator when the irrigator was running. However, the need for software maintenance following completion of an irrigation event necessitated the fitting of an alternative power source. A 55Ah battery, charging regulator and solar panels to charge the battery were added. The irrigator would also charge the battery when the machine was running. Maintenance of the computer system required on-site presence.



Irrigator main control panel

Variable rate irrigation (VRI) control box

Touch screen computer

Figure 2.4. Photo showing irrigator control systems for variable rate irrigation (VRI) system on linear move irrigator.

In addition, the use of a WSN to enable real-time soil moisture data capture was deployed to provide data to assist irrigation scheduling and also provide soil moisture information for post irrigation evaluation. As part of this project a real-time soil moisture WSN developed by the Commonwealth Science and Industrial Research Organisation (CSIRO) Information & Communication Technology (ICT) was deployed to monitor soil moisture. Initially this sensor technology was developed to regularly gather and store information on soil dynamics and provide a feedback loop to improve irrigation efficiency. In 2007 a total of 70 sensor nodes referred to as 'sensor pods' were deployed in pasture production at the Tasmanian Institute of Agriculture (TIA) Dairy Research Facility (TIA DRF), Elliot, Tasmania. Each sensor pod was designed to record temperature, humidity and soil moisture. Soil moisture sensors were placed at three different depths and consisted of granular matrix sensors. The main aim of the project was to provide an understanding, at the root zone of a plant, of spatial-time soil water behaviour (McCulloch et al. 2008). The sensor pods were further developed to a commercial available sensor pod called the Fleck^{TM} and licensed to a Tasmanian company, PowerCom. The Fleck^{TM} WSN platform, with the addition of a daughterboard, could be used to measure many environmental variables. In our study the Fleck^{TM} WSN platform, architecture enabled soil moisture data to be collected from five Granular Matrix Sensors (GMS) for each Fleck^{TM}. Data collected from each Fleck^{TM} was sent to on-site Datacall gateway (low-power telemetry computer with built-in Fleck ^{TM} and Next-G$^{\circledR}$ module), and from there to a Sensor Observation Service (SOS) database, for presentation via a web based front end.

Figure 2.5. Photo showing Fleck^{TM} (CSIRO ICT) and GBug (Measurement Engineering Australia) in green bean crop during 2010 season.

The use of WSN soil moisture sensors in the project was based on the following assumptions about the WSN system:

- Internet connectivity would be available at the location of the irrigation trial.
- The Fleck ^{TM} and base unit had been tested and calibrated by the institution providing the equipment.

A brief description of WSN soil moisture operation description is provided below. Fleck ^{TM} were installed with granular matrix sensors (GMS) Watermark$^{\circledR}$ soil moisture sensors at three different depths (20, 30 and 40 cm) below the soil surface to monitor soil moisture changes. Sensors were wired as per the instructions provided with the equipment. The base unit (Datacall gateway) was set up next to the location of the irrigator so that a number of flecks where within communications range (<700 m), to ensure the mesh-network could communicate to the base unit. Once installed, the system was to operate continuously for the duration of the growing season. Flecks^{TM} and sensors were installed after crop planting and removed prior to harvest. A conceptual diagram of the irrigation field with linear move irrigator and wireless sensor network (WSN) soil moisture sensors (developed by CSIRO ICT) equipment installed, and connectivity is shown (Figure 2.6). Further details on Fleck ^{TM} deployment set up and retrieval are provided in section 2.310.

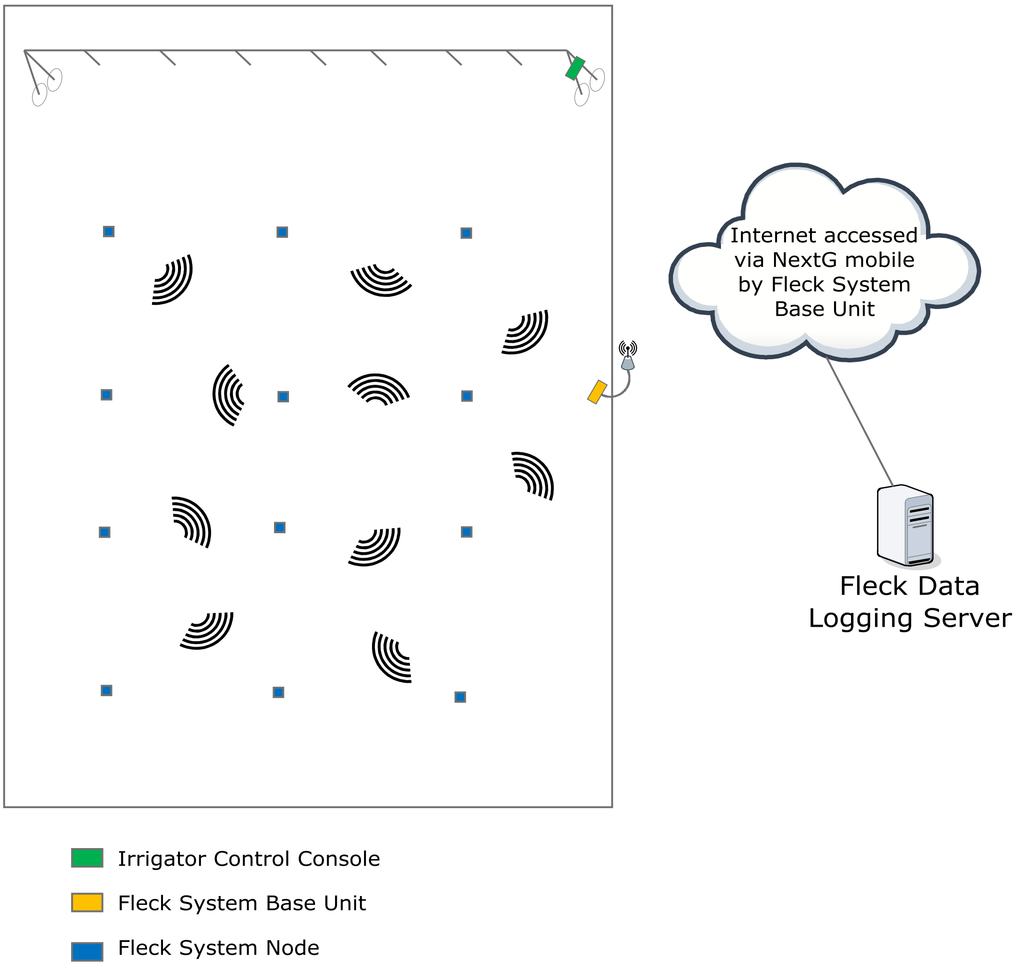


Figure 2.6 Conceptual diagram of irrigation field with linear move irrigator and wireless sensor network (WSN) soil moisture sensors (developed by CSIRO ICT) equipment installed and connectivity.

In the second season (2011), the main technical objectives included obtaining readings from the soil moisture sensor network and integrating the soil moisture measuring system with the irrigation control computer. Access codes of the soil moisture WSN were made available and this enabled changes to be made to the base unit. A mathematical formula was provided by the CSIRO ICT to convert the sensor readings to kPa readings that could be used in determining the moisture content of the soil. The system was modified based on the assumption that the voltages being received from the Watermark sensors were calibrated correctly to ensure accurate sensor readings.

The base unit and flecks were initially tested in a controlled environment. The following issues were found:

1. Incorrect timestamp for data logged from Fleck^{TM}. Each time the unit was reset, the date would revert to the 1/1/1970, which would be logged against the reading from the Fleck^{TM}. The date reset ensured that there was no way of knowing when a reading was logged. This was caused by lack of a battery backup of the real-time clock on the system board of the fleck base unit.
2. Battery and solar panel did not have the required capacity to charge or power the base unit for more than 4 hours. The battery drained unless the panel received almost continuous sunlight with no clouds. The base unit could draw up to 2A and the 9Ah battery only kept the base unit operating for 4 to 6 hours.
3. If the battery was flat, when the solar panel began to charge the battery and power the base unit, the base unit would crash and not start up due to the low voltage. The base unit would remain in a crashed state even with a fully charge battery or bright sunny day to power the device. Once the base unit crashed as a result of low voltage supply, the only solution was to open the sealed base unit case and unplug and re-plug the power cable to the base unit.

Issues mentioned above were corrected by applying the following modifications to the base unit:

1. On start up of the base unit, it automatically connected to the Internet via the NextG$^{®}$ phone board attached to the system. A script was added to connect to a web site and update the system clock to the current time. The system clock is at start up and every 10 minutes from the internet source. The regular time check was conducted to overcome problems if the initial start up check failed.
2. The base unit was moved to reside on the irrigator and was powered from the same source of power that the controlling computer system used. The power system that runs the irrigator computer system had proved itself as reliable and stable.
3. The charging unit on the irrigator was changed to a unit that would only supply power to the devices once a minimum voltage level had been reached. This would prevent the low voltage start up crashes that the base unit was prone to.

4. The existing base unit code was modified to only log data and not to forward the data to the internet server. The internet server that the data was forwarded to in the 2010 season was unreliable at times, and resulted in data loss. Further code was added to enable computers on the Internet to connect to the base unit and extract the Fleck^{TM} data as required.

A data extraction utility was built to process Fleck^{TM} data into time series kPa values. This enabled further processing in software able to analyse time-series data. Remote system maintenance and monitoring of the VRI control system was possible through the connectivity established between the base unit and the VRI control system.

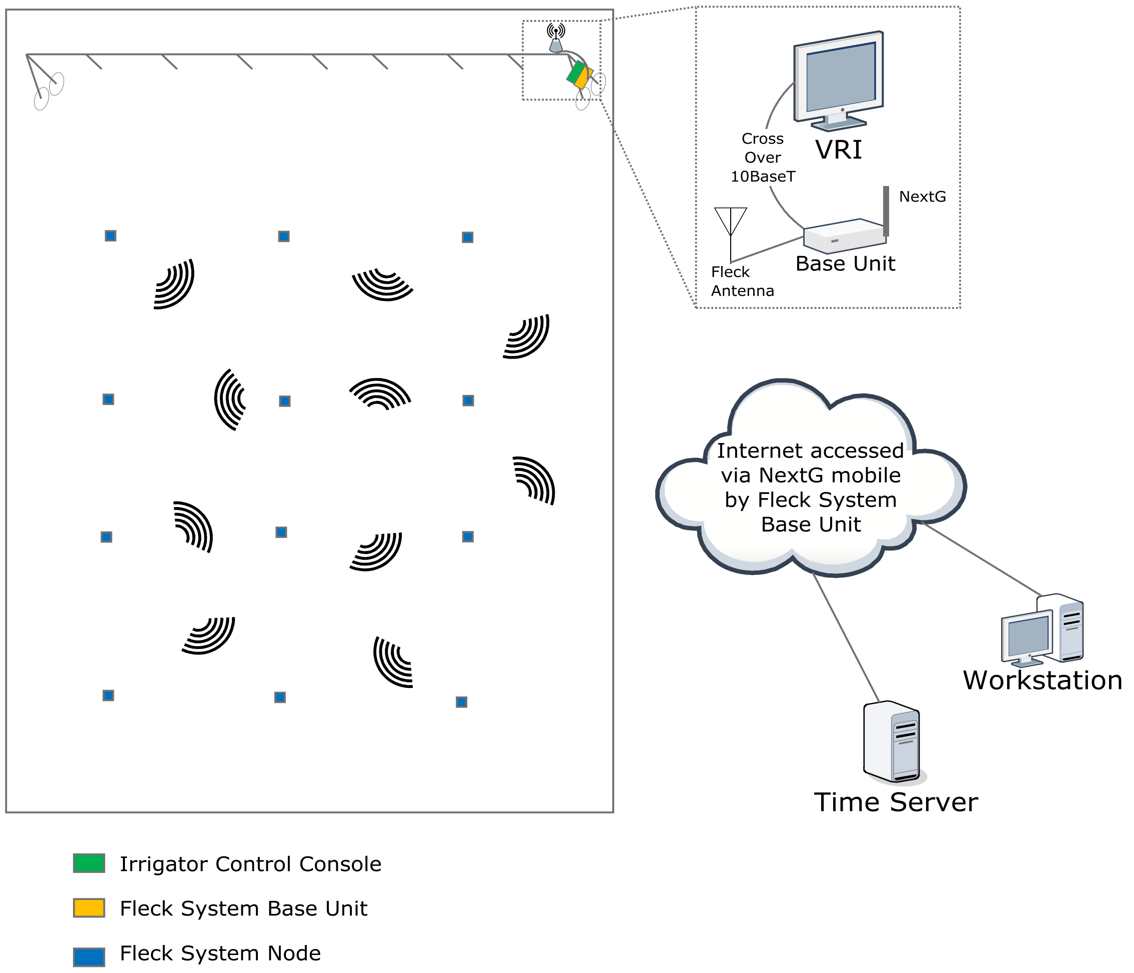


Figure 2.7 Conceptual diagram of irrigation field in 2011 season with linear move irrigator and wireless sensor network (WSN) soil moisture sensors (developed by CSIRO ICT) equipment installed and connectivity.

The aim of this component of the project was to assess the two systems (VRI and WSN soil moisture systems) and develop a decision support system to integrate the two systems enabling site specific irrigation when and where required by the crop in the field. The advantage of such a system is the real-time feedback from the WSN during the season. Prior to any integration of the VRI system and the WSN (Flecks^{TM} developed by the CSIRO ICT) the two systems were independently assessed.

2.3 Field trials

2.3.1 Experimental site description

Three consecutive field trials were established at the Tasmanian Institute of Agriculture Vegetable Research Facility (TIA VFR), Forthside, Tasmania (41°12´S 146°15´E 126 m elevation). Soil type at the site was free draining ferrosol soil, typical of soils used for vegetable production in Tasmania. Standard commercial agronomic practices were conducted over three consecutive growing seasons (2009/10 (2010) season, 2010/11 (2011) season and 2011/12 (2012) season. The trial site is typical of vegetable growing fields on the northwest cost of Tasmania, with undulating topography and ferrosol soil. Field trials for each retro-fit system, pressure control system and VRI are outlined below.

2.3.2 Pressure control system- treatments

An important consideration for site selection for this project was variation in topography (e.g. sloping field) to test system performance of the pressure control system. During each growing season, one irrigation run was dedicated to one of two irrigation treatments, travelling gun irrigator control (conventional irrigation, TC) and travelling gun irrigator retro-fitted with the pressure control system (modified irrigation, TM). Each treatment was approximately 350 m in length with 12 plots (14 m x 20 m) plots on either side of the irrigator (total of 24 plots per treatment) with 9 m buffers between plots and lane spacing of 45 m. The field site area was 2.8 ha. Elevation of irrigation runs ranged between 125-150 m in elevation from the base to the top of the irrigation run, respectively. The irrigation pump shed was located at the base of the ascending runs. In 2011 the run for the TM treatment was established on the northern side (closest to the fence) of the field and the TC treatment was located on the southern side of the field, and in 2010 and 2012 this was reversed. Figure 2.8 shows the irrigation runs for treatment TM and TC for 2010 season. The same travelling gun irrigator was used for both treatments in the field, with telemetry irrigation equipment switched off during the TC treatment. For TM treatments a gun nozzle pressure of 414kPa (60 psi) was set using irrigation telemetry equipment via the control unit (located in the pump shed). Gun nozzle pressure for TM treatment was determined by assessing nozzle pressure of the gun nozzle pressure recorded at the top of the TC run, furthest away from the pump shed and most elevated location.

2.3.3 Variable rate system - treatments

Two adjacent irrigation treatments were established under a two span linear move irrigator, the northern span was retrofitted with VRI technology and dedicated to variable rate treatments (LVR) and the southern span was dedicated to conventional blanket application of water (LC) for the three trial seasons. Each treatment zone area was 1.4 ha (273 m x 50 m), with a total of 18 -plots (each 20 m x 20 m) with 9 m buffers (Figure 2.8). Elevation of the treatment site ranged from 130-142 m at the eastern end of the field to the western end of the field. A real-time kinematic (RTK) GPS (Leica 1200 GPS) was used to provide plot location (and relocation in subsequent seasons) maps which were uploaded into the VRI computer program. The touch screen computer enabled irrigation requirements to be set on the irrigation day, and changes could be easily made through the irrigation event if needed.

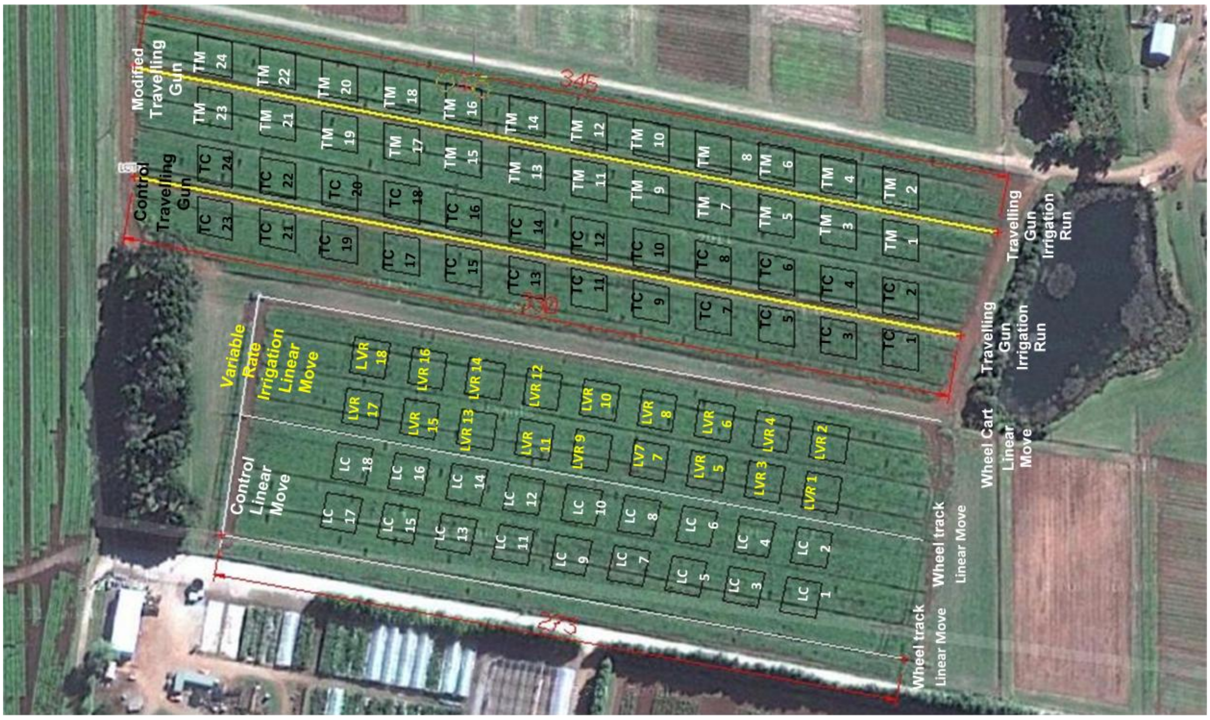


Figure 2.8 Trial site showing plot and treatment configuration for i) pressure control system (TC = conventional travelling gun irrigator, TM = modified travelling gun irrigator), and ii) variable rate irrigation trial (LVR = variable rate linear move irrigator, LC = conventional linear move irrigator).

2.3.4 Season 2010 – Bean crop

A field trial was established in a commercial green bean (*Phaseolus vulgaris*, var. Valentino) crop at TIA Vegetable Research Facility, Forthside, Tasmania. Two staggered plantings occurred on 8 and 11 January 2010 under TM and TC treatments, respectively. Planting occurred on the 14 January 2012 and 16 January 2010 for VRI and LC treatments, respectively (Table 2.1). Row spacing was 50 cm apart with three rows per 2 m, with seed plant spacing 6.2 cm. The crop was grown under normal commercial cultural practices. Dates of hand harvest and commercial harvest are listed (Table 2.1).

2.3.5 Season 2011 – Carrot crop

Trials were conducted during the 2011 season (9 November 2010- 21 March 2011) in a commercial carrot crop (*Daucus carota* L., var. Stefano) at the TIA Vegetable Research

Facility (Table 2.1). Trials commenced after establishment of the crop in early December. Dates for planting, hand harvest and commercial harvest are listed (Table 2.1).

2.3.6 Season 2012 – Bean crop

In 2012 a trial was conducted in a commercial green bean (*Phaseolus vulgaris,* var. Valentino) crop. Trials commenced after establishment in early January 2012. Planting dates and harvest (hand and commercial) dates for 2012 season bean crop are shown (Table 2.1).

Table 2.1. Planting dates and harvest (hand and commercial) dates for 2010, 2011 and 2012 season retro-fit irrigation trials at the Tasmanian Institute of Agriculture (TIA) Vegetable Research Facility (VRF), Forthside, Tasmania.

Treatment	Plant date	Hand-harvest date	Commercial harvest date
		2010 Season	
TC	11 January 2010	17 March 2010	22 March 2010
TM	8 January 2010	15 March 2010	18 March 2010
LC	16 January 2010	19 March 2010	26 March 2010
LV	14 January 2010	18 March 2010	24 March 2010
		2011 Season	
TC	9 November 2010	9 March 2011	20 March 2011
TM	9 November 2010	9 March 2011	20 March 2011
LC	9 November 2010	10 March 2011	22 March 2011
LV	9 November 2010	10 March 2011	22 March 2011
		2012 Season	
TC	12 January 2012	12 January 2012	20 March 2012
TM	12 January 2012	12 January 2012	20 March 2012
LC	9 January 2012	9 January 2012	19 March 2012
LV	9 January 2012	9 January 2012	19 March 2012

2.3.7 Trial monitoring

During each trial, monitoring included emergence and plant density, plant disease assessments and yield quality and growth of plants during the season assessed using a Greenseeker$^{®}$ radiometer (Crop Optics Australia Pty. Ltd.). Data on emergence and plant population density, yield and quality of crop and plant disease assessments were collected to examine the effect of the irrigation treatments on crop performance and disease incidence. Yield in 2010 and 2012 (green bean crop) for each irrigation treatment was determined from two randomly located linear quadrats (1 m x 2 rows) in each plot. For 2011 (carrot crop), carrots were classified into grade categories viz. 'No. 1' grade and 'No. 2' and size categories according to diameter viz, 'below small' (<25mm), 'small' (25 to 30mm), 'medium' (30 to 40mm) and large (>40 mm). Yield was determined from two randomly located linear quadrats (1 m x 1 row) in each plot.

Reflectance from the crop canopy was recorded with a Greenseeker® 505 Handheld sensor (Crop Optics Australia Pty. Ltd.) at 0.8 – 1.2 m above the crop canopy and recording reflectance from a strip 61 cm wide, every 100 msec. The sensor measures reflectance in the near infrared (774 nm) and visible red (656 nm), with band widths of approximately 25 nm spectral width at 50% of peak. The sensor calculated Normalised Difference Vegetative Index (NDVI): (NIR reflected [774 nm] – Red reflected [656 nm]) / (NIR reflected [774 nm] + Red reflected [656 nm]). NDVI measurements were taken in LC and LV plots on 11 January 2011 (63 days after planting, DAP), 11 February 2011 (94 DAP), 1 February 2012 (23 DAP) and 17 March 2012 (68 DAP). In plots TM and TC NDVI measurements were taken on 11 January 2011 (62 DAP), 11 February 2011 (92 DAP), 2 February 2012 (21DAP) and 17 March 2012 (65 DAP). Higher values for NDVI are indicative of a greater amount of living plant tissue. Healthy plants absorb more red light and reflect larger amounts of NIR than those that are unhealthy.

Energy consumption was measured and recorded via the variable speed drive internal parameters observed on a digital display before and after an irrigation event to determine energy consumed. In addition energy was also monitored automatically by a data logger connected to the pressure control unit. Water consumption was recorded from a water meter before and after each irrigation event.

2.3.8 Measurement of application uniformity

Evenness of water distribution for the two irrigation treatment runs (TM and TC treatments) was assessed on 14 and 15 February 2012. A total of 144 catch cans were placed in each treatment area to measure water distribution of the modified and conventional travelling gun irrigator. The catch can consisted of plastic container (11.8 mm diameter) attached to a plastic peg to anchor the catch can in the ground. Three rows of catch cans were placed 3 m apart in the lower, middle and upper regions of the run, perpendicular to the irrigator run. The travelling gun irrigator set at was set to the same 270° sector angle for both treatment runs.

To verify that the VRI control did not adversely affect the sprinkler uniformity along the linear move, three application tests were performed and replicated three times as outlined by Perry and Pocknee (2004) and similar to the ASAE Standard S436.1 (1998). On the 19 February 2010, distribution uniformity along the length of the two span linear move irrigator was assessed for water application of both the conventional (LC) and variable rate irrigation (LVR) treatments. A blanket application of 15 mm application depth was applied to the entire LC area. For plots located under the LVR treatment, water application depths were set between 11-15mm, with the base rate of 15 mm with 20 second cycling times for sprinklers to pulse on and off. Catch cans were located in plot areas and set at 2 m intervals across the path of the span of the linear move irrigator. No wind conditions were observed during data collection.

2.3.9 Soil moisture variability

Soil moisture variability across the field was investigated using a penetrometer to determine differences in resistance across the field at different times of crop development. In this case the difference in penetration resistance was recorded between flowering and sowing time of a bean crop during the growing season of 2010. Penetrometer reading and soil samples were collected on 21 Jan 2010 (TM, TC, LC and LV plots) and 2 March 2010 (TM and TC plots) and 11 March 2010 (LC and LV plots). Three penetrometer (Rimik Agricultural Electronics CP20 Cone Penetrometer) readings were taken at random locations within each plot (TC, TM, LC and LVR) to a depth of 600 mm. Soil samples were collected with a 50-mm-diameter tube sampler (at depth of 0-150 mm and 150-300 mm) adjacent and in close proximity to penetrometers measurement location. Soil samples were weighed before and after being dried for 24 hours in an oven (at 150°C) to determine soil moisture (g/g). The average resistance values for 0-150 mm and 150-300 mm depths were plotted again soil wetness. The relationship between soil moisture content and average penetrometer resistance was assessed by linear regression using Genstat 13th edition statistical software (VSN International Ltd., Hempstead, UK).

2.3.10 Soil moisture monitoring and irrigation scheduling

Within the linear move irrigator trial site, two types of soil moisture monitoring equipment were deployed, CSIRO ICT Fleck™ WSN and an example of more commonly used moisture logger equipment in agriculture (GBug®, Measurement Engineering Australia). In 2010 a total of 22 Fleck™ were deployed within plots under the linear move irrigator, with each Fleck™ having the capacity to provide data from 5 soil moisture sensors. This enabled three soil moisture monitoring depths (20cm, 30cm and 40cm depth) in each LVR and LC plot. Fleck™ were attached to Watermark® gypsum block soil moisture sensors, with a total of 108 sensors deployed. In addition 12 GBug® loggers were deployed under the linear move irrigator trial area. Each GBug® has the capacity to be attached to 4 sensors. Nine GBug® loggers were deployed within the LVR trial plots, with each logging two adjacent plots of LVR treatments. Loggers were attached to two Watermark® sensors in each plot at depths of 20cm and 30cm. Three GBug® loggers were placed within the LC trial plots with 20cm and 30cm sensors placed in the following plots, LC3, LC4, LC9, LC10, LC15, and LC16 (Figure 2.8) at depths of 20cm and 30cm. The additional GBug® monitoring enabled comparison with Fleck™ wireless soil moisture system data and provided an alternative scheduling strategy if the Fleck™ were not operational.

In the traveller irrigator trial, soil moisture was measured with GBug® loggers fitted to Watermark® soil moisture sensors. Loggers were placed in the modified and conventional traveller side of the paddock at depths of 20cm and 30cm at the following plot locations TC5, TC6, TC13, TC14, TC21, TC22, TM5 TM6, TM13, TM14, TM21 and TM22, (Figure 2.8) providing soil moisture data for the lower, middle and upper areas of the both the modified and conventional traveller runs.

Soil moisture sensors were installed soon after planting and removed just prior to commercial harvest. In 2010, 2011 and 2012 soil monitoring equipment was deployed on 15 November 2010, January 2011 and 17 January 2012. Retrieval of soil moisture equipment occurred on 11 March, 7 March and 16 March for each of the 2010, 2011 and 2012 seasons, respectively. Soil moisture was recorded by the GBug® loggers at 2 hour intervals and downloaded daily. Soil moisture data collected by the Fleck™ was transmitted at random intervals with many readings taken within one hour. Data was manually sorted, and reading of those closest to two hourly intervals (data not shown).

An automatic weather station (WatchDog® Model 2900ET Weather Station, John Morrison Scientific) was deployed in 2010, 2011 and 2012 season from January 2010- February 2010, January - March 2011 16 January-19 March 2012, respectively. The automatic weather station recorded rainfall, evaporation, wind speed and air temperature at 15 minute intervals. Day values were calculated the previous day and current day at 9:00am for a 24 hour period.

Irrigation at both field trials was managed by both soil moisture sensors monitoring (mentioned above) and replacement of crop evaporation (ETc). Irrigation scheduling involved cooperation of farm manager and was based on empirical methods including visual and manual assessments of soil. Irrigation events occurred approximately once a week depending on rain fall events and soil moisture sensors were used to monitor irrigation events. Irrigation applied to each LVR and LC plot was recorded.

The Pennman-Monteith method (Walter et al. 2000), ETc (from weather data) and suggested FOA crop coefficients for green beans (0.7 for initial, 1.05 for mid and 0.95 for end season) (2010 and 2012) and carrots (0.5 for initial, 1.05 for mid and 0.80 for end season) (2011 season) was used to estimate crop water use (Allen et al. 1998).

On 15 September 2009, an EM38 survey was conducted at the trial site by Terrapix (Hobartto provide a map of the apparent electrical conductivity of soil across the site. This measure is influenced by factors that affect the concentration of conductivity materials including salt levels, soil moisture content and soil texture (see Appendix IV for EM38 map).

2.4 Cost benefit analysis

A key component of the project was to evaluate the economic potential of the new technologies. Information was collected to assess the potential benefits of using precision irrigation compared to conventional (uniform application) irrigation regimes and associated cost of changing from current irrigation systems to precision irrigation systems. Information collected from each site included capital costs, operating and energy costs, associated labour costs, water usage, crop yield and disease severity. For the pressure control system costs on the following components were recorded, solar power supply, variable speed drive, and components for the control unit and radios. Additional information was collected for the variable rate irrigation system and included irrigation system capital costs, set up costs of soil moisture sensors, control values, wireless sensor network system, GPS, soil and field mapping and controller hardware and software.

Economic evaluation of retro-fit irrigation system developed and demonstrated in this project included three economic evaluation indexes used to assess economic viability of the two systems and included benefit-cost ratio (BCR), net present value (NPV) and payback period. Data generated from this project and Mushtaq and Maraseni (2011) were used for an economic analysis. Following the methodology of Mushtaq and Maraseni (2011) irrigation costs were divided into variable costs and fixed costs (machinery, pipes and equipment). Information from trials in this study and literature (Mushtaq and Maraseni 2011) provided the basis for the following assumptions:

- Irrigation efficiency was 85% for sprinkler irrigation.
- Over the analysis period food prices and commodity prices remained constant.
- Economies of scale were managed by assigning an average of 20 ha area.
- There was no inclusion of tax savings in the analysis.
- Technology life span for the two systems is 15 years with an interest rate of 5%.

Water use efficiency refers to irrigation performance indicators (Purcell and Currey 2004). To determine the relationship between water used during crop production and crop produced the indicator of water productivity (WP) can be used. Water productivity can be defined as ‘crop production per unit of water’ (Ali and Talukder 2008). Three water use indices were used in this study and include Irrigation Water Use Index (total product (kg) ÷ irrigation applied (ML) and Gross Production Economic Water Use Index (gross production ($) ÷ irrigation applied (ML)) (Purcell and Currey 2004).

2.3 Statistical analysis

As the practical requirements of the irrigation systems made randomisation of plots difficult, data on emergence, growth and yield was analysed as an unpaired t-test to test for equality of means between LVR and LC and between TM and TC. Data was analysed using PASW Statistics 18 Release 18.0.0, with all significant effects reported at $P < 0.05$, unless shown otherwise.

3. Results

Results on water use, energy use, yield and quality, soil moisture and retrofit technology performance for each of the retro-fit irrigation system (pressure control system and variable rate irrigation system) are given below. Results for the pressure control system are presented first followed by results for the variable rate irrigation system retro-fit to the linear move irrigator.

3.1 Pressure control system – travelling gun irrigator

3.1.1 Water use

Total irrigation applied during the 2010 season is shown in Table 3.1. In 2010 irrigation trials commenced on 14 January 2010. Two conventional irrigation events occurred prior to the commencement of the trial (to enable establishment of the commercial crop) on 8 and 11 January 2012 (not recorded). During the trial period five irrigation events occurred within each treatment. Rainfall from the beginning of November 2009 to end April 2010 was 256.4 mm, with 87.2 mm received within the trial period (Table 3.1). Approximately 2.0 ML/ha and 1.8 ML/ha was used during the irrigation trial period for TC and TM respectively (Table 3.1).Due to several breakdowns of the irrigator during treatments, irrigation data provides only an indication of the water used during 2010. However, the 2010 trial suggested water savings of 10% for the modified treatment compared to the conventional treatment. Rainfall records from the Forthside Research Station (Bureau of Meteorology) for trial periods 2010, 2011 and 2012 are shown in Appendix I-III.

Table 3.1. Rainfall and irrigation applied with modified and conventional travelling gun irrigation treatments in a commercial bean crop during 2010 season.

		Irrigation Applied			
Date	**Total In-crop Rain (mm)**	**Conventional (ML/run area)**	**Conventional (mm)**	**Modified (ML/run area)[a]**	**Modified (mm)**
8-30 Jan 2011	4.6	0.96*	68.6	0.87	62.1
1-28 Feb 2011	43.2	1.87	133.6	1.68*	120.0
1-26 Mar 2011	39.4	0	0	0	0
Totals	**87.2**	**2.83[b]**	**202.2**	**2.55 [b]**	**182.1**

[a] Conventional and modified run area is 1.4 ha (ML/1.4ha).

[b] Values given for ML/1.4ha, equivalent to 2.0ML/ha for the control and 1.8ML/ha for the modified irrigation.

*simultaneous irrigation occurred during one irrigation event (TC) in January and a breakdown of the irrigation machine occurred in TM treatment in February.

In 2011, irrigation frequency was reduced due to high seasonal rainfall (513 mm, compared to long term average 238 mm). During the 2011 season irrigation applied to the control and modified treatments were 2.7 ML/ha and 2.6 ML/ha, respectively (Table 3.2), indicating a 5% water saving using the modified treatment compared to the conventional treatment.

Table 3.2. Rainfall and irrigation applied with modified and conventional travelling gun irrigation treatments in a commercial carrot crop during 2011 season.

		Irrigation Applied			
Date	**Total In-crop Rain (mm)**	**Conventional (ML/run area)**	**Conventional (mm)**	**Modified (ML/run area)[a]**	**Modified (mm)**
9-30 Nov 2010	91.8	0.55	39.3	0.55	39.3
1-31 Dec 2010	149.8	0.46	32.9	0.44	31.4
1-30 Jan 2011	188.2	0.99	70.7	0.89	63.6
1-28 Feb 2011	71.8	1.46	104.3	1.43	102.1
1-21 Mar 2011	11	0.37	26	0.34	25
Totals	**512.6**	**3.83[b]**	**273.2**	**3.65 [b]**	**261.4**

[a] Conventional and modified run area is 1.4 ha (ML/1.4 ha).

[b] Values given for ML/1.4ha, equivalent to 2.7 ML/ha for the control and 2.6 ML/ha for the modified irrigation.

A total of three irrigation events occurred during the 2012 season, with irrigation treatments reduced due to regular rain events occurring throughout the season (Table 3.3). Approximately 1.0 ML/ha and 0.9 ML/ha was used during the irrigation trial period in 2012 for TC and TM respectively, with water savings of 10% with the modified treatment compared to the conventional treatment (Table 3.3).

Table 3.3. Rainfall and irrigation applied with modified and conventional travelling gun irrigation treatments in a commercial bean crop during 2012 season.

		Irrigation Applied			
Date	**Total In-crop Rain (mm)**	**Conventional (ML/run area)**	**Conventional (mm)**	**Modified (ML/run area)[a]**	**Modified (mm)**
12-30 Jan 2011	23.8	0.9	64.3	0.9	64.3
1-28 Feb 2011	47.0	0.48	34.3	0.41	29.3
1-19 Mar 2011	92.4	0	0	0	0
Totals	**163.2**	**1.38[b]**	**98.6**	**1.31[b]**	**93.6**

[a] Conventional and modified run area is 1.4 ha (ML/1.4 ha).

[b] Values given for ML/1.4 ha, equivalent to 1 ML/ha for the control and 0.9 ML/ha for the modified irrigation.

Catch can data was collected on irrigation applied to both travelling gun irrigator treatments (TM and TC) at different locations along the field including the following locations; i) lower field (plots TM 3 and 4, and TC 3 and 4) (Figure 3.1); ii) mid-field (plots TM 13 and 14, and TC 13 and 14) (Figure 3.2); and iii) upper field (plots TM 23 and 24, and TC 23 and 24) (Figure 3.3). Catch can results are shown in Figure 3.1-3.3. As mentioned previously the travelling gun irrigator was set to operate in the same 270°C sector angle for both runs. In the lower part of the field where the irrigator was applying a lower pressure (414 kPa) by the TM irrigator the average depth (mm) applied across all cans was 25 mm for TM compared with 34 mm for TC, 24.2% less water applied in TM. In the middle part of the field average depth (mm) applied across all cans for the TM and TC treatments was 28 mm and 34 mm, respectively, i.e 17.6% less water in TM. At the top of the field average depth (mm) across all cans for TM and TC was 28mm and 33mm, respectively, equating to 15.2% difference.

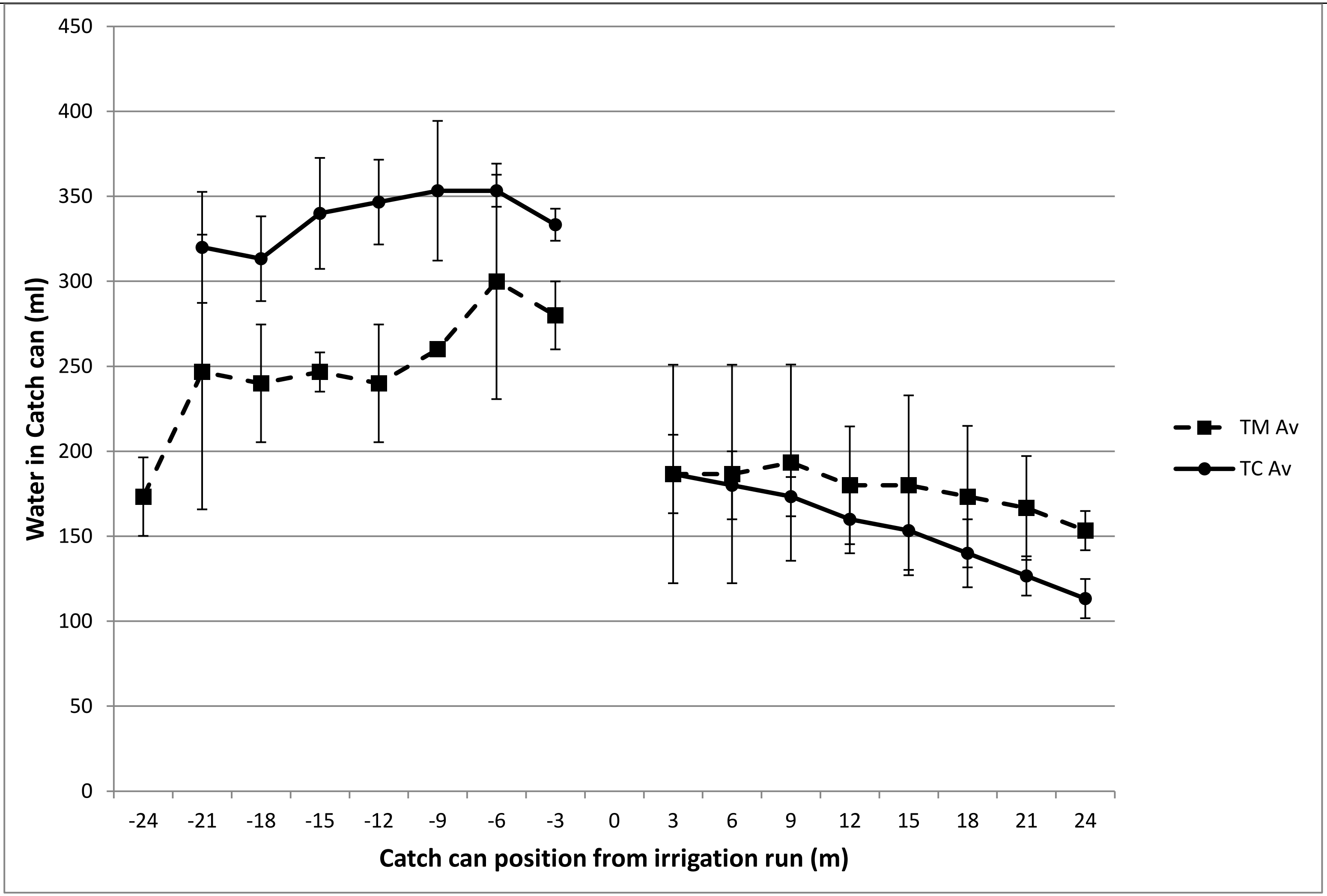


Figure 3.1. Catch can data for travelling gun irrigator (TM, modified treatment and TC, conventional treatment) at the lower part of the field.

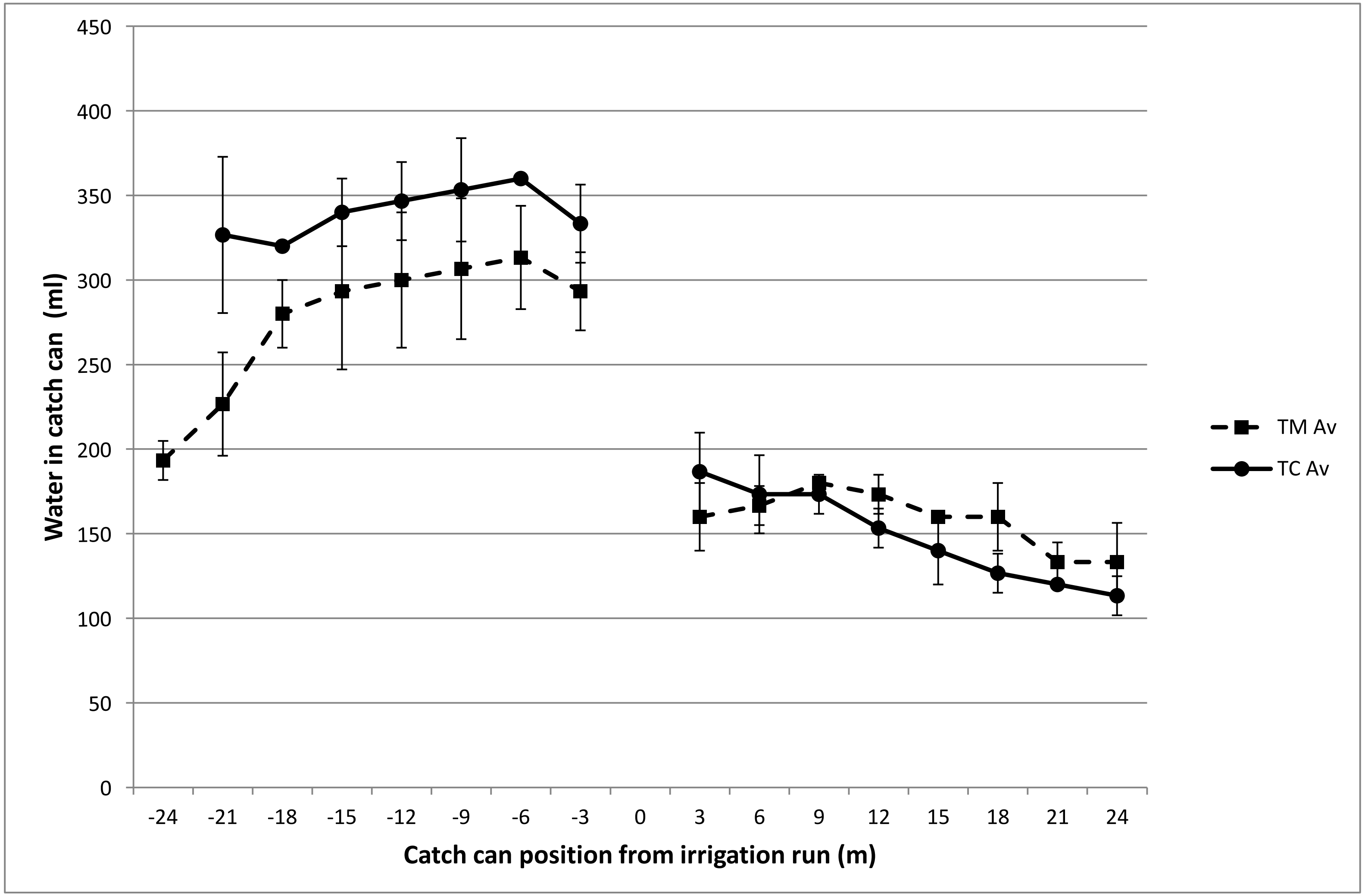


Figure 3.2. Catch can data for travelling gun irrigator (TM, modified treatment and TC, conventional treatment) at the middle of field.

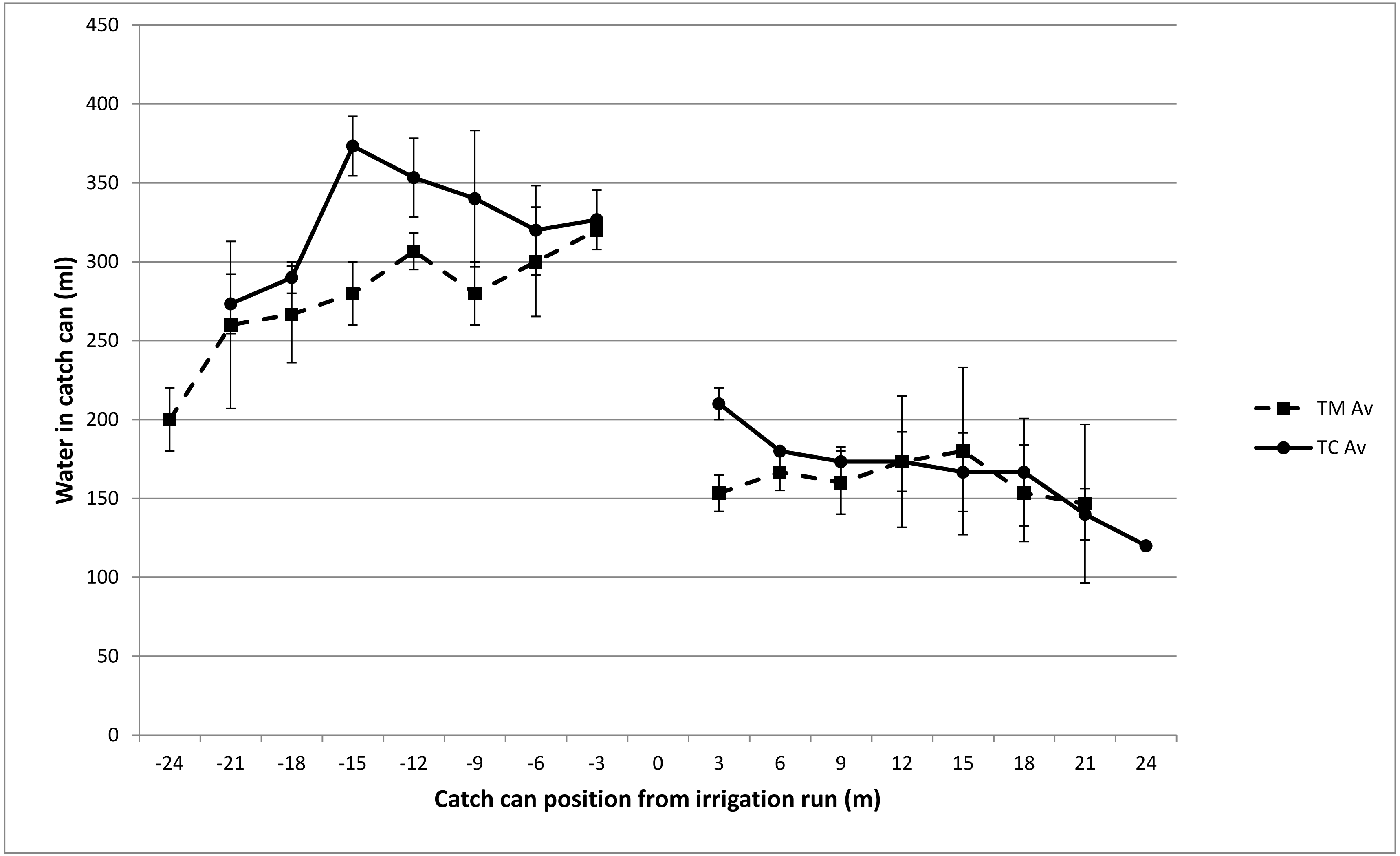


Figure 3.3. Catch can data for travelling gun irrigator (TM, modified treatment and TC, conventional treatment) at the top of field.

A digital water meter was operational during the final season (2012), although rain events limited the number of irrigation events during the 2012 season. An example of water use for modified (TM) and conventional (TC) treatments is shown in Figure 3.4.

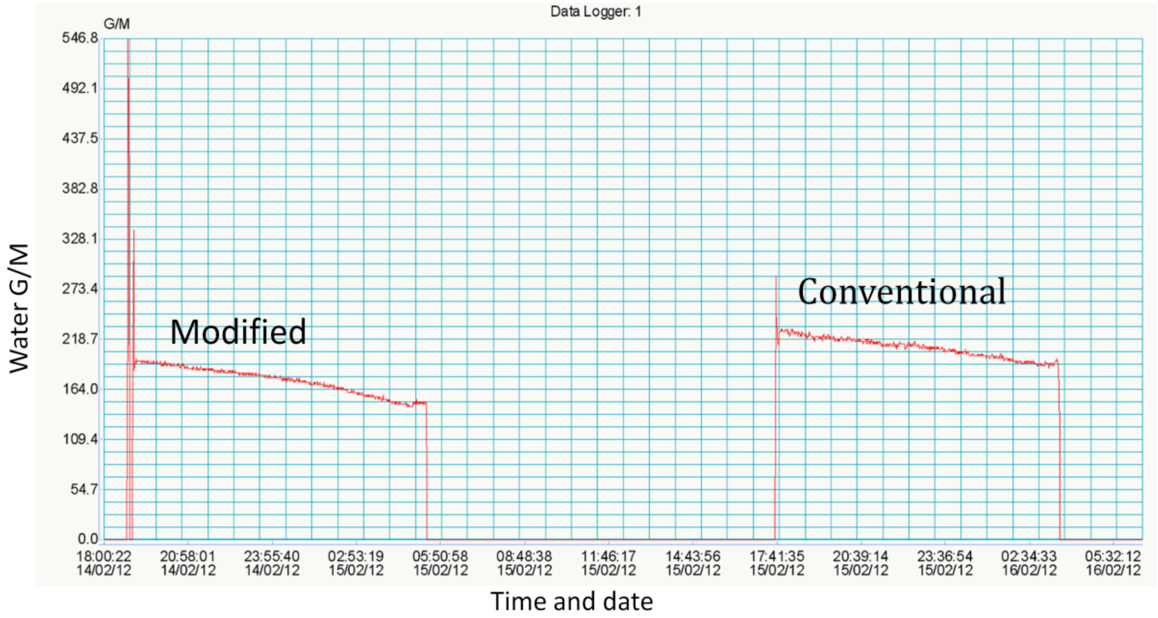


Figure 3.4 Digital water meter data showing gallons per minute (G/M) of modified (retro-fit pressure control system) irrigation treatment and conventional irrigation using a travelling gun irrigator.

3.1.2 Energy use

In 2010 energy data collected from readings on the VSD prior to, and after, an irrigation event indicated a 5.1% energy saving using the TM compared to the TC treatment. However, during 2010 several of the irrigation runs were disturbed by breakdowns of the soft-hose irrigator. Energy data collected in the second season (2011) from a data logger located on the pressure control system and to a lesser extent the 2012 season enabled comparisons of energy use between the two travelling gun irrigation treatments, TM and TC (Table 3.4). Energy consumption data obtained from the data logger (Table 3.4) during 2011 over 540 minutes of each run showed an energy saving of 21.8% for the TM treatment compared to the TC treatment. Data collected from the VSD prior to, and post, irrigation suggested a similar energy saving (17%). The slightly lower value obtained from the VSD was probably due to slight differences in run length. Data collected from the 2012 season was not reliable with kPa falling below the target pressure of 414kPa (60 psi), suggesting possible problems with the pump. In addition only three irrigation events occurred during the season due to regular rain events through the season.

Table 3.4. Data from pressure control system data logger showing results from three runs (9 hour run) during 2011 trials of modified and conventional irrigator results for a) pressure (kPa at gun), b) pump speed (revolutions per minute, rpm) and c) energy consumed (kWh) consumed. Target pressure for TM treatment was 414kPa (60 psi) at the gun.

Date	**Treatment**	**Actual pressure Range (kPa)**	**Energy (kWh)**	**Pump speed (rpm) range**	**Mean kWh**
20/01/2011	TM	407-421 (59-61 psi)	191.3	2694-3009	
31/01/2011	TM	407-421 (59-61 psi)	192.6	2559-3100	
10/02/2011	TM	414-421 (60-61 psi)	195.5	2568-3100	
	TM				**193.1**
21/01/2011	TC	469-690 (68-100 psi)	248.6	3100	
02/02/2011	TC	434-669 (63-97 psi)	245.8	3100	
11/02/2011	TC	-*	246.5	3100	
	TC				**247.0**

TM = modified travelling gun irrigator with retro-fit pressure control system.
TC = conventional travelling gun irrigator.
kPa = kilopascals
psi = pounds per square inch
kWh = kilowatt hour
rpm = revolutions per minute
* No data recorded for kPa on 11/02/2011 for TC run.

Figure 3.5 shows an example of modified (TM) and conventional (TC) irrigator results for the pressure control system data logger with TM treatment set at 414kPa (60 Psi) at the gun and include: a) pressure (414kPa at gun), b) pump speed (revolutions per minute, rpm) and c) energy consumed (kW) consumed.

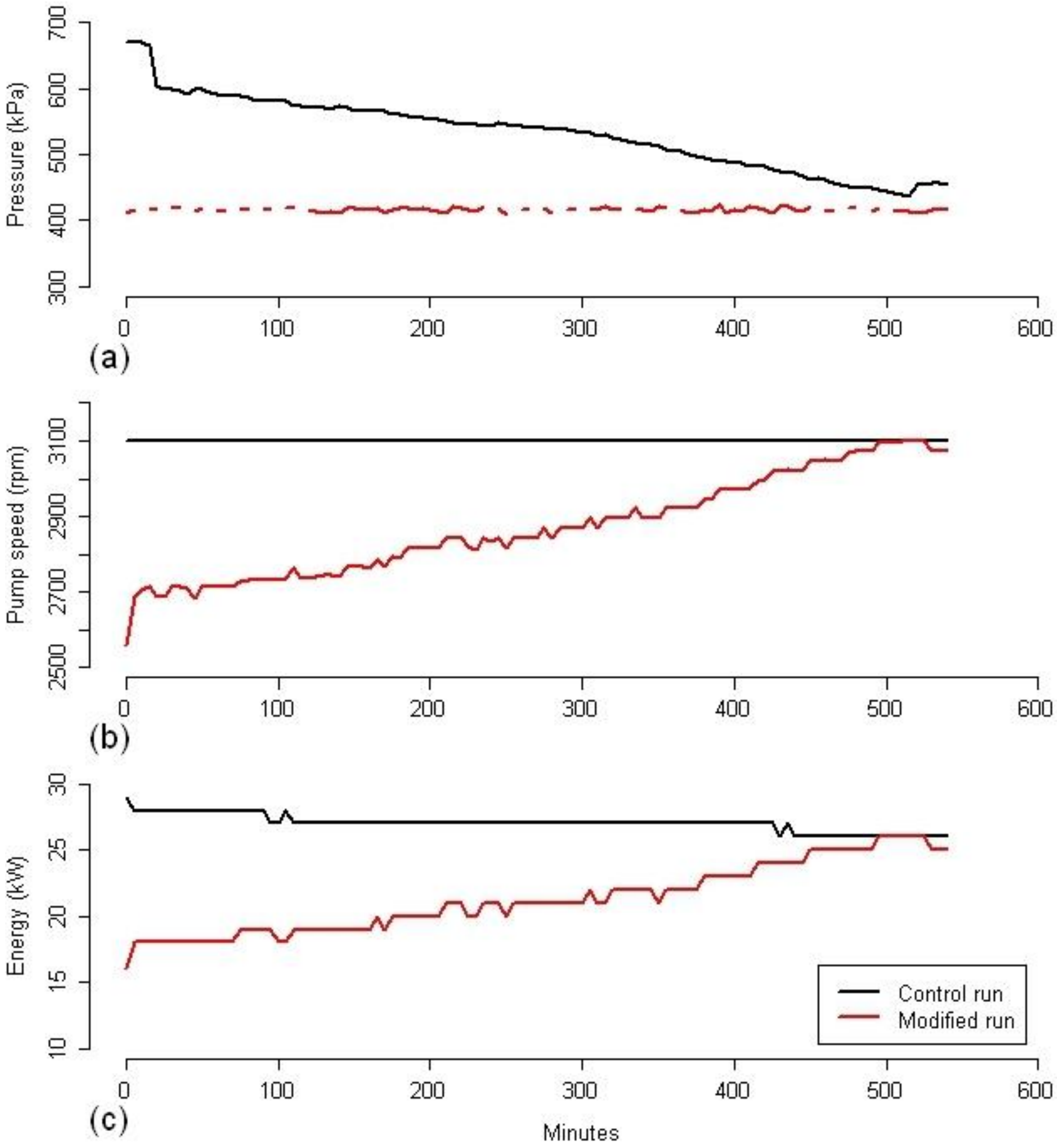


Figure 3.5 An example of modified and conventional irrigator results for a) pressure (414kPa at gun), b) pump speed (revolutions per minute, rpm) and c) energy consumed (kW).

3.1.3 Yield and quality

In 2010 green bean crop mean plant densities between the two travelling gun irrigation treatments, TM and TC, were not significantly different, indicating that the yield potential of the two treatments at emergence was similar (Table 3.5). However, the modified (TM) traveller treatment has significantly (*P*<0.001) greater total yield of marketable pods than the conventional (TC) traveller treatment by some 14.6% (Table 3.5). The estimated yield for the modified and conventional irrigation treatments was 19,870 and 16,969 kg/ha, respectively.

The percentage of diseased plants in the trial was low, and there was no significant difference in the incidence of diseased pods between the two treatments. The modified traveller treatment (TM) had significantly longer pods (*P*<0.001) that the conventional treatment (TC) (Table 3.5).

Table 3.5. Comparison of mean total yield and mean yield of commercial grades of green beans grown (2010 season) under conventionally operated and modified travelling irrigator.

Treatment	**Emergence (plants/lineal metre)**	**Marketable pod yield (kg/ha)**	**Diseased pods (g/m^2)**	**Pod length (cm)**	**Plant density at harvest (/m^2)**
TC	17.4	16,969	1.04	7.4	34.4
TM	17.1	19,870	1.92	8.3	33.1
+					
t =	0.90	-8.94	-1.16	-7.26	1.89
***P* =**	0.372 (ns)	<0.001	0.255 (ns)	<0.001	0.066
df	46	46	32.1*	46	46

*unequal variances so calculated separately for each treatment
TM = modified travelling gun irrigator with retro-fit pressure control system.
TC = conventional travelling gun irrigator.

In the 2011 carrot crop, mean yields of 77.4 t/ha and 85.1 t/ha were produced for conventional and modified traveller, respectively, from similar plant population densities. (Table 3.6). Carrot yield was significantly greater (by 7.7 t/ha, 10%) under the modified traveller than the conventional (Table 3.6). No significant difference was reported in the yield of carrots in the ‘below small’, ‘small’ and ‘medium’ categories (Table 3.6) but, significantly greater yield occurring in the ‘large’ category in the modified traveller treatment. The conventional treatment yielded only 67.8% of yield of large category carrots achieved under the modified irrigation practice. Significantly greater yield of ‘large No. 1 grade’ (P<0.01) and significantly less ‘small No. 2 grade’ (*P* < 0.01) and ‘large No. 2 grade’ carrots were produced under the modified irrigator (Table 3.6), with no differences in other size - grade combinations. Also, there were no significant differences in ‘pack-out’ (proportion of marketable carrots) in any size – grade combinations (Table 3.6). Little foliage disease was detected during the season.

Table 3.6. Comparison of mean total yield and mean yield of commercial grades of carrots grown under conventionally operated and modified travelling irrigator.

	Conventional	**Modified**	**t-value (2-tailed)**[A]	***P*=**[B]
Yield of carrots (g/m^2)	7737.5	8510.8	-2.274	<0.05
No. plants/m^2	58.9	59.7	-0.399	ns
Yield of carrots (g/m^2) in size categories:				
Below Small	232.8	241.0	-0.316	ns
Small	822.0	758.1	0.910	ns
Medium	3901.3	4120.2	-1.048	ns
Large	691.4	1020.1	-2.491	<0.05
Yield of carrots (g/m^2) size – grade categories:				
Small No.1 grade	669.0	660.8	0.118	ns
Medium No.1 grade	3281.4	3496.8	-1.093	ns
Large No.1 grade	482.7	830.9	-2.791	<0.01
Small No.2 grade	144.9	89.0	2.822	<0.01
Medium No.2 grade	565.4	568.1	-0.034	ns
Large No.2 grade	187.6	99.1	2.000	=0.05
Waste	89.2	145.8	-1.623	ns
Total waste	326.0	390.8	-1.495	ns
Diseased	3.9	4.0	-0.18	ns
No.1 grade as % of total yield (%)				
	57.1	58.9	-1.229	ns
No.1 and 2 grade as % of total yield (%)				
	69.1	67.8	1.255	ns

[A] two-tailed t-test conducted to test equality of means (46 df).

ns = no significant difference.

In 2011, NDVI was recorded twice during the growing season with a Greenseeker® radiometer (Table 3.7). The TM treatment had significantly higher NDVI values ($P < 0.01$) than TC treatment at both assessment times (62 DAP and 92 DAP), indicating greater green leaf area in the TM treatment (Table 3.7).

Table 3.7. Comparison of reflectance from the crop canopy with Normalised Difference Vegetative Index (NDVI) of carrot crop grown (2011 season) under conventionally operated and modified travelling irrigator.

Treatment	**NDVI (62 DAP)**	**NDVI (92 DAP)**
TC	0.678	0.887
TM	0.762	0.896
t =	-4.50	-2.58
P =	<0.001	0.013
df	28.8*	46

*unequal variances so calculated separately for each treatment
TM = modified travelling gun irrigator with retro-fit pressure control system.
TC = conventional travelling gun irrigator.`

In the 2012 green bean crop mean plant densities were not significantly different between TM and TC treatments of the travelling gun irrigator, indicating the two treatments had similar yield potential (Table 3.8). Total marketable pod yield was significantly higher (14.8%) for TM treatments compared to TC treatments, with estimated yields of 14,724 and 12,542 kg/ha of for the modified and conventional irrigation treatments, respectively. The modified traveller treatment (TM) had significantly longer pods ($P < 0.001$) than the conventional treatment (TC) (Table 3.8). No significant difference was reported for diseased pods or plant density at harvest between the two treatments. TM treatment had significantly greater NDVI than TC treatment at first assessment (21 DAP), but there was no difference between treatments at the second assessment (65 DAP) (Table 3.8).

Table 3.8. Comparison of mean total yield, mean yield and reflectance from the crop canopy with Normalised Difference Vegetative Index (NDVI) of commercial grades of green beans grown (2012 season) under conventionally operated and modified travelling irrigator.

Treatment	**Emergence (plants/lineal metre**	**NDVI (21 DAP)**	**NDVI (65 DAP)**	**Marketable pod yield (kg/ha)**	**Diseased pods (g/ m^2)**	**Pod length (cm)**	**Plant density at harvest (/m^2)**
TC	13.2	0.306	0.816	12,542	1.02	7.3	26.9
TM	13.1	0.341	0.826	14,724	0.40	8.2	27.8
t =	0.31	-4.97	-0.81	-2.77	1.49	-8.51	-1.20
P =	0.757 (ns)	<0.001	0.426 (ns)	0.008	0.143 (ns)	<0.001	0.238 (ns)
df	46	46	33.8*	46	46	46	46

*unequal variances so calculated separately for each treatment
TM = modified travelling gun irrigator with retro-fit pressure control system.
TC = conventional travelling gun irrigator.

3.1.4 System evaluation and technical outcome – 2010-2012 seasons

In 2010 the pressure control system retro-fit equipment was mounted on a soft hose gun irrigator. All components of the pressure control system were operating correctly during the growing season. Unfortunately, the second-hand soft hose travelling gun irrigator had several mechanical breakdowns during the season that prevented a full season's data to be collected. In between the 2010 and 2011 seasons the pressure control system components were refitted to a newer hard hose irrigator to reduce potential risk of irrigator breakdown experienced during the previous season. All components of the pressure control system were operating correctly during the growing season of 2011. In 2012, radios were replaced with only a few irrigation runs conducted during the season. Valuable data was provided by the custom built data logger which operated during the 2011 and 2012 seasons.

3.2 Variable rate irrigation system – linear move irrigator

3.2.1 Water use

To ensure uniform germination, trials started approximately 10 days after planting. Initially the same amount of water was applied to each treatment (15 mm at planting). For the remainder of the season, irrigation was applied to replace green bean (2010 and 2012 season) or carrot (2011 season) ET. In 2010, the total amount of irrigation water applied to LC treatments plus rainfall was approximately 15% more than estimated ETc (Figure 3.6). Five irrigation events occurred during 2010 season trial period, with total irrigation water of 75 mm and 67 mm applied to treatments LC and LVR, respectively (Figure 3.3). In the 2011, carrot season the total amount of water applied was 27.3% more than estimated by ETc and this may be due to heavy rain events following irrigation.

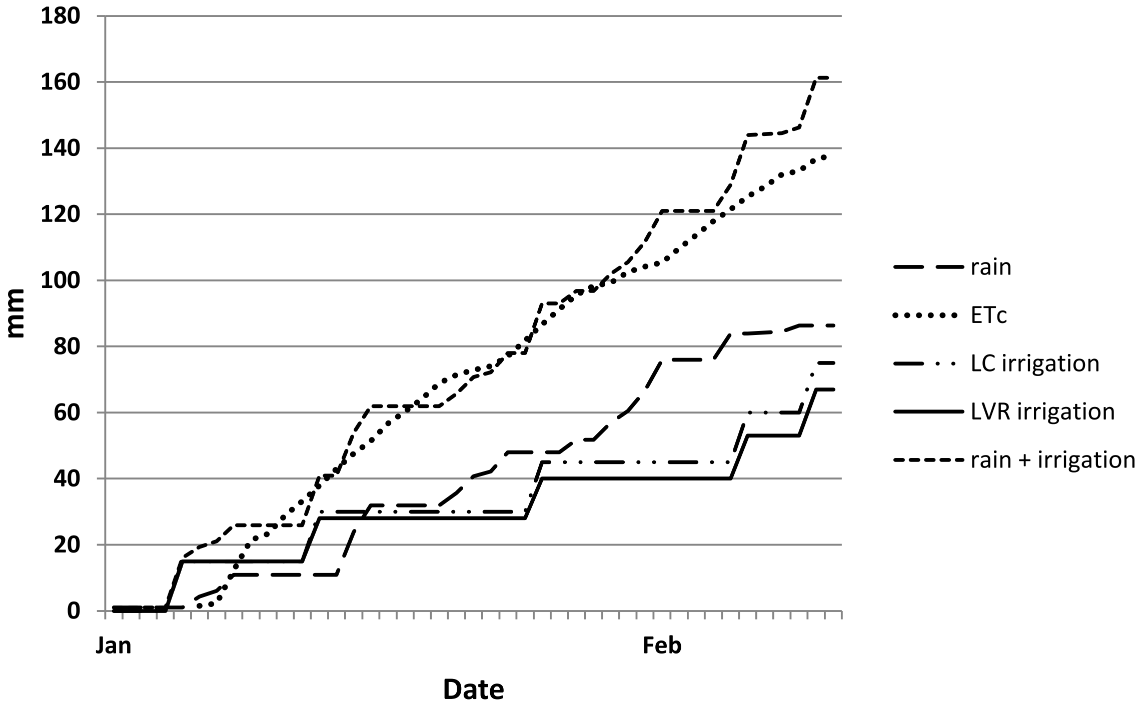


Figure 3.6. Cumulative crop water use (ETc) and water inputs from rainfall and irrigation over the green bean crop period (data presented from 13 January 2010- 24 February 2010) for conventional linear move irrigator (LC) and variable rate linear move irrigator (LVR) treatments.

The total amount of irrigation water applied to LC treatments plus rainfall was approximately 32% more than estimated ETc, similarly this may be due to heavy rain events following irrigation (Figure 3.7). A total of seven irrigation events occurred during the 2011 trial with total irrigation water applied to treatments LC and LVR was 105 mm and 94 mm, respectively (Figure 3.7).

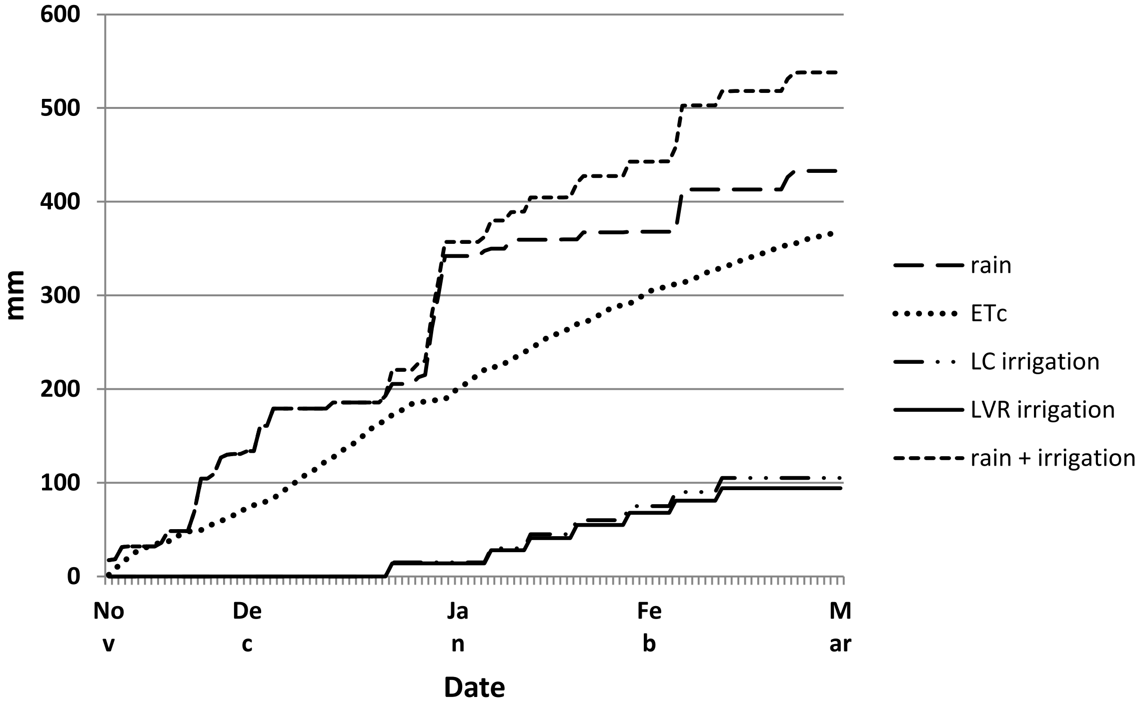


Figure 3.7. Cumulative crop water use (ETc) and water inputs from rainfall and irrigation over the carrot crop period (Nov 2010-March 2011) for conventional linear move irrigator (LC) and variable rate linear move irrigator (LVR) treatments.

As a result of regular rain events, only three trial irrigation events occurred during the 2012 season. In 2012 the total amount of water applied (LC treatment) plus rainfall was 11.3% more than estimated by ETc (Figure 3.8). Total irrigation water for the 2012 season for LC treatment and LVR treatments was 45 mm and 36 mm, respectively (Figure 3.8).

A 10.5% and 10.7% water saving was reported for the LVR treatments compared to the LC treatments in green bean crops in 2010 and 2012 respectively. A 20% water saving was reported for LVR treatments compared to LC treatments in the 2011 carrot crop.

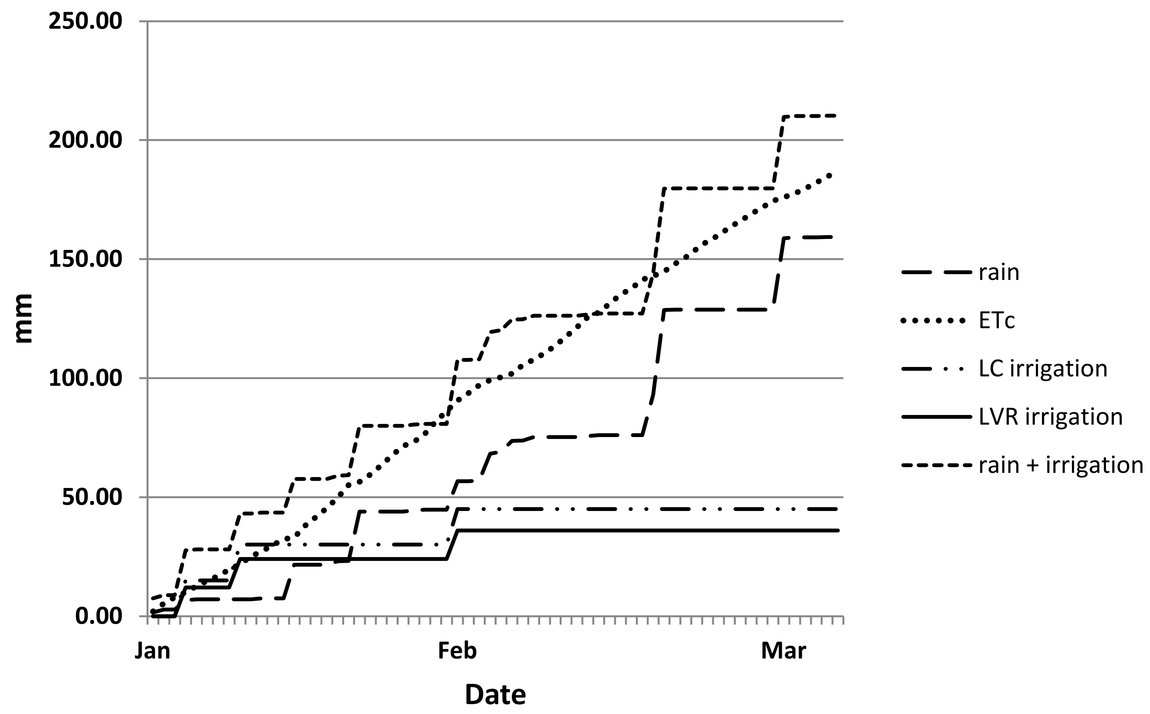


Figure 3.8. Cumulative crop water use (ETc) and water inputs from rainfall and irrigation over the green bean crop period (Jan 2012-March 2012) for conventional linear move irrigator (LC) and variable rate linear move irrigator (LVR) treatments.

3.2.2 Yield and quality

In the 2010 green bean crop emergence was slightly higher in LVR treatment than in LC treatment (Table 3.9). However, at harvest, mean plant densities between the two linear move irrigation treatments, LVR and LC, were not significantly different, suggesting a similar yield potential of the both treatments (Table 3.9). However, LVR treatment has significantly ($P < 0.001$) greater total yield of marketable pods than LC treatment, with 2.8 t/ha (14.8%) greater yield (Table 3.9). Estimated yield for LVR and LC treatments was 18,783 and 16,000 kg/ha, respectively. Although the incidence of diseased plants and pods was low, LVR treatment had more diseased pods than LC treatment. Pod length was longer in LC than LVR treatment ($P < 0.001$) (Table 3.9). There was no significant difference between LVR and LC treatments in plant density at harvest (Table 3.9). No foliage disease was detected during the season.

Table 3.9. Comparison of mean total yield and mean yield of commercial grades of green beans grown (2010 season) under conventionally operated and modified (variable rate irrigation) linear move irrigator.

Treatment	**Emergence (plants/lineal metre)**	**Marketable pod yield (kg/ha)**	**Diseased pods (g/ m^2)**	**Pod length (cm)**	**Plant density at harvest (/m^2)**
LC	17.1	16,000	0.44	8.4	35.5
LVR	17.8	18,783	2.08	7.5	35.1
t =	-3.30	-5.24	-2.62	6.74	0.49
P =	<0.001	<0.001	0.016	<0.001	0.624
df	34	25.6*	21.7*	34	34

*unequal variances so calculated separately for each treatment
LVR = modified (retro-fit with variable rate irrigation) linear move irrigator
LC = conventional linear move irrigator

The 2011 carrot trial produced an acceptable commercial yield, with mean yields equivalent to 78.7 t/ha and 75.3 t/ha under the LC and LVR treatments, respectively. There was a slight but statistically significantly lower plant density in the LVR treatment compared to the LC treatment (Table 3.10). There was no significant difference between treatments in the yield of carrots in the ‘below small’, ‘small’, ‘medium’ or ‘large’ categories (Table 3.10). Similarly there was no significant difference between treatments in the weight of no. 1 carrots or weight of no. 2 carrots in each of the size categories or in ‘waste’ or ‘diseased’. However, the weight of ‘large no. 1 carrots’ bordered on statistical significance ($P = 0.10$), with 726.5 g/m^2 in the variable rate and 445.5 g/m^2 in the LC treatment. The weight of small, medium and large no. 1 grade carrots as a percentage of total yield was significantly higher in the LVR treatment than the LC treatment (Table 3.10). Foliage disease was not minimal during the season.

Table 3.10. Comparison of mean total yield and mean yield of commercial grades of carrots grown under conventionally operated and modified (variable rate irrigation) linear move irrigator.

	Conventional	**VRI**	**t-value (2-tailed)**	***P* =**[B]
Yield of carrots (g/m^2)	7867.2	7525.0	1.090	0.283 ns
No. plants/m^2	65.2	58.4	2.264	0.030
Yield of carrots (g/m^2) in the following categories:				
Below Small	282.5	245.2	0.886	0.382 ns
Small	909.0	821.4	0.900	0.275 ns
Medium	3832.3	3706.8	0.579	0.566 ns
Large	648.0	853.0	-1.148	0.259 ns
Yield of carrots (g/m^2) in the following categories:				
Small #1 grade	755.4	729.0	0.327	0.745 ns
Medium #1 grade	3298.8	3216.8	0.425	0.674 ns
Large #1 grade	445.5	726.5	-1.723	0.094 ns
Small #2 grade	136.2	74.4	1.887	0.068 ns
Medium #2 grade	448.2	399.8	0.541	0.592 ns
Large #2 grade	135.0	71.1	1.323	0.195 ns
Waste	173.1	163.9	0.156	0.877 ns
Total waste	503.0	436.9	0.768	0.448 ns
Diseased	47.3	27.8	0.980	0.334 ns
Small, medium and large #1 grade as % of total yield (%)	57.1	62.5	-2.549	0.015
Small, medium and large #1 and #2 grade as % of total yield (%)	66.3	69.8	-1.905	0.065 ns

[A] two-tailed t-test conducted to test equality of means (34 df).

[B] For non significant (ns) results, the mean values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability.

VRI = variable rate irrigation

The NDVI at 63 DAP bordered on statistical significance with LC treatment higher than LVR treatment. However at 94 DAP (second assessment) there was no significant difference (Table 3.11).

Table 3.11. Comparison of reflectance from the crop canopy with Normalised Difference Vegetative Index (NDVI) of carrot crop grown (2011 season) under conventionally operated linear move irrigator (LC) and variable rate irrigation (LVR) on a linear move irrigator.

Treatment	NDVI (63 DAP)	NDVI (94 DAP)
LC	0.699	0.878
LVR	0.661	0.878
t =	1.93	0.03
P =	0.062 (ns)	0.979
df	34	25.2*

*unequal variances so calculated separately for each treatment
LVR = modified (retro-fit with variable rate irrigation) linear move irrigator
LC = conventional linear move irrigator

In the 2012 green bean crop there was no significant difference between LC and LVR treatments for emergence, marketable pod yield, weight of diseased pods, pod length, plant density at harvest or NDVI 23 DAP (Table 3.12). The LVR treatment had higher NDVI values than LC treatment at the second assessment (68 DAP), indicating greater green leaf area in LVR treatment (Table 3.12). Minimal foliar disease was detected during the season. Effects of LC and LVR treatments on yield and quality were minimal (Table 3.12) and this may be due to the frequent and at times high rainfall during all trial seasons.

Table 3.12. Comparison of mean total yield, mean yield and reflectance from the crop canopy with Normalised Difference Vegetative Index (NDVI) of commercial grades of green beans grown (2012 season) under conventionally operated and modified (variable rate irrigation) linear move irrigator.

Treatment	Emergence (plants/ lineal metre)	NDVI (23 DAP)	NDVI (68 DAP)	Marketable pod yield (kg/ha)	Diseased pods (g/ m^2)	Pod length (cm)	Plant density at harvest (/m^2)
LC	14.7	0.423	0.817	16,812	0.80	8.2	29.9
LVR	14.3	0.412	0.838	16,006	0.83	8.2	28.9
t =	1.60	1.76	-3.18	1.62	-0.13	0.13	1.18
P =	0.119 (ns)	0.08 (ns)	0.003	0.116 (ns)	0.898 (ns)	0.899 (ns)	0.245 (ns)
df	34	34	34	27.2*	34	34	34

*unequal variances so calculated separately for each treatment
LVR = modified (retro-fit with variable rate irrigation) linear move irrigator
LC = conventional linear move irrigator

3.2.3 Soil moisture

Prior to any integration the VRI and soil moisture WSN system need to be independently operating to ensure components would integrate efficiently. In 2010 the soil moisture WSN system did not provide usable data and this was resolved before the 2011 season. In 2011 the Fleck^{TM} base unit reliably recorded logs from the majority of the fleck units. A small number of Fleck^{TM} units were inoperable. This could only be determined through the base station fleck logging. A few of the Fleck^{TM} units that were not operating were recovered through reset procedures. The Fleck^{TM} units transmitted sensor readings every 15 to 30 minutes. The readings from the sensors connected to the Fleck^{TM} were compared with data obtained in the field at the same time from sensors adjacent to Fleck^{TM} sensors from a commercially available soil moisture sensor system (MEA GBug^{TM}). Throughout the season it became apparent that the readings from the fleck sensors (the same sensors as used in the third-party commercial system) were inconsistent. The readings from the Fleck^{TM} sensors did indicate rain and irrigation events and showed the soil drying over time, but the values where variable from those of the commercial sensor system. Results suggest, that while the sensor system was recording readings reliably, there appeared to be a possible issue with calibration of Fleck^{TM} sensor regarding voltage reading. In the 2011 season, data was recorded, however, calibrations were not resolved (data not shown).

The difference in penetration resistance was recorded between flowering and sowing time in bean crop plots (TC, TM, LC and LVR treatments) during the growing season of 2010 (Table 3.13). The average penetrometer resistance (kPa) were plotted again soil wetness for depths of 0-150 mm (Figure 3.9) and 150-300 mm (Figure 3.10). Mean values for each treatment are shown (Table 3.13). Across all treatments, there was a significant negative relationship between soil moisture content and average penetrometer resistance for 0-150 mm (Figure 3.9), but with a low coefficient of determination (R^2 = 0.113). There was a stronger negative relationship between soil moisture content and average penetration resistance for 150-300 mm depth (Figure 3.10), with R^2 = 0.607. . Within the individual treatments there was a significant negative relationship between soil moisture content and average penetrometer resistance at 150-300 mm for TC (Figure 3.11), TM (Figure 3.13) and LVR (Figure 3.14), but not LC. Within individual treatments, there was a significant negative relationship between soil moisture content and average penetrometer resistance at 0-150 mm depth only for TM treatment (Figure 3.12).

Table 3.13. Mean penetration resistance and soil moisture content at 0-150 mm and 150-300 mm depth for irrigation treatments.

	0-150 mm		**150-300 mm**		
Treatment	**Moisture content %**	**Mean resistance kPa**	**Moisture content %**	**Mean resistance kPa**	**Maximum resistance kPa**
TC[a]	37.8	494	35.6	1149	1920
TM[b]	38.8	415	37.0	1071	1674
LC[c]	36.5	369	34.3	1253	2379
LVR[d]	36.4	678	32.7	2151	3140

[a] TC = Control treatment under the travelling gun irrigator.

[b] TM = Modified treatment under the travelling gun irrigator, retro-fit of pressure control system

[c] LC = Conventional irrigation treatment under the linear move irrigator

[d] LVR = Variable rate irrigation treatment under the linear move irrigator

Soil moisture variability across the field was investigated using a penetrometer to determine differences in resistance across the field at different times of crop development. Penetrometers resistance (kPa) verses soil moisture content (%) and for all treatments (TC, TM, LC and LVR) at 0-150 mm depth and 150-300 mm depth are shown in Figures 3.9-3.10, respectively. Averages for 150-300 depth for each treatment (TC, TM, LC and LVR) are shown in Figures 3.11-3.15.

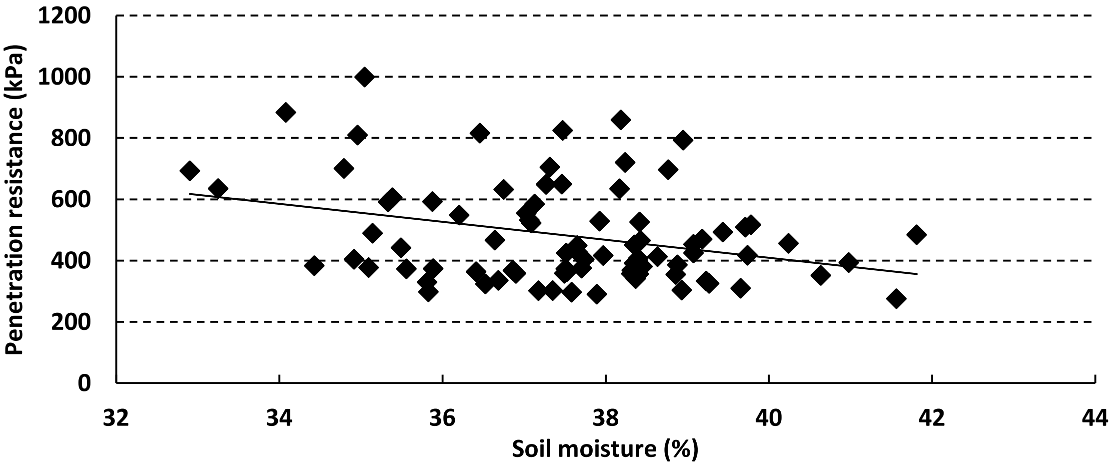


Figure 3.9. Penetration resistance vs moisture content for 0-150 mm depth for all treatments (conventional and modified travelling gun irrigator (TC and TM) and conventional and variable rate irrigation on linear move irrigator (LC and LVR)). (P = 0.002, R^2 = 0.113)

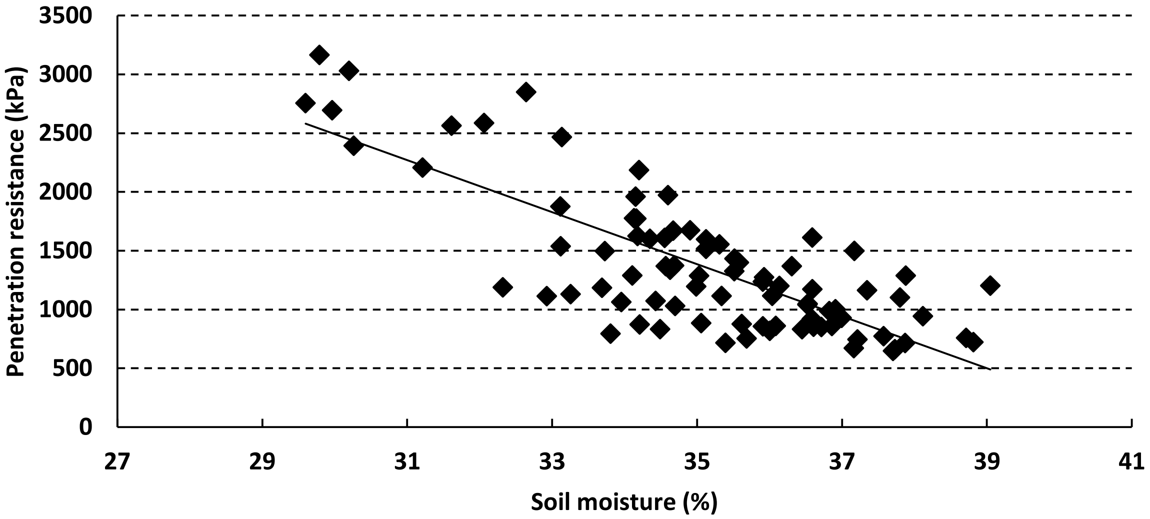


Figure 3.10. Penetration resistance vs moisture content for 150-300 mm depth for all treatments (conventional and modified travelling gun irrigator (TC and TM) and conventional and variable rate irrigation on linear move irrigator (LC and LVR)) plots. (P < 0.001, R^2 = 0.607).

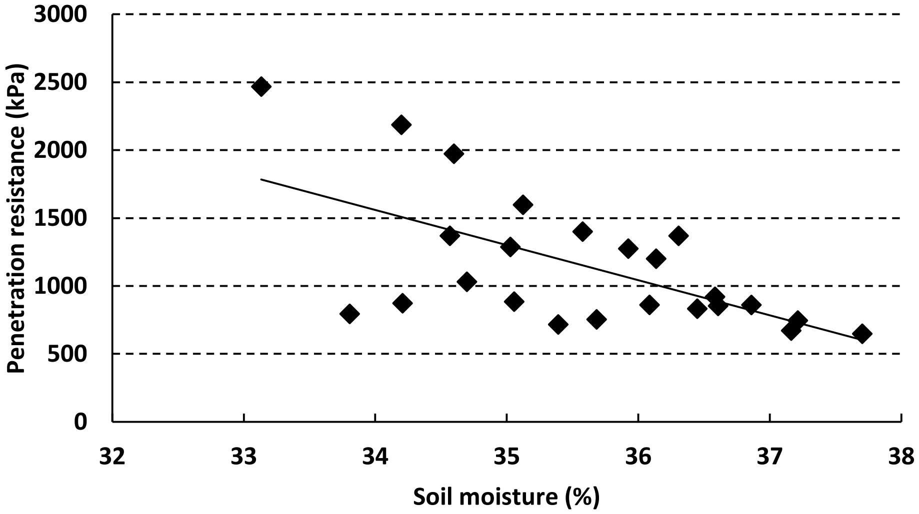


Figure 3.11. Average penetration resistance vs moisture content at 150-300 mm depth for conventional travelling gun irrigator (TC) treatment plots. (P = 0.004, R^2 = 0.384).

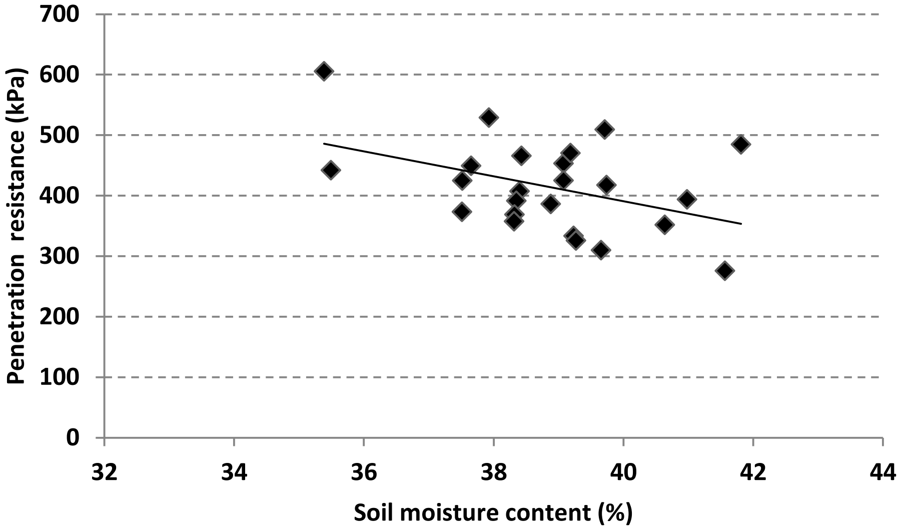


Figure 3.12. Average penetration resistance vs moisture content at 0-150 mm depth for modified travelling gun irrigator (TM) treatment plots. (*P* = 0.035, $R^2 = 0.186$)

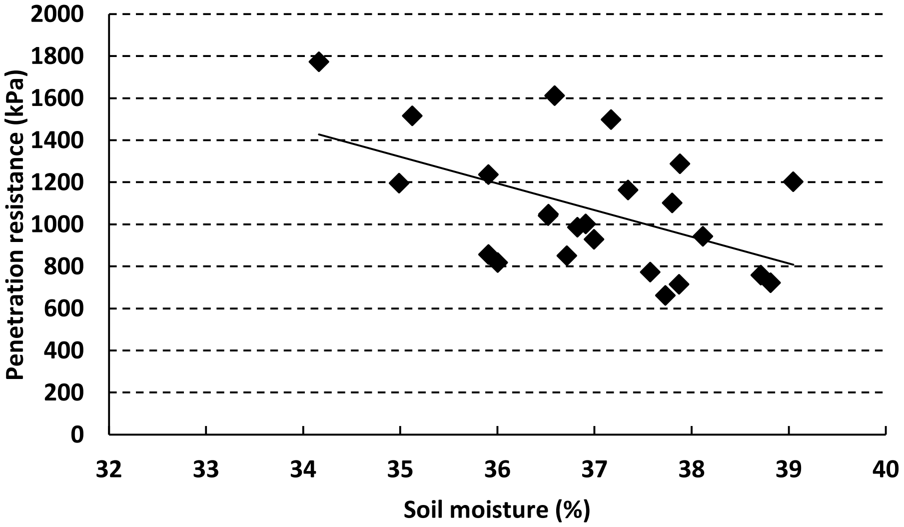


Figure 3.13 Average penetration resistance vs moisture content at 150-300 mm depth for modified travelling gun irrigator (TM) treatment plots. (*P* = 0.01, $R^2 = 0.266$).

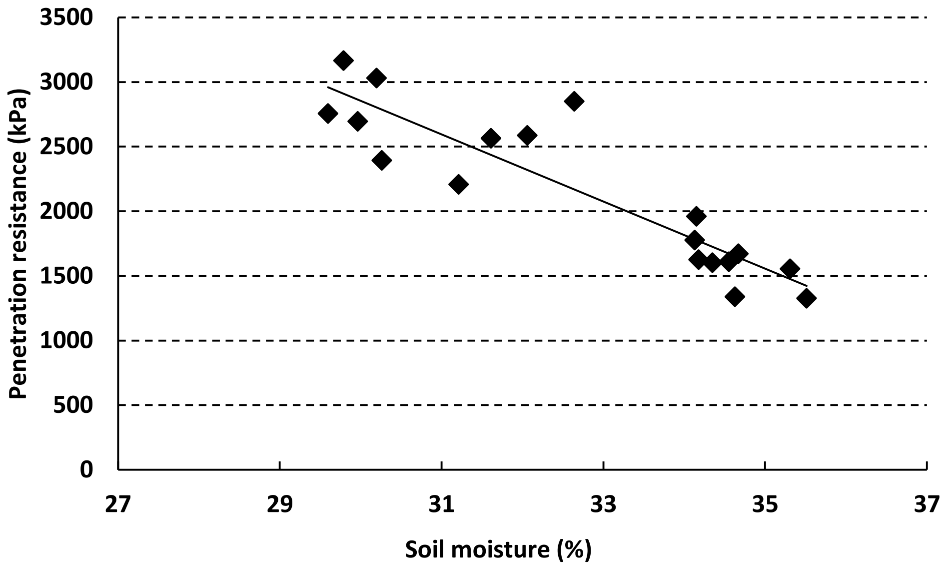


Figure 3.14. Average penetration resistance vs moisture content at 150-300 mm depth for variable rate irrigation linear move (LVR) treatment plots. ($P < 0.001$, $R^2 = 0.812$).

3.3.4 System review

Currently the variable rate irrigation system is a proof-of-concept and has operated successfully over the past three seasons with some minor issues. The VRI system operated as designed and was verified through observation, measurement and system log review. Early testing of Fleck^{TM} WSN system conducted in 2009 found issues with data retrieval from the Fleck^{TM} and telemetry improvements were made including the addition of a larger antenna to improve the radio link between the Fleck and gateway computer. No soil data was recorded for Flecks readings during the 2010 growing season. Issues were addressed and Fleck data was retrieved in 2011 season. However, despite these issues the software of the Fleck^{TM} WSN appears sound. The VRI system operated as designed in all seasons (2010, 2011 and 2012) and was verified through observation, measurement and system log review.

Further work is required to move to a hardware platform that would be suitable for commercialisation and rebuild the system to match the hardware platform, maintaining current functionality. In addition building an integration point to enable different sensor networks and data to be "plugged in" into the system would be optimal. Also ensuring the data is available via an application/technology that will enable commercialisation of the system. Overall the architecture of the Fleck^{TM} platform was sound and suited the task, although there were some high-level application software and backhaul infrastructure that was problematic at times. While the sensor array proved suitably reliable, unresolved issues remain regarding calibration of sensors.

3.4 Cost benefit analysis

Component costs of the retro-fit pressure control system are listed in Table 3.14. Total capital cost for pressure control system is estimated at $2,500 (plus installation costs of $1,000). In addition to component and set up costs for the pressure control system the purchase of a variable speed drive (VSD) (approximately $5,000-$12,000) would be required if the pump is not fitted with a pre-existing VSD.

Table 3.14 Cost of the components required for the pressure control system (TM)[A].

Components	**Modified ($)**
In pump shed	
Pressure control unit	900
Installation and integration of system with commercial variable speed (VSD) (electrician costs)	300
Antenna for radio	50
On the Irrigator	
Pressure sensor	90
battery	60
Solar panel	200
Micro processor	500
Radio transmitter	200
Installation cost	200
Total cost	2500

[A] An additional $5,000 to $12,000 would be required if pump was not fitted with a variable speed drive.

Component costs of retro-fit system for VRI are listed in Table 3.15. Total capital cost for VRI system is estimated at $25,000 (plus installation costs of $1,000).

Table 3.15 Cost of components required for the variable rate irrigation (VRI) for the linear move irrigator.

Components	**Cost ($)**
Control terminal/system and GPS	5 190
Computer components and software	9 500
Connection cables, wiring and other connection parts	1 000
Valves and all other components listed: e.g. all components on the linear (hardware)	2 000
DGPS	150 (included above)
Software	2000 (included above)
WSN (Flecks ($770 each including Watermark ^{TM} sensor and rechargeable batteries) and base station ($5,000) (approximately 3Flecks)) Plus EM 38 mapping costs ($27/ha)	7 310
Total	**25 000**

WSN = wireless sensor network

Additional installation costs for each system would equate to approximately $1,000 for irrigation specialists and electricians. Irrigation costs were divided into fixed costs (e.g. machinery, retro-fit system and soil moisture sensor) and variable costs (e.g. operation costs such as power, maintenance and labour). The capital cost of the retro-fit irrigation system for the pressure control system fitted to the travelling gun irrigator was $1,925/ha compared to $1,750/ha the conventional travelling gun irrigator (Table 3.16). The capital cost of the retro-fit irrigation system for the variable rate irrigation fitted to the linear move irrigator was $5,143/ha compared to $3,500/ha the conventional linear move irrigator (Table 3.16). Variable costs for the pressure control system retro-fitted to the travelling gun irrigator include maintenance ($28.88/ha) and power ($65.30/ha) compared to conventional travelling gun irrigator variable costs of $26.25/ha and $53.10/ha for maintenance and power, respectively (Table 3.16). Variable cost of labour was $21.54/ha for both modified and conventional travelling gun irrigator. For the variable rate irrigation retro-fit system, variable costs included maintenance ($71.25/ha) and power ($20.48/ha) compared to $52.50/ha and $18.33/ha, respectively, for conventional linear move irrigator (Table 3.16). Labour costs for both the variable rate irrigation system and control system were $21.54/ha.

Table 3.16 Capital and operating costs of irrigation retro-fit technology (based on 20 ha area of irrigation).

	Linear Move Irrigator		**Travelling Gun Irrigator**	
Parameters	LC [a] ($)	LV [b] ($)	TC [c] ($)	TM [d] ($)
Capital cost				
Traveller/linear ($/ha)	3500	3500	1750	1750
Soil moisture monitoring ($/ha)	-	366	-	-
Retro-fit system ($/ha)	-	1250	-	175
EM38 map ($/ha)	-	27	-	-
Total capital cost per hectare	3500	5143	1750	1925
Variable costs				
Maintenance ($/ha) (1.5% of new cost)	52.50	71.25	26.25	28.88
Power (electricity, $/ML)[*]	18.33	20.48	53.10	65.30
Labour (@ $21.54) h/ha	10.77	10.77	21.54	21.54
Total annual operating cost per hectare	81.60	102.50	100.89	115.72
Net Present Value (NPV)		3,318.25		-21,681.75
Benefit Cost Ratio (BCR)		1.95		0.27
Payback period		2.5 years		11 years

[a] Linear Move Irrigator - control (LC)
[b] Linear Move Irrigator - variable rate irrigation (LV)
[c] Travelling Gun Irrigator - control (TC)
[d] Travelling Gun Irrigator – modified (TM)
[*] Power based on day rates, not including variable power costs.

Results of the economic evaluation indicate the pressure control system is economically beneficial under trial conditions and assumptions. Economic evaluation of the retro-fit pressure control system showed 1.95 for benefit-cost ratio (BCR), $3,318 for net present value (NPV) and 2.5 years for payback period. However, results indicate the retro-fit variable rate irrigation system is not economically beneficial under trial conditions and assumptions. Depending on the variability of the site the payback period could more than 11 years. The BCR was 0.27 and a negative NPV (-$21,681.75). Suggesting the retro-fit variable rate irrigation system would not be viable at the current price and would require economic evaluation of each site to determine if the system would be of economic benefit.

Irrigation water use indices relating to water application by conventional or modified travelling irrigator to a carrot crop are shown for the 2011season (Table 3.17). Gross

Production Economic WUI was 12.4% higher in the modified compared to the conventional (control) irrigation treatment.

Table 3.17 Irrigation water use indices relating to water application by modified and conventional travelling gun irrigator in 2011 season.

	Travelling Irrigator Treatment	
	Control	**Modified**
Yield (t/ha)	77.4	85.1
Rain (mm)	512.6	512.6
Irrigation (ML/ha)	2.7	2.6
IWUI[1]	28.7	32.7
GPWI[2]	9.9	11.0
Gross Production Economic WUI[3]	3080.5	3517.2

[1]Irrigation Water Use Index (WUI) = Yield ÷ Applied Irrigation
[2] Gross production WI (GUPWI) = Yield ÷ (Total rainfall + Applied Irrigation)
[3]Gross Production Economic Water Use Index (WUI) = (payment$/tonne × Yield) ÷ Applied Irrigation ML/ha.

Irrigation water use indices relating to water application by conventional (control) or VRI linear move irrigator to a carrot crop in 2011 are shown (Table 3.18). Total irrigation was 20% less in VRI treatments than in conventional linear move irrigation. Gross Production Economic WUI was 14.8% higher in the VRI treatment compared to the conventional linear move irrigation treatment (Table 3.18).

Table 3.18. Irrigation water use indices relating to water application by conventional and variable rate irrigation (VRI) on linear move irrigator in 2011 season.

	Linear Move Irrigator Treatment	
	Control	**VRI**
Yield (t/ha)	78.7	75.3
Rain (mm)	512.6	512.6
Irrigation (ML/ha)	1.35	1.1
IWUI[1]	58.3	68.5
GPWI[2]	12.2	12.1
Gross Production Economic WUI[3]	6237.7	7324.6

[1]Irrigation Water Use Index (WUI) = Yield ÷ Applied Irrigation
[2] Gross production WI (GUPWI) = Yield ÷ (Total rainfall + Applied Irrigation)
[3]Gross Production Economic Water Use Index (WUI) = (payment$/tonne × Yield) ÷ Applied Irrigation ML/ha.

4. Discussion

Options for climate change adaption by irrigated agriculture include improved technology and scheduling to enhance on-farm water use efficiency as identified in Stokes and Howden (2010) and Jackson (2009). The two retro-fit irrigation technology systems developed and tested in this project, or similar type systems, have the potential to reduce water and energy use during vegetable production. Trials conducted over three consecutive vegetable growing seasons (2010-2012) using a pressure control system retro-fitted to a travelling gun irrigator indicated a 15% and 10% energy and water saving respectively compared to a conventional traveller. The retro-fit of the pressure system to a hardhose irrigator in 2011 resulted in energy savings of 17-21.8% and water savings of 5-10% with the modified equipment. Frequent rain events in 2012 reduced the requirement for irrigation applications, but still resulted in an estimated 10% saving of water. If a crop receives 4ML/ha and electricity price is $0.22/kWh (day rate) then a 17-21.8% saving represents $64.30-$82.45/ha. Given electricity prices are expected to increase by 27% by 2013 (Sutton 2012) this represents a substantial saving. If the irrigator was used on 20 ha per year then the $3,500 (plus a variable speed drive if not one located in the pump shed) cost of the system would be recouped in 2-3 years. Similarly if a crop receives 4ML/ha and water price is $0-$3000/ML then a 5-10% saving would represent $0-$1200. In all three seasons yield was significantly higher in modified compared to conventional traveller gun irrigation treatment, with increased yields of 14.6% (bean), 10.0% (carrot) and 14.8% (bean), for 2010, 2011 and 2012 seasons, respectively. However, trials conducted by Koech and Raine (2010) suggested carrot yield was not greatly influenced by irrigation non-uniformity using a travelling gun irrigator. Further testing and assessment would be required prior to any commercialisation. However, there is significant potential in the vegetable and dairy industries. For example, an estimated 50% of energy costs on-farm in New Zealand dairy farming systems is as a result of irrigation energy costs (Barber and Pellow 2005 cited in Hedley et al. 2012). Pemberton (2005) and Tolvanen (2005) report the addition of a variable speed drive (VSD) can reduce pumping costs, with savings of up to 20-50% of energy consumed by a pump during irrigation. For two irrigation districts in Southern Italy, Lamaddalena and Khila (2012) reported energy savings of 27-35% using a VSD fitted to pumping stations. Therefore any cost effective retro-fit system capable of reducing energy costs warrants further investigation.

The project also investigated the integration of soil moisture measurements collected from real-time from a wireless sensor network (WSN) (developed by the CSIRO ICT) to schedule irrigation events applied with VRI (developed by Seattle Services Pty Ltd.). As highlighted by Evans and Kim (2012) power requirements can be an issue for field wireless systems. Although initial power issues occurred with the use of the WSN these were addressed in subsequent seasons. Over the three cropping seasons the variable rate system operated with estimated water savings of 10-15%. Similar results have been obtained in other studies. For example, Hedley et al. (2009) reported water savings of 9-19% using VRI compared to uniform irrigation. Simulation studies on the potential savings of variable rate irrigation compared to conventional blanket irrigation from a trial 2004-2009 showed a 5% water saving (increased with additional rain events) with 16-33% reduced drainage (Hedley et al. 2012) and estimated savings of $52/ha/yr. Earlier studies indicated water savings of 8% and 21% under VRI with crops such as potatoes, dairy pasture and maize grain (Hedley et al. 2010).

Barriers for growers adopting WSN have been outlined by Lea-Cox (2012) and include calibration and maintenance of soil moisture sensors. A possible benefit of using VRI includes increasing water use efficiency by matching crop requirements accurately with irrigation inputs (Wigginton 2007). In addition rather than maximising yield, each part of the field can be targeted to maximise profit (Wigginton 2007). Adoption by farmers of variable rate irrigation may result in a costly exercise if the system is not managed correctly. McCarthy (2010) described a recent survey of 100 growers that had installed Farmscan variable rate technology sometime over the past 10 years in Georgia. Results of the survey showed that only four growers continued to use the variable rate hardware of the 100 growers that had invested in the technology of variable rate (McCarthy 2010). One reason for this suggested by Jake Larue (Valmont Irrigation Project Manager) was that growers found that irrigation volumes for the site-specific system were difficult to determine. To support existing growers with VRI technology and encourage the uptake of VRI a decision-making aid (CropMetrics) for irrigation was commercialised by Valmont (McCarthy 2010).

Barber et al. (2002) stated an increase of $30 million per annum had been achieved for horticultural growers in the Darling Downs, Lockyer Valley and Granite Belt as a result of changing irrigation practices and modifying irrigation design. The decision to alter irrigation equipment and practices was based on renewed interest from growers for information relating to cost-benefit of crop response (yield) and irrigation system performance from an engineering aspect (Barber et al. 2002). In irrigated cropping the water use efficiency provides a performance indicator (Purcell and Currey 2004). In our study retro-fit telemetry for travelling gun irrigator and linear move irrigator based on 2011 trial data indicated Gross Production Economic WUI was 12.4% and 14.8% higher in the modified compared to the conventional irrigation treatment. Economic evaluation results from our study suggest the pressure control system for the travelling gun irrigator was economically beneficial under our trial conditions and assumptions. However, the retro-fit variable rate irrigation system (with WSN and soil moisture sensors) was not economically viable under our trial conditions and assumptions. Lu et al. (2004) also suggest VRI was not profitable compared to conventional uniform applications in trials conducted with experimental VRI system used in South Carolina. Evans and Kim (2012) highlight the fundamental importance of knowing within a field the soil moisture variability. This is essential for site-specific irrigation management given that different water holding capacity occurs in different soils. Economic evaluation of the variable rate irrigation system on a range of variable sites may show adoption of this technology is a viable option. A reduction in sensor cost is required to enable VRI integrated with WSN and soil moisture sensors to be a cost effective option for growers. Up take of water saving technologies is influenced by change in inputs costs and economic factors such as availability of finance and commodity prices (Hafi et al. 2006). Evans and Kim (2012) have also developed a site-specific irrigation system for a linear move irrigator with an integrating a wireless sensor network for automated irrigation. However, Evans and Kim (2012) suggest although site specific irrigation provides a valuable research tool, limited research has been conducted to determine the full agronomic potential benefits of such a system. Further studies are required to assess the economic viability of variable rate irrigation systems.

5. Technology transfer

Communication activities for this project included conference presentations, field days interviews and articles for both hard copy and web based publications. Industry article on the project include the following; i) Southern Precision Agricultural Association (SPAA) (Volume 6 (Issue 2) Summer/Autumn 2010, page 13); ii) 'Cost-saving solutions for the future' (Vegetables Australia July/August 2011, page 42-43), iii) an article in Irrigation Australia Journal (August 2011), iv) article entitled 'Telemetry technology improves irrigation efficiencies', on the Climate Ready – Horticulture website DPI Victoria (September 2011edition, online); v) project update articles in Tasmanian Regions magazine (Autumn 2012, page 38), Vegie Info (Vegetable Industry Development Program, Vol. 1, No. 2 March 2011).

Additional communication activities for this project included the following presentations and papers; i) an invited speaker to present at the 2010 AUSVEG National Convention held at Jupiter's Hotel Casino (Gold Coast, Queensland) 27-30 May 2010; ii) project update presentation provide at the Tasmanian Institute of Agricultural Staff Convention held at the University of Tasmania (Hobart, Tasmania) on 3 November 2010; iii) two presentations at the Irrigation of Australia Conference held in Launceston (Tasmania) on 22-25 August 2011, iv) a presentation entitled 'Irrigation and telemetry technology for energy and water use efficiency in irrigation of carrots' was given at the Horticulture for the Future Conference (18-22 September 2011, Lorne Tasmania), v) a poster project update was given at the TIA Industry Conference held in July 2011; vi) project update presentation was given at the Australian Processing Potato Research (APPR) II day (4 October 2011) and also as part of TIAR seminars series (28th October 2011) both were presented at the University of Tasmania, Cradle Coast campus, Burnie Tasmania; and ii) a paper entitled 'Producing more with less using retro-fit telemetry to reduce energy and water consumption during carrot production' was submitted to the 16th Australian Agronomy Conference 2012 (*Capturing Opportunities and Overcoming Obstacles in Australian Agronomy*) to be held University of New England, Armidale (14-18 October 2012).

Communication activities for this project included field days were held during each growing season and included the following: i) a field day was held on the 16 February 2010 for a

Climate Ready Farming Leaders group and was attended by 25 vegetable growers and industry representatives; ii) a field day was held on the 1st March 2011 with two field walks held during the day. The field day was attended by two groups of 10 and 25 vegetable growers and industry representatives, respectively; and iii) a field day was held on the 15th March 2012 and attended by 12 vegetable growers and industry representatives.

A radio interview was undertaken with the ABC radio, conducted by Eliza Wood on 2 March 2011 entitled ‘Giving paddocks what they deserve, and that’s all’ (http://www.abc.net.au/rural/tas/content/2011/03/s3153079.htm). Also communication actives included meeting held for the Irrigation Water Use Efficiency (WUE) Advisory Group during April 2009 (UTAS, Cradle Coast Campus), March 2010 and March 2011 at TIAR VRF followed by a field demonstration (industry personnel attended).

6. Recommendations and further research

- Conduct a study to assess variability and suitability across vegetable cropping fields for retro-fit irrigation technology such as variable rate irrigation (VRI).

- Further on-farm research is required to determine potential economic benefits of VRI for farmers.

- Improved matching of spatial variability of plant available water across the field and zoning of field.

- Sensor placement and numbers of sensors required within zones requires further investigation to maximise VRI potential.

- Auditing of irrigation energy use on farms and distribution uniformity of irrigation equipment is required to ensure irrigation systems are performing to their optimum prior to any retro-fit irrigation technology.

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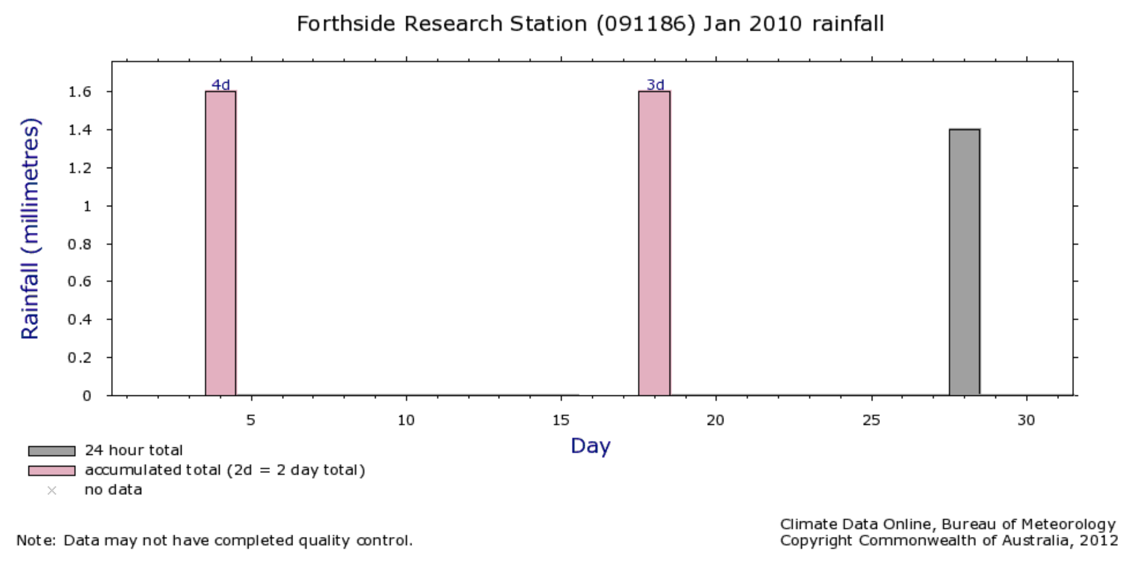
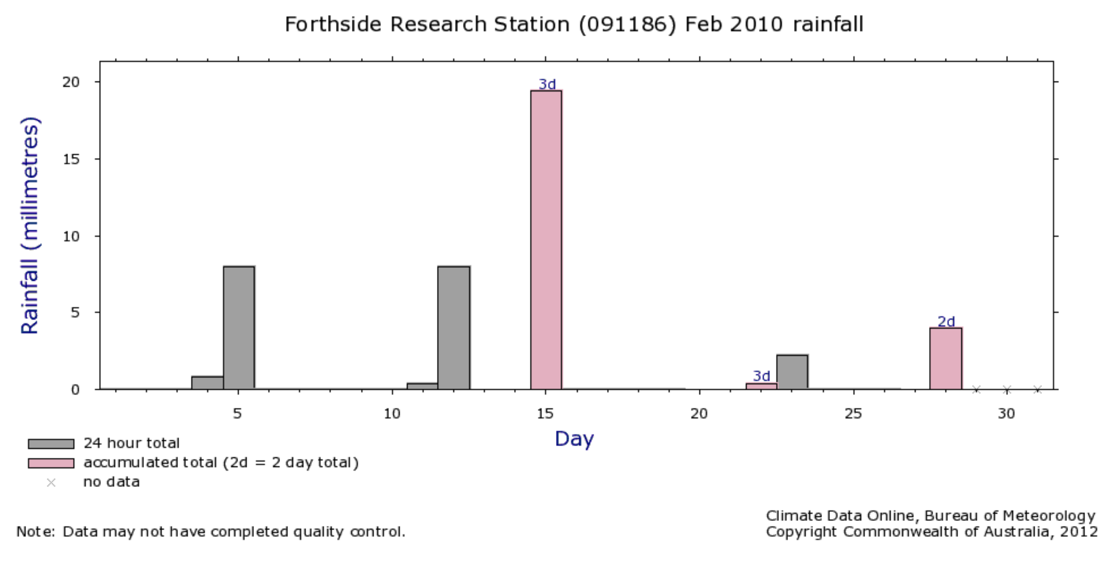
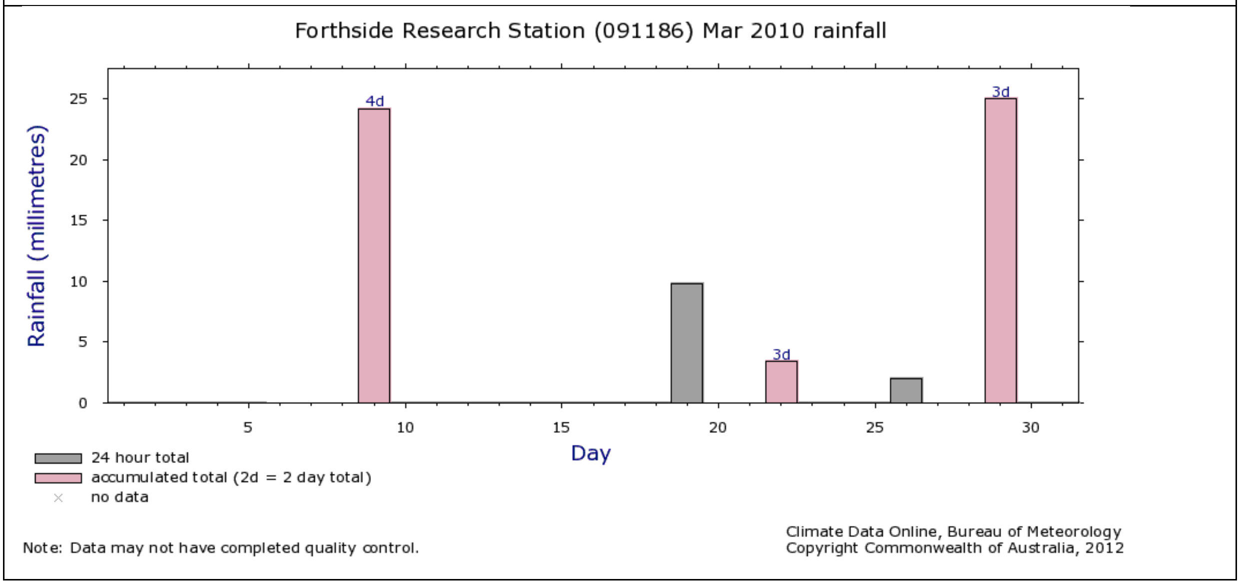
Appendix I – Rainfall Jan-March 2010 (BOM online)

http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=2010&p_c=-1670245786&p_stn_num=091186

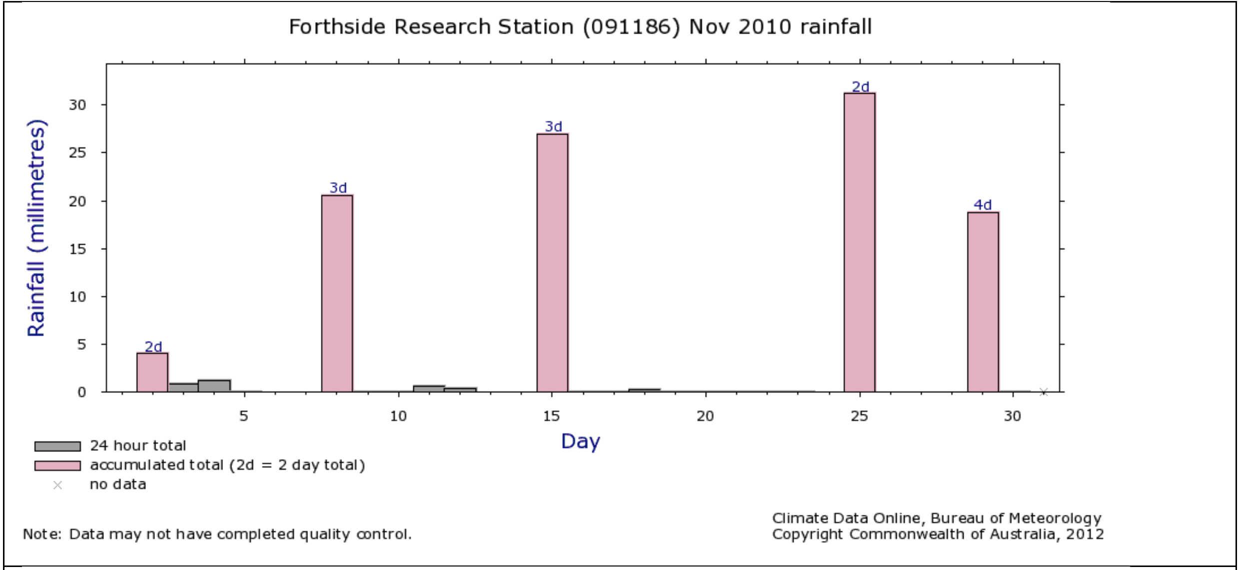


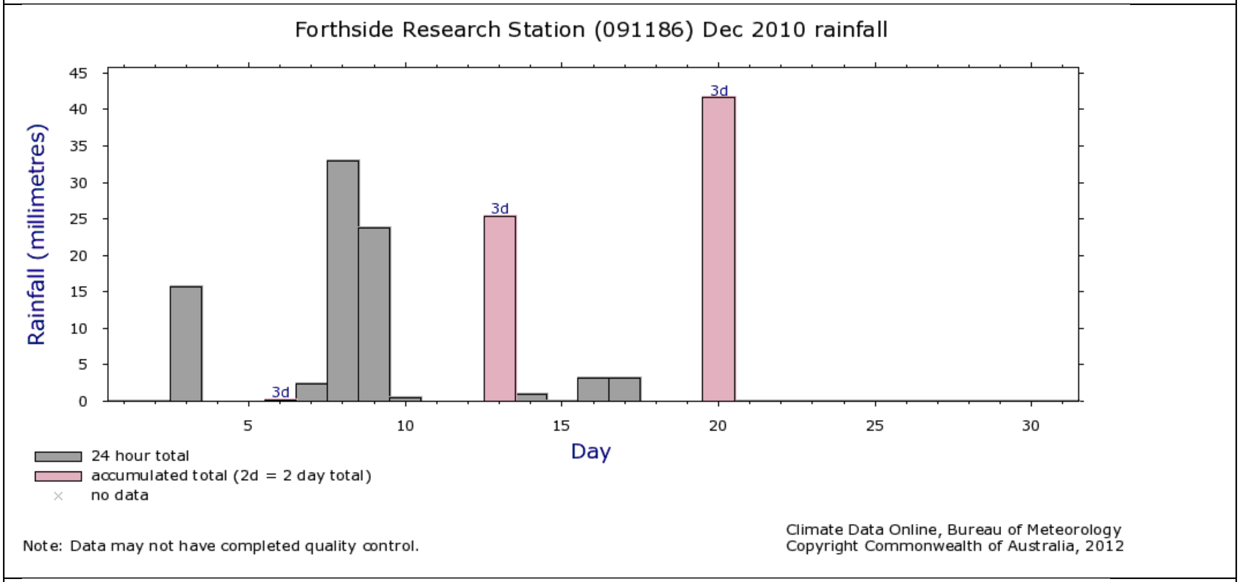


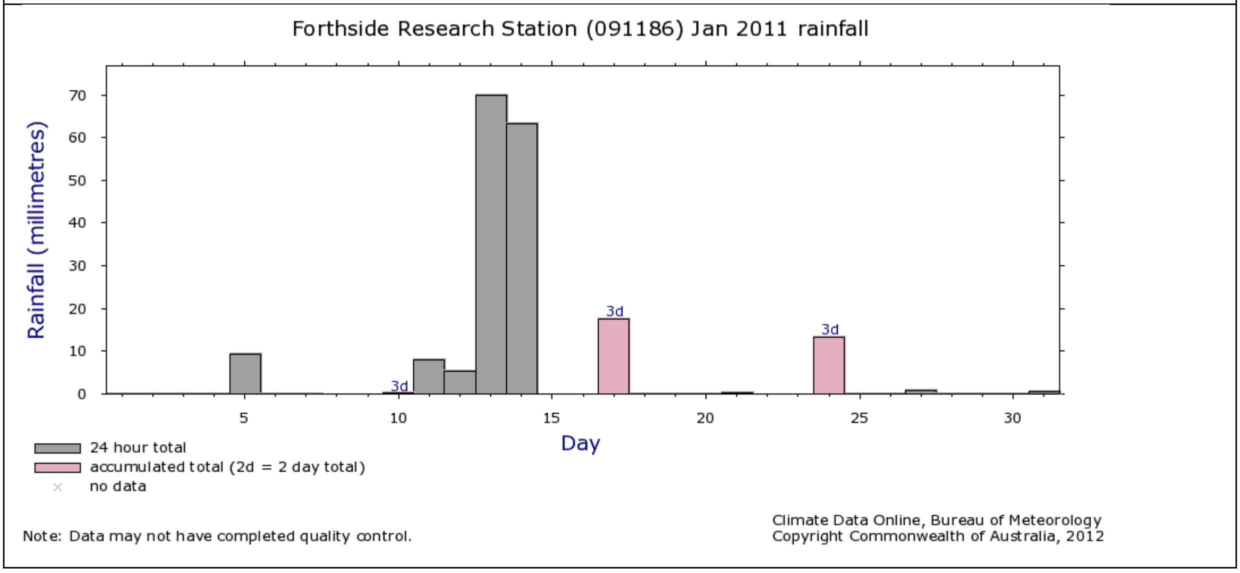


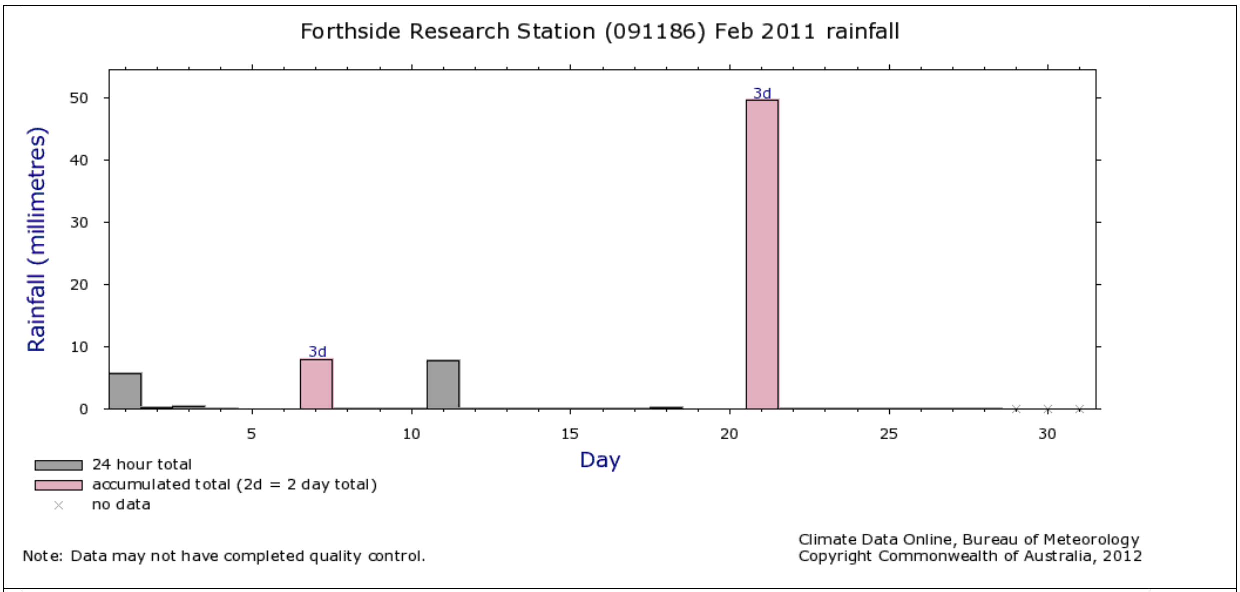
Appendix II Rainfall Nov-March 2010/2011 (BOM online)

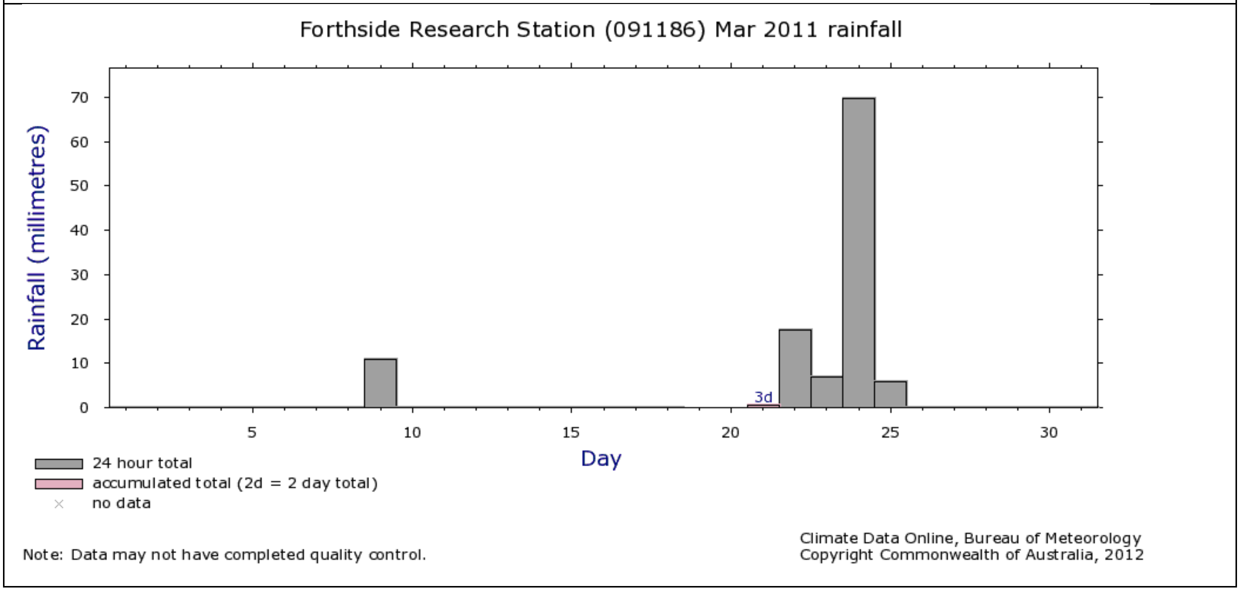
http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=2011&p_c=-1670253024&p_stn_num=091186





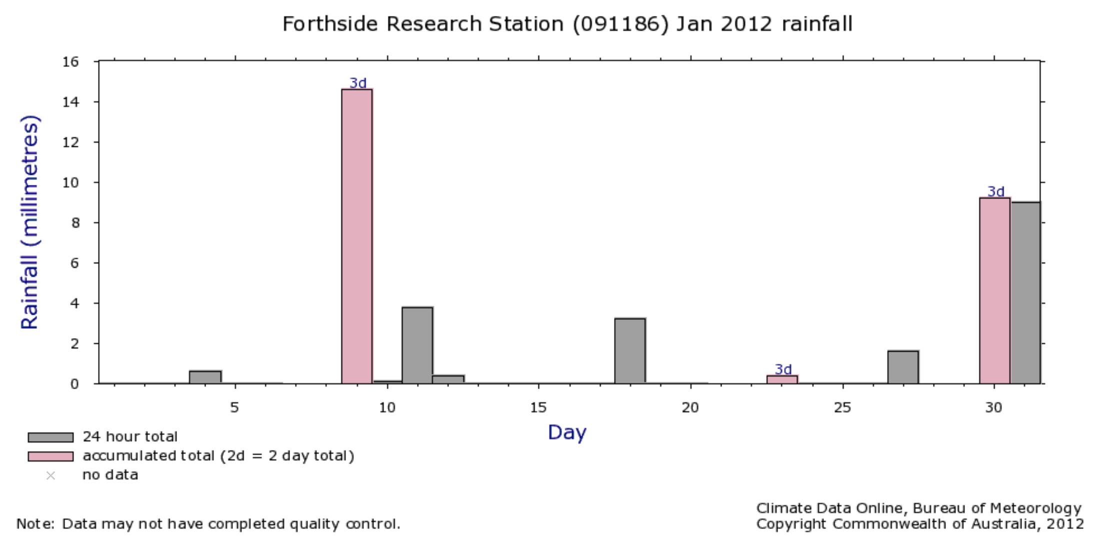


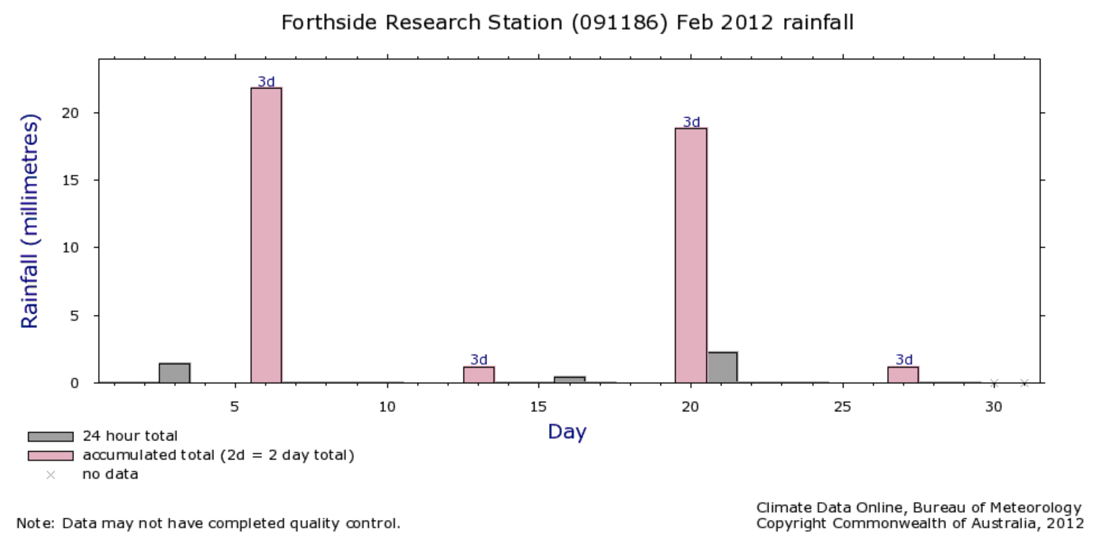

Forthside Research Station (091186) Feb 2011 rainfall
Rainfall (millimetres)
0
10
20
30
40
50
3d
3d
5
10
15
20
25
30
Day
24 hour total
accumulated total (2d = 2 day total)
no data
Note: Data may not have completed quality control.
Climate Data Online, Bureau of Meteorology
Copyright Commonwealth of Australia, 2012

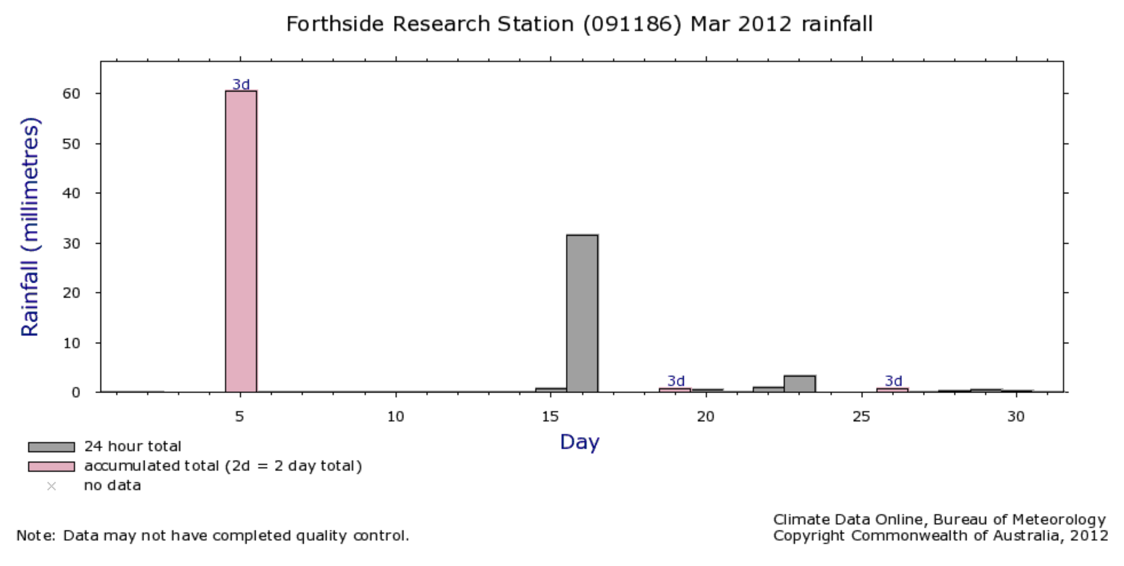

Forthside Research Station (091186) Mar 2011 rainfall
Rainfall (millimetres)
0
10
20
30
40
50
60
70
3d
5
10
15
20
25
30
Day
24 hour total
accumulated total (2d = 2 day total)
no data
Note: Data may not have completed quality control.
Climate Data Online, Bureau of Meteorology
Copyright Commonwealth of Australia, 2012

Appendix III Rainfall Jan-March 2012 (BOM online)

http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=2012&p_c=-1670260266&p_stn_num=091186



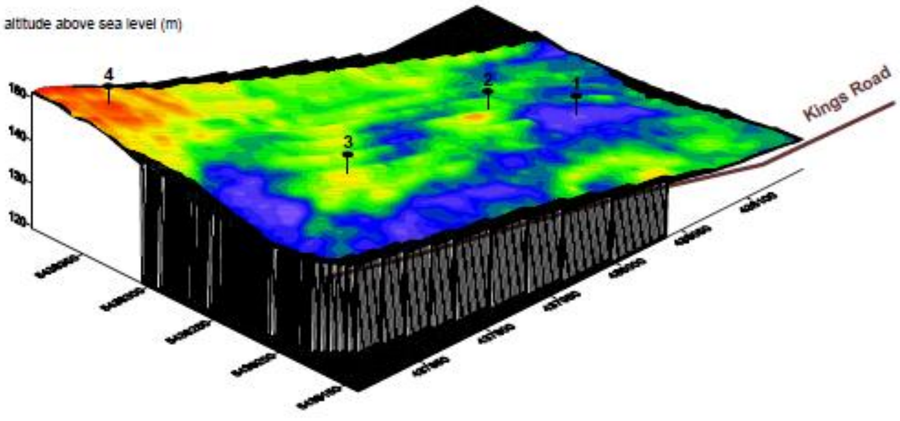


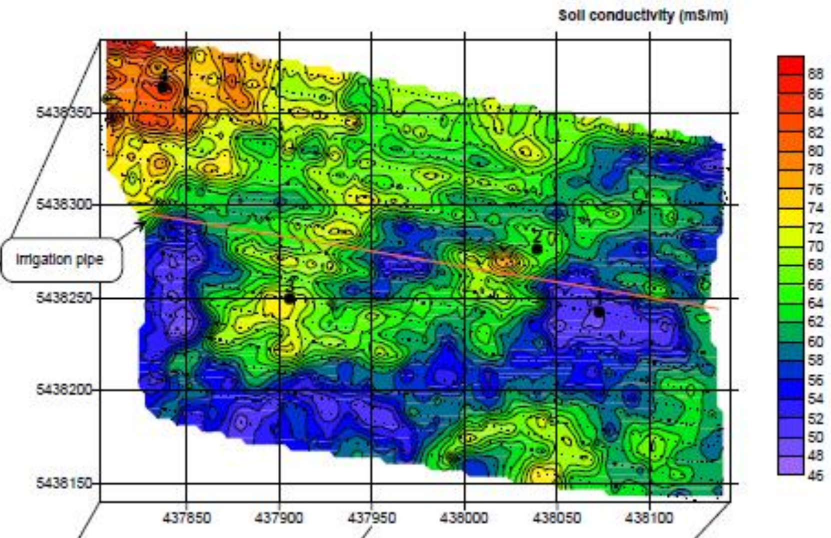


Appendix IV EM38 Map (Forthside, Paddock No. 1 2009)

TERRAPIX
www.terrapix.com.au

Forthside Research Station
EM38 soil survey
15 September 2009
6.5 hectares





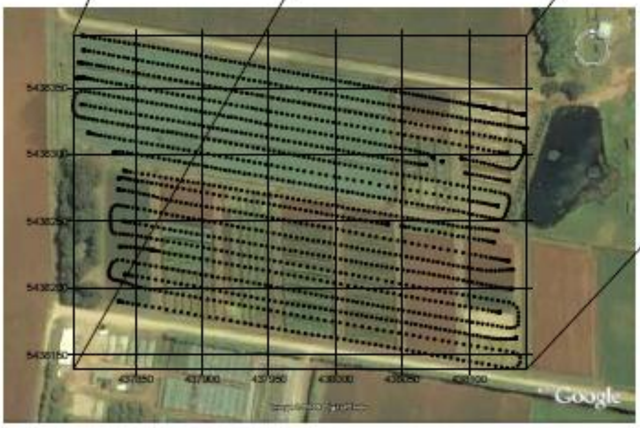
N

EM38 soil conductivity data captured at 1 sec interval & 10 m transects onto Earth's surface using non-differentially corrected GPS.

0 50 100 m

Datum - GDA 94
Aerial photograph sourced from Google Earth

EM38 soil mapping measures the apparent electrical conductivity (ECa) of soil. Factors such as soil moisture content, salt levels and soil texture affect the concentration of conductive materials and influence this measure.



Suggested Soil Sample Site Coordinates

East	North	Site
438072.634775	5438242.46826	1
438039.124615	5438276.43126	2
437905.48021	5438249.7137	3
437837.10137	5438363.88599	4