BROADBAND AND THE SUSTAINABLE USE OF WATER RESOURCES

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Agriculture accounts for more than seventy percent of total fresh water consumption. Water use efficiency in the industry is often less than fifty percent. A changing climate and increasing competition for fresh water are stressing water supplies globally and limiting the scope for further expansion of agriculture to meet growing food production requirements. This situation is threatening the economic viability of many agricultural regions both in Australia and around the globe. It is a national imperative to develop solutions that will sustain this vital industry in the future.

Improving water use efficiency through better irrigation practices is one method for coping with these challenges. Costs associated with capital outlays and engineering complexity are barriers to widespread adoption of efficient irrigation technologies. This paper presents a platform that leverages broadband communication networks to reduce these barriers to technology adoption and thereby vastly improve water use efficiency in agriculture. Results from recent field trials are presented that demonstrate increases in water productivity in dairy pasture and horticultural production.

1. INTRODUCTION

It is widely accepted that Australia will experience diminishing supplies of fresh water in the coming decades. This will be caused by a combination of a changing climate and demand pressures (PMSEIC 2007). In Australia, agriculture accounts for almost 70% of total fresh water consumption, and irrigated agriculture represents 90% of this total volume (ABS 2006). With such a high reliance on a dwindling resource, the irrigated agricultural sector, and the rural communities reliant upon it, will be severely impacted by this "water crisis". This paper focuses on irrigated agriculture; however the concepts described herein can be applied equally well to numerous other water users.

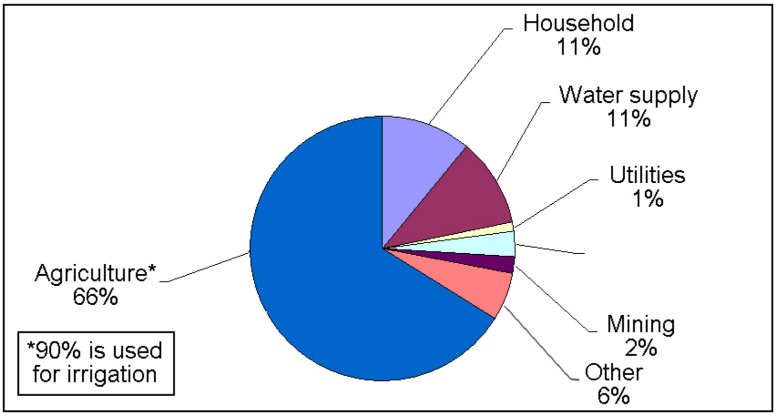

Figure 1 Breakdown of water consumption in Australia during 2004–05

In a landmark report, the United Nations Educational, Scientific and Cultural Organization (UNESCO) has suggested that the aforementioned water crisis is equally a "water resource management" problem as a "water resource shortage" problem (UNESCO 2003). Water resource management is a multi-disciplinary field and considers varying spatial and temporal scales. Long-term management, such as balancing water uses and allocations across large regions, must be complemented by short term decisions such as irrigation practices on the farm. This paper addresses the latter, short-term decisions.

Water use efficiency (WUE) is a widely used metric to gauge the performance of water management strategies in agriculture. Three commonly used definitions include (Marlow 1999):

1. *Economic efficiency*: The value of product(s) produced per unit of water volume consumed ($/ML).
2. *Technical efficiency*: The mass of agricultural produce per unit of water consumed (kg/ML).
3. *Hydraulic, irrigation or application efficiency*: The portion of water actually used by irrigated agriculture of the volume of water withdrawn (percentage).

Different irrigated industries rely on different definitions of WUE. Economic efficiency is important in horticulture whereas the dairy industry relies on measurements of hydraulic or technical efficiency.

In (Marsden 2003) it is shown that the average application efficiency in Australia measured across a collection of irrigated industries is close to 50 percent, ranging from 30 percent in flood/furrow irrigation up to 75 percent in cotton irrigation. This statistic highlights that only half of harvested fresh water that is intended for production is actually delivered to the plant, the ultimate user in this case. The remainder is "lost" to farm productivity.

It is also shown in (Marsden 2003) that there is considerable variation in the economic efficiency within each irrigated industry. For example, in pasture for livestock, gross margins range from a low of $30/ML to a high of $120/ML. This points to a range of irrigation practices within a sector that are sub-optimal with respect to "best practice" in the industry. As stated in (Marsden 2003), improving the best practice benchmark and narrowing the variability in each sector is critical as part of a wider solution to the sustainable and economic use of water.

Many factors contribute to sub-optimal WUE. An overriding problem that has been widely studied is the use of deficient irrigation practices on the farm. Examples of this include poor timing of irrigation events and over-watering.

Numerous strategies are employed for raising WUE. These include:

i. improvements to irrigation
ii. (improvements to soil fertility,
iii. (efficient recycling of agricultural runoff and
iv. (soil-water conservation measures through less intensive tillage operations that preserve crop residue from previous plantings, thereby improving soil moisture storage capacity.

Irrigation has received the most attention as it has the greatest impact on productivity outcomes. Novel irrigation technologies include:

i. deficit irrigation (limiting irrigation to plant growth stages that have greatest impact on yield) and
ii. drip irrigation (targeting irrigation inputs to the plant root zone).

Despite the proven benefits of better irrigation practices, widespread adoption is still slow. Two key impediments are:

i. unreliable water supply infrastructure and
ii. high capital outlays on the farm (GoWA 2006).

Water supply infrastructure has largely remained untouched over the last century. In many regions, water allocations for irrigation need to be ordered one or more weeks in advance and with limited guarantee that orders will be fulfilled. There is a growing awareness, at both state and federal levels, of the need to upgrade existing water distribution networks to ensure a reliable and timely supply. As an example, the State Government of Victoria is investing $2 billion to modernise gravity-fed open canal networks in the Goulburn-Murray Irrigation District (GoV 2008).

However, today there is no such large-scale effort to address the second impediment listed above. The anticipated availability of "water on demand" (Mareels et al 2005) and the use of low cost wireless sensor networks on the farm, coupled with carrier-grade broadband networks, have the potential to revolutionise irrigation operations and management across the country.

It is important to note, however, there are irrigated agricultural sectors that have adopted efficient practices. Nevertheless, by and large most irrigation operations in Australia and around the globe are predominantly manual and labor intensive. Therefore there is considerable scope for improvement.

This paper presents innovations in information and communication technologies (ICT) that can be used to better manage irrigation on the farm, to optimise WUE and to maximise profitability and sustainability across entire irrigation regions. As described above, high capital outlays are a key barrier to the widespread adoption of new irrigation technologies in agriculture. This paper addresses this fundamental problem by proposing a **service-based** model for managing irrigation. It is shown here that wide coverage, high throughput, and low latency communication networks are a core enabling component. Only carrier-grade broadband networks meet this requirement. This work is the result of a four-year collaborative research program involving NICTA Ltd and The University of Melbourne and supported by the State Government of Victoria (Business Victoria 2006).

This paper is structured as follows. Section 2 outlines the physical system under consideration. Section 3 outlines the concept of precision irrigation. Section 4 outlines a new service-based model for precision irrigation. Section 5 presents results from a series of pilot trials that improved water use efficiency on the farm in several enterprises.

2. IRRIGATION REGIONS – INFRASTRUCTURE AND OPERATION

Figure 2 is a schematic representation of a typical irrigation region considered in this paper. Water is delivered to farms via a water distribution network typically composed of gravity-fed open canals. The water distribution network sources water from a reservoir and river system.

Farms operate internal water distribution networks to deliver water, extracted from the distribution network off-take, to the individual fields, orchards, or paddocks.

The scale of irrigation regions is substantial. One of the largest such network in Australia operates in the Goulburn-Murray Irrigation District, covering an area of 68,000 km^2 and over 21,000 farm off-takes (Mareels et al 2005).

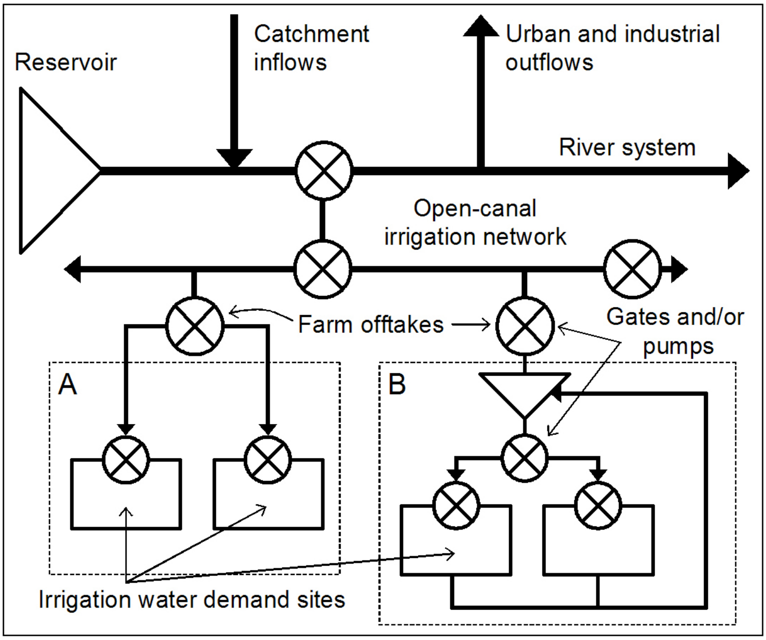

Figure 2 Schematic representation of an irrigation region

Farms are diversified enterprises with multiple demand sites. Demand sites are the primary production units on the farm. In some cases, farms extract water from the distribution network to on-farm storage ponds. Locally stored water is distributed to demand sites using the internal distribution network. Excess runoff water from irrigation re-enters the water hydro cycle through groundwater recharge and in some cases is routed back to on-farm storage. Internal distribution networks range from open canals for flood irrigation to sophisticated pressurised systems serving centre-pivot and drip irrigation.

Figure 2 illustrates two representative internal water distribution networks on farms. In **Network A** water is extracted from the distribution canal and routed directly to the demand sites, excess runoff is not captured. **Network B** employs on-farm storage; a combination of open canals and a pressurised pipe distribution network deliver water to the demand sites and route excess runoff back to the on-farm storage.

Requests for water are often flow set-points at the farm off-take. It was stated earlier in this paper that farms often request water days or weeks in advance of irrigation. This is due to low hydraulic efficiency of water distribution networks, many of which are operated manually. Recent advances in open-channel automation have improved this situation and removed a long standing barrier to wider adoption of new irrigation technologies on the farm (Nayar and Smith 2007).

The above description highlights the structural variability and complexity of farming systems. It is this lack of uniformity that hinders the development of turn-key solutions in irrigation. This also shows that scalability is a critical requirement for any technology platform to be applicable across an irrigation region.

3. PRECISION IRRIGATION – STATE-OF-THE-ART PRACTICES

This section presents state-of-the-art methods for scheduling irrigation events on the farm. The techniques outlined here form the basis of the new model proposed in the section 4.

Irrigation scheduling is a process that determines the timing and quantity of water to apply to a plant. Irrigation scheduling generally has the largest impact on plant growth, productivity and WUE. This process also determines when and how much water should be delivered to the farm.

The most common approach is to apply a fixed volume of water at regular time intervals, conditional upon prevailing weather forecasts. The reason for this heuristic approach is largely historical and based on experience. The outcomes are inefficient because fixed-schedule irrigation often leads to over-watering since too little water can have adverse effects on yield (Mareels et al 2005).

Conventional irrigation scheduling takes limited notice of a plant's water requirements. Closer monitoring a plant's physical state can be used to vastly increase yield per unit input of irrigation water (Jones 2004). This is the basis of a process called *precision irrigation scheduling*. Precision irrigation involves sensing a plant's physical state in real-time and using this data in a feedback control system that automatically delivers water to the plant's root zone to track a specified reference physical state. The reference state is selected to optimise biomass, fruit quality/size, or other relevant metrics. Examples of physical state include soil moisture, canopy or leaf temperature, sap flows in the plant stem or infrared signature. Figure 3 illustrates the main elements of a precision irrigation network.

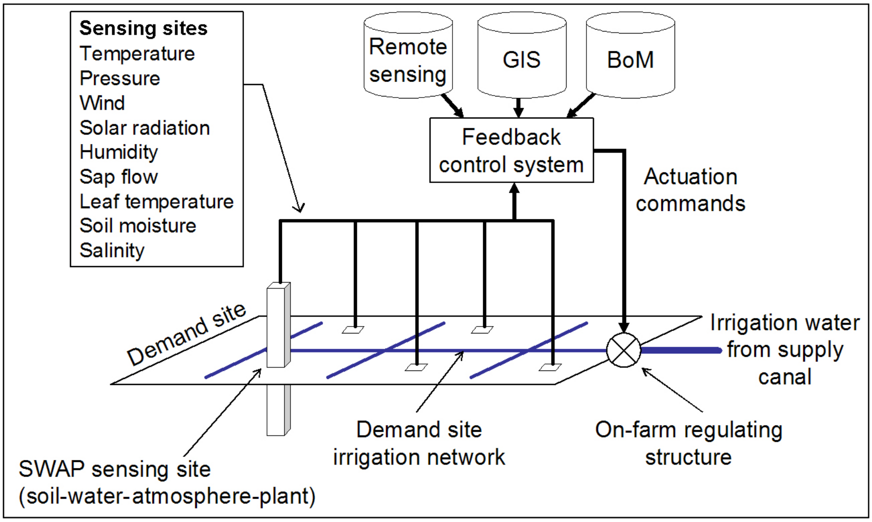

Figure 3 Precision irrigation network

Each demand site contains one or more locations for measuring plant physical state. Measuring the physical state of a plant is achieved by sensing in and around the plant, including the soil and atmosphere. This may require the deployment of many sensors in the field. As an example, when measuring soil moisture, a single sensor is not often sufficiently accurate. Most practical applications require measurements of soil moisture at multiple depths along the root zone, and a measurement of temperature both within and above the soil sub-surface. There is also an increasing use of satellite-based remote sensing data sources and the incorporation of GIS data sets such as soil type maps and salinity data to complement on-farm sensor suites. It is widely expected that to realise this scale of sensing on the farm, wireless broadband sensor networks (WSNs) will play a key role in this space. This is the subject of section 3.1.

The purpose of the feedback control block is to automatically trigger irrigation commands using measured data and employing plant process models to track a reference physical state. This process ensures demand sites receive the right amount of water at the right time and is the key to efficient water use in irrigated agriculture.

An interesting research question is how to set the reference physical state. One approach is to use the concept of potential evapotranspiration to establish the amount of water that could be evaporated and transpired if there was sufficient water available. Comparing potential evapotranspiration to the actual evapotranspiration provides one measure of the soil moisture deficit. Measurement of evapotranspiration is a complex process requiring elaborate, and often expensive, sensor suites. However, satellite-based remote sensing services have been successfully used to accurately estimate and predict evapotranspiration over large areas (Verstraeten et al 2008). This is an example of how high costs and engineering complexity associated with precision irrigation hinder its adoption. The use of evapotranspiration and remote sensing data is leveraged in Section 4.

Figure 4 illustrates a schedule of irrigation events resulting from the application of precision irrigation in a horticulture application (Cooley et al 2008). In this case the reference state is an acceptable band of soil moisture with values between 41 percent and 37 percent. This is the percentage volume of water per unit volume of soil.

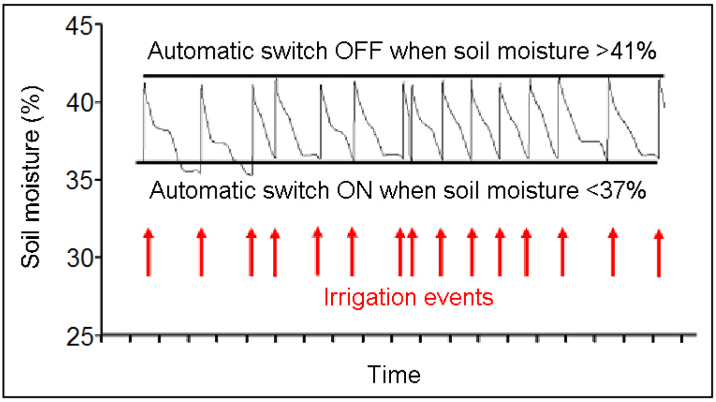

Figure 4 Precision irrigation event schedule in a horticulture application

An important feature to note in Figure 4 is the variability in the interval between irrigation events. This translates to more frequent and shorter-duration requests for water at the farm off-take. Manual water ordering is not practical in this case. This indicates that implementing precision irrigation requires an automatic water ordering system. A broadband communication network has a clear role to play in this case.

In summary, Figures 3 and 4 tell us there are three key elements needed to successfully implement precision irrigation on the farm:

1. Extensive use of on-farm sensing,
2. Linking on-farm feedback control systems to remote data sources and,
3. An automatic water ordering system.

It has been emphasised that high cost and engineering complexity are barriers to the wide scale adoption of precision irrigation. Points two and three above outline a role for broadband networks. Linking on-farm systems to remote data sources and order processing systems requires a reliable, cost-effective and geographically scalable communication system; only carrier-grade broadband networks meet this requirement.

Carrier-grade broadband networks are not suited to on-farm sensor networks however. Today's WSN solutions, such as Zigbee™, may have a place on the farm. Experience has shown that there is still a large degree of engineering complexity and cost when deploying WSNs on the farm. Furthermore, low-rate networks, including Zigbee™, are not capable of supporting the data rates expected from sophisticated on-farm sensors, such as infrared imaging devices. Recent developments in RF technology for high-rate, short-range, small-scale wireless sensor networks, could offer the correct balance between cost and throughput to enable mass deployments of wireless sensor networks on the farm. This is briefly discussed in the following section.

3.1. MILLIMETRE WAVE – NEXT GENERATION ON-FARM BROADBAND NETWORKS

Before wireless sensor networks become commonplace on farms, they must be:

i. easy to deploy,
ii. require minimum configuration,
iii. have low total cost of ownership, and
iv. provide a seamless interface between radio and sensor devices.

To date, no technology meets these requirements. In addition, current systems including Zigbee™, Bluetooth™ and IEEE 802.11 have insufficient bandwidth, are power inefficient or cost prohibitive for deployment in applications on the farm.

Millimetre-wave technology, utilising the region of spectrum ranging from 30 to 300 GHz, promises to allow a next generation of on-farm sensing. Sensors utilising this spectrum have a number of benefits over current technology including significantly larger bandwidth, reduced interference, and most critically, a reduced form factor due to higher levels of integration. The ability to integrate radios and sensors into a single unit results in a dramatic reduction in engineering complexity and total cost of ownership.

Numerous international regulatory bodies including the Federal Communications Commission (FCC) have allocated up to 7 GHz of continuous unlicensed spectrum between 57 ~ 66 GHz. This allocation experiences reduced interference and is ideally suited for high data rate wireless communications. An important advantage of this technology is the integration of mesh and low-power mode networking protocols that facilitate easy deployment and minimal configuration. The protocols are defined in the standards IEEE 802.15.3c and IEEE 1451.

The maximum possible data rate of a channel is given by the Shannon Capacity. This figure is directly proportional to the bandwidth and transmission power. Figure 5 compares the designated unlicensed regions showing significantly greater bandwidth that the 60 GHz channel offers over other systems. Typical state-of-the-art WSN systems utilise spectrum at 2 bits/second/Hz. As an example, the total bandwidth for all possible IEEE 802.11n channels is ~660 MHz, with each channel 40 MHz, compared to a total bandwidth for the 60 GHz channels of 7 GHz with each channel 2.5 GHz allowing in excess of 80 times the maximum possible data rate.

An absorption peak due to the attenuation of oxygen molecules exists in the 60-GHz channel. This attenuation reduces the interference from distant sources and neighboring sensors. Whilst this characteristic reduces the transmission distance to within a range of ~500 metres, it also allows for higher density of sensors.

Utilising millimetre waves and higher transmission frequencies in general dramatically reduces the form factor of devices, including the antenna. This allows for integration of very small high-gain arrays leading to higher efficiency than conventional omni-directional antennas at lower transmission frequencies. These arrays result in a more focused beam with a greater proportion of the transmit energy in the intended direction and are able to be implemented with the radio in a single package.

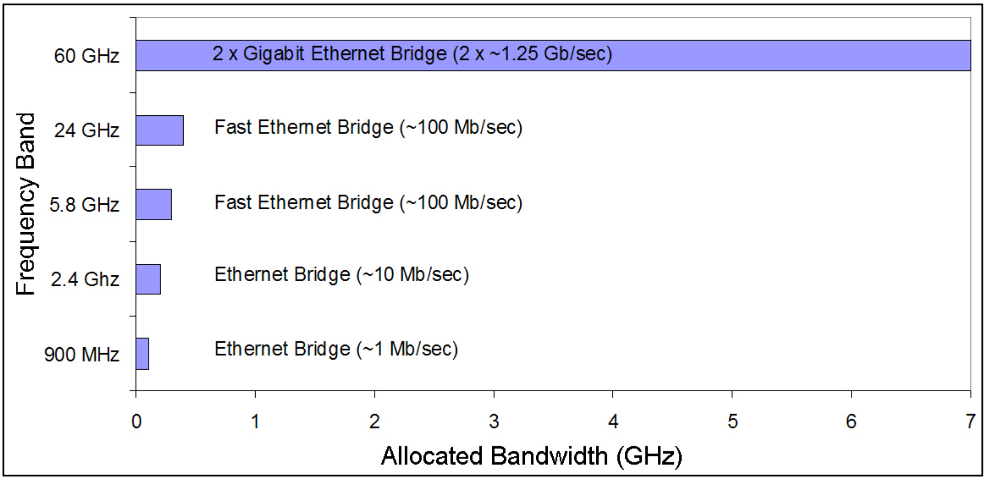

Figure 5 Comparison of effective data-rates across commonly used WSN frequencies

4. PRECISION IRRIGATION – A NEW SERVICE-BASED MODEL

This section outlines a novel *irrigation-as-a-service* (IaaS) model. Providing precision irrigation as a service to farmers will increase the uptake of the technology by reducing capital outlays on the farm. A broadband communication network underpins this approach.

Figure 6 illustrates a simplified architectural overview. Irrigation Service Providers (IrSPs) lease precision irrigation ICT infrastructure to farmers. The leased infrastructure includes wireless sensor/actuator networks deployed across demand sites and local feedback controllers. In addition to leasing infrastructure, IrSPs would provide the following services:

1. Local feedback controller tuning,
2. Local network troubleshooting and maintenance,
3. Water ordering,
4. Water accounting and,
5. Specialised data services using remote sensing inputs, such as accurate weather forecasting, soil maps, evapotranspiration estimation, runoff analysis, disease and pest onset prediction and nutrient analysis.

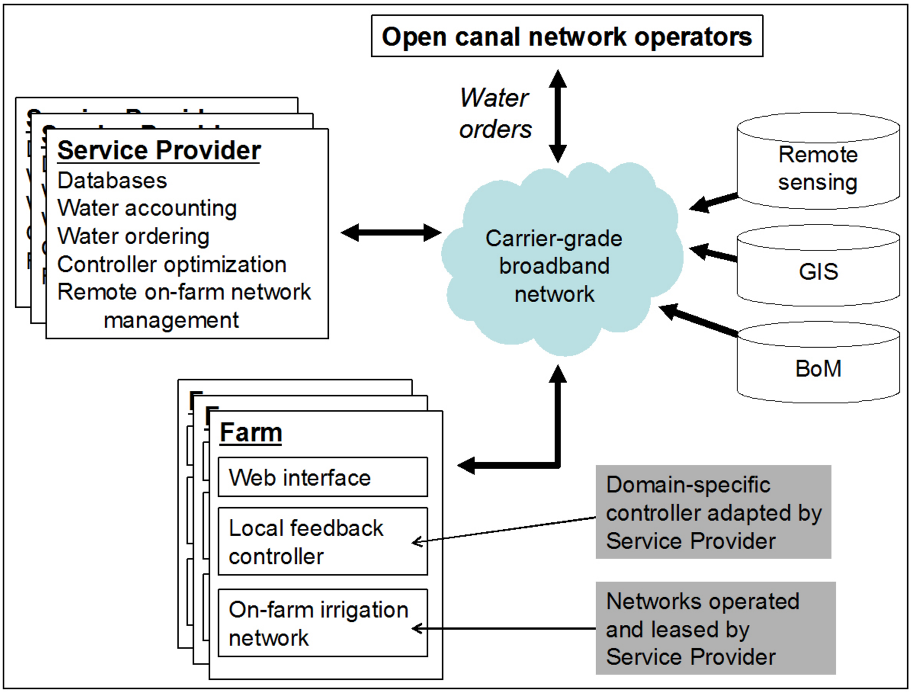

Figure 6 Irrigation-as-a-Service architecture

IrSPs collect data from a number of sources including sensor systems on the farms, remote sensing systems, GIS datasets and weather forecasts. This data is combined and used to tune local feedback controllers on the farms.

The following is an example of this tuning process where soil moisture in the plant's root zone is used to trigger irrigation events. Each farm demand site is equipped with a local feedback controller that tracks a reference soil moisture value by comparing it to a measured value obtained from sensors located in the soil. The controller triggers irrigation events, which may include setting flow at a gate or a pump. The configuration parameter at the local controller on the farm is the reference soil moisture value. Each demand site will have a different reference value. As described in Section 3, it is possible to use the difference between the actual and potential evapotranspiration to accurately determine the reference values. The IrSP collects on-farm data from the local sensor suites and remote sensing data sources to estimate and predict evapotranspiration across varying spatial and time scales. The IrSP then remotely configures local controllers as required.

This highlights the one of the most important advantages of the IaaS model. The use of evapotranspiration estimates for calculating plant water requirements is a well-known and standardised approach to precision irrigation (Ishigooka et al 2008). However, implementing the approach requires the use of extensive sensing both on and off the farm. The capital outlays associated with the installation of sensing equipment, gathering and processing the data often detract farmers from adopting the technology. The IaaS model presented, in conjunction with a carrier-grade broadband network, is the path to widespread adoption of precision irrigation in agriculture.

5. A CASE STUDY IN THE GOULBURN VALLEY

A recently completed case study in Victoria's Goulburn Valley demonstrates the benefits of the proposed IaaS architecture in improving WUE and productivity in irrigated agriculture (Dassanayake 2007). A pilot network was created, consisting of five independent farm networks. The farm networks were set up to cover major irrigated agricultural enterprises in the northern irrigation districts of Victoria, including dairy and horticulture.

Figure 7 shows locations of on-farm field sites strategically located across the northern irrigation areas. Individual sites were connected to an IrSP server at the University of Melbourne's Dookie Agricultural College via a 3G broadband network. This provided remote access to each local control site and enabling local sites to be controlled centrally.

On-farm wireless networks used unlicensed 2.4GHz radio system employing mesh networking technology. The primary on-farm sensor suite consisted of multi-depth soil moisture sensor nodes, as well as ambient temperature, relative humidity, barometric pressure, net radiation, rainfall and wind direction and speed for estimation of evapotranspiration. Actuator nodes employed were variable flow gates in the dairy trials and latching solenoids in the horticulture trials.

The results of the dairy trials are summarised in Table 1 (Dassanayake 2008). The manual approach is a heuristic approach with water applied on a fixed schedule. The gross margin has been computed assuming a cost of irrigation water at $40/ML. The water savings, assuming runoff is re-used, is 23 percent per season. There was a 27 percent improvement in water productivity and a 38 percent improvement in gross margin.

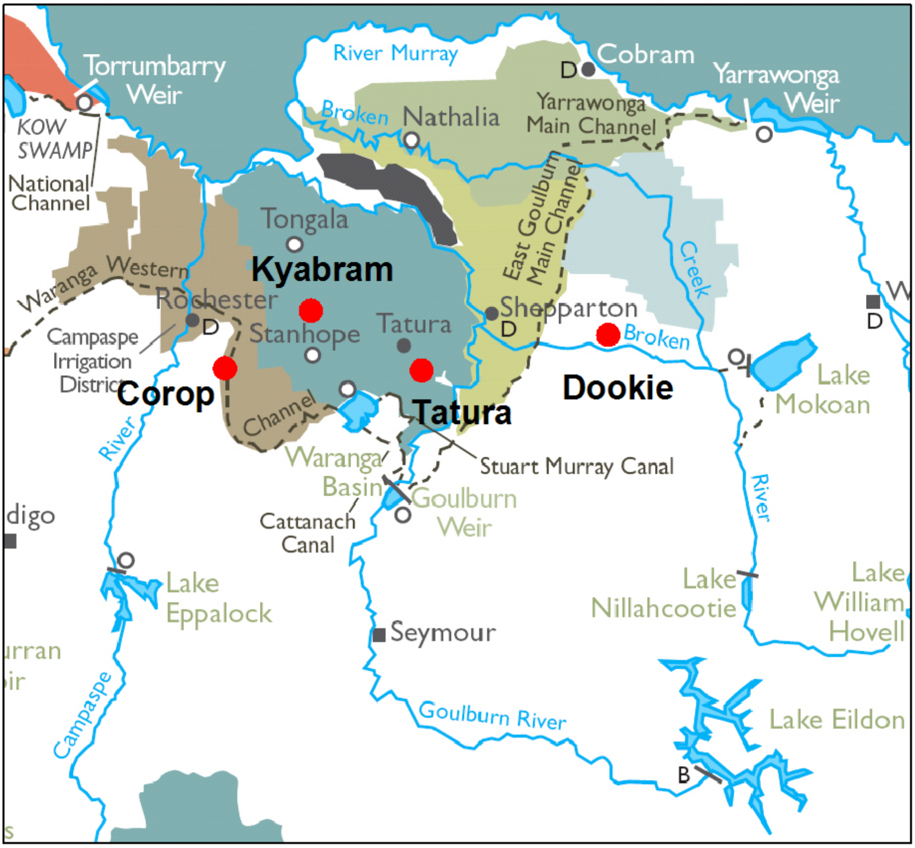

Figure 7 Case study test sites

Irrigation system	Total volume of water consumed each season (ML/ha)	Productivity (tonnes dry matter/ML)	Gross margin ($/ha/yr)
Manual irrigation	11.25	1.32	550
Automated irrigation using only soil moisture	8.27	1.81	760

Table 1 Results of dairy trials

The benefits of the proposed IaaS architecture have been demonstrated through pilot trials across a range of farming enterprises. A practical implementation of such a system over a wide area incorporating thousands of users is underpinned by a reliable and scalable communication network. Only carrier-grade broadband networks can meet this challenge.

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