



Review of Precision Irrigation Technologies and their Application

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Toowoomba**

A Report for National Program for Sustainable Irrigation

*NCEA Publication 1003017/1
November 2010*

University of Southern Queensland





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This document should be cited as follows:

Smith, R.J., Baillie, J.N., McCarthy, A.C., Raine, S.R. & Baillie, C.P. (2010) Review of Precision Irrigation Technologies and their Application. National Centre for Engineering in Agriculture Publication 1003017/1, USQ, Toowoomba.

Acknowledgments

This review was funded by the National Program for Sustainable Irrigation (www.npsi.gov.au).

The National Program for Sustainable Irrigation is a partnership of Australian Government Department of Environment, Water Heritage and the Arts, Cotton Research & Development Corporation, Gascoyne Water Co-operative, Goulburn-Murray Rural Water Corporation, Grains Research & Development Corporation, Harvey Water, Horticulture Australia Limited, Lower Murray Water, Ord Irrigation Co-operative, South Australian Research and Development Institute, Sugar Research & Development Corporation, SunWater, and Western Australia Department of Water.

We are grateful to our many colleagues at USQ and from a number of other organisations for sharing their experience with various irrigation tools and technologies and for helpful advice in compiling this report.

We would also particularly like to thank those colleagues who gave permission to include examples of their work in the case studies presented in this report.

ISBN 1 921025 29 8

NPSI Publication Reference NPSI 6-10

EXECUTIVE SUMMARY

Precision Irrigation

An irrigation system that:

1. knows what to do;
2. knows how to do it;
3. knows what it has done; and
4. learns from what it has done.

The Review

Precision irrigation is still in its infancy both in Australia and internationally. Despite the widespread promotion and adoption of precision agriculture in dry land cropping systems, the concept of precision irrigation or irrigation as a component of precision agricultural systems has not been widely canvassed nor its potential evaluated. This report is the outcome from a NPSI funded review of relevant irrigation research, existing technologies and the use of precision irrigation. It includes an assessment of the role of current irrigation application technologies in precision irrigation, as well as variable rate applications, adaptive control and the sensing and decision support requirements. The review also provides a framework to guide research and development of precision irrigation and its associated sensing, control, and decision support technologies.

The aim of the review was to detail the current state of the art of precision irrigation, including:

- an agreed conceptualisation and definition of precision irrigation,
- conceptualisation of how precision irrigation might be implemented for each of the current irrigation application systems (sprinkler surface and micro), including as appropriate the sensing, control and decision support requirements,
- identification of opportunities for and potential benefits from precision irrigation,
- identification of current research in precision irrigation and more particularly a clear direction for future research in precision irrigation, and
- development of a series of case studies where precision irrigation is being implemented in whole or part.

It is significant that no systems were identified in this country that could truly be classified as precision irrigation systems. However research is active in a number of areas relevant to precision irrigation and many of the component tools and technologies have been or are being developed. Examples of these are illustrated in the case studies included throughout the review and include:

- use of management zones in horticulture,
- automation of surface irrigation,
- real-time optimisation of surface irrigation,
- spatially varied applications from centre pivot and lateral move machines,
- vision sensing of crop attributes, and
- irrigation scheduling using remotely sensed crop factors.

Conceptualisation

Precision farming requires a real-time knowledge regarding the processes which are limiting production at any time in all areas of the field. The experience from precision agriculture suggests that the variables controlling crop yield are those that require within season management (e.g. water, nitrogen, pests and diseases), in other words those requiring an automatic response. It also suggests that the temporal variations (within and between seasons) are greater than the spatial variability that the variable rate technologies attempt to address.

Experience also suggests that the practice of precision agriculture might be far more effective when applied in irrigated rather than dry-land agricultural systems. It might also be possible that spatially varied inputs to production (other than water) will be less necessary for irrigated crops as the improved water management reduces the significance of variations in the other inputs. The role of irrigation as a spatially varied input to production is a natural extension of its present and primary role of minimising the temporal variation in crop water supply.

The move toward precision irrigation implies a system that can adapt to the prevailing conditions. Also implied is the idea that the system will be managed to achieve a specific target which, for example, may be maximum water use efficiency, maximum yield or maximum profitability.

It is likely that the control requirements will be specific to the irrigation application system employed. However, in all cases there will be a need to:

- sense the water application and crop response at a scale appropriate for management,
- make a decision for improved irrigation management using both historical (and possibly predictive) data, and
- control either the current (in real-time) or subsequent irrigation applications at an appropriate spatial scale.

This leads directly to the conceptualisation of a precision irrigation system as one that can:

1. Determine the timing, magnitude and spatial pattern of applications for the next irrigation to give the best chance of meeting the seasonal objective (i.e. maximisation of yield, water use efficiency or profitability);
2. Be controlled to apply exactly (or as close as possible to) what is required;
3. Through simulation or direct measurement knows the magnitude and spatial pattern of the actual irrigation applications and the soil and crop responses to those applications; and
4. Utilise these responses to best plan the next irrigation.

A potential stumbling block to the introduction of effective precision irrigation is the necessary understanding of the crop production systems and the ability to identify the interactions between the various crop inputs, the productivity gains and the operating constraints/costs. The relatively recent development of crop simulation models for crops provides the first step towards a framework which may enable the identification of optimal strategies. These models are an essential part of the real-time decision systems required for precision irrigation by incorporation into controllers on irrigation application systems. Limitations of these models aside, the lack of low-cost, non-invasive (proximal) sensors able to provide measures of crop and soil responses across entire fields at relevant

spatial scales means that precision irrigation systems will have to rely on simulation for the foreseeable future.

In conceptualising how the current irrigation application systems can be reinvented as precision irrigation systems, four spatial scales are important. The first of these is the scale at which the irrigation applications can be controlled. This is clearly a characteristic of the application system and varies from about 1 m² for a low energy precision application (LEPA) system on a centre pivot machine up to about a hectare for bay irrigation. The second is the scale of the actual spatial variability in the irrigation applications. In practice this will be the scale at which the variation of the actual applications can be measured or predicted. This will also be the scale at which the crop simulation model will determine the crop response to the irrigation and predict forward in time to predict the effect on yield and water use efficiency. The data at this scale will also be used in planning the next irrigation. In the case of LEPA this will be the same as the control scale but for bay irrigation it could be unit length of the bay. The third scale is the scale of the crop variability which will be related to the root zone extent of the individual plants. The final scale is that associated with any sensing of crop or soil parameters. This will most likely be the largest of the four scales and needs only to be sufficiently frequent to ground truth the relevant simulation model.

Benefits of Precision Irrigation

The published literature contains little on the benefits of precision irrigation and what has been published tends to focus on the single aspect of spatially varied applications.

Precision irrigation has the potential to increase both the water use and economic efficiencies by optimally matching irrigation inputs to yields in each area of a field and either reducing the cost of inputs or increasing yield for the same inputs.

By applying the optimum amount of irrigation throughout fields, most researchers expect a reduction in water use on at least parts of fields and in the total application, if not a reduction aggregated over entire fields. Results from case studies of variable rate irrigation showed water savings in individual years ranging from zero to 50%, and savings averaged over a number of years from 8 to 20%.

There is potential for yield improvements but the data here are far more variable and less conclusive. It is also suggested that the yield benefits may not cover the costs of the technology required. It was also suggested that spatially varied applications increased risk and that the potential economic benefit from it is small when the farmer's tolerance for risk is low. Others suggested that substantial field variability and high crop prices are required for VRI to be profitable. It also depends heavily on the useful life of the equipment, with payback periods from 5 to 20 years suggested for variable rate irrigation in dairy and cropping in New Zealand.

It remains to be seen whether the costs can be reduced significantly or whether a simpler form of precision irrigation is needed that does not involve spatially varied applications.

Research Opportunities

While many of the tools and technologies that will comprise precision irrigation systems are currently available, substantial research and development is required before a truly

precision system is available for testing and adoption by the irrigation community. The R & D opportunities that emerge from the review fall into four categories.

Integration of technologies

Integration of the various component technologies for precision irrigation stands out. Combining the crop and soil sensing with appropriate crop growth simulation models to provide the seasonal decision making model is a necessary first step for all of the major crops. Combining that with the system for the control and optimisation of the particular irrigation application system completes the precision irrigation system. Given the dominant position in the irrigation sector occupied by the various forms of surface irrigation and the substantial gains possible in application efficiency and yield (and hence water use efficiency) this would seem the likely priority area.

Technical feasibility

The technical feasibility of precision irrigation needs to be established at two levels, conceptual and practical. At the conceptual level, simulation can establish the optimum spatial scales for the range of crops and application systems. This will account for the spatial limitations of the application system, the constraints imposed by the sensing needs and capability, and the ability of the simulation tools to accurately predict the affects on crop growth and yield of small variations in applied depths. This stage must also determine if the diagnostic tools needed to determine the causes of particular crop responses are available and sufficiently accurate. At the practical level, precision irrigation systems need to be proven and demonstrated in field trials across the breadth of the Australian irrigation sector.

Economic benefits

Current and past work has established that there are benefits to be obtained from adoption of precision irrigation (including spatially varied irrigation applications). However it is far from clear if the benefits outweigh the costs by a sufficient margin to warrant the adoption. Work needs to be undertaken across a sufficient range of crops, soils and irrigation application systems to determine where the maximum benefit can be obtained and to direct the priorities for research investment. This will also establish the advantages of full versus staged or partial adoption.

Specifically, quantifying the costs/benefits of full automation of surface irrigation and the agronomic benefits of spatially varied applications for a range of crops appear to be of high priority. It also remains to be shown, via the mechanism of field trials rather than simulation, that adaptive systems can provide substantially greater benefits than simple automation and/or traditional irrigation scheduling.

Component technologies

Development of improved tools and technologies will need to be on-going. However there are some clear immediate needs for particular sensing and simulation tools for the PI systems currently under development. These are:

- low-cost, spatially-distributed, non-invasive sensing of soil moisture and crop response;
- development of a fully deterministic sprinkler pattern model for centre pivot and lateral move machines that can account accurately for varying sprinkler pressure and height, sprinkler pattern overlap, wind, and machine movement;

- Development of a hydraulic diagnostic model for drip irrigation systems capable of interaction with the system control to deliver spatially varied applications;
- Improved crop models sensitive to small variations in irrigation management and with a self learning capability; and
- Verification of the use of short range radar for the measurement of the spatial distribution of rainfall at the sub-field scale.

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1 INTRODUCTION

1.1 Background to Review

Spatial variability in crop production occurs as a result of spatial and temporal variations in soil structure and fertility; irrigation applications; pests and diseases; and plant genetics. It is argued that this variability can be managed and economic benefit from irrigation maximized by meeting the specific irrigation needs of individual management zones through a Precision Irrigation approach.

Despite the widespread promotion and adoption of precision agriculture in dry land cropping systems, the concept of irrigation as a component of precision agricultural systems is still in its infancy both in Australia and internationally. No cohesive framework is available to guide research, development or adoption of its associated sensing, control, and decision support technologies.

This report is a review of published and unpublished information on precision irrigation technologies. It includes review of:

- international experience with precision irrigation,
- current research directed toward the development of precision irrigation,
- technologies that might be adopted as components of precision irrigation systems,
- evidence to support (or otherwise) spatially varied applications, and
- potential benefits from adoption of precision irrigation.

It also includes an assessment of the role of current irrigation application technologies in precision irrigation, variable rate applications, adaptive control and the sensing and decision support requirements. Opportunities for adoption, future research and extension needs are identified.

1.2 Project Objectives

The aim of the review was to detail the current state of the art of precision irrigation, including:

- an agreed conceptualisation and definition of precision irrigation,
- conceptualisation of how precision irrigation might be implemented for each of the current irrigation application systems (sprinkler surface and micro), including as appropriate the sensing, control and decision support requirements,
- identification of opportunities for and potential benefits from precision irrigation,
- identification of current research in precision irrigation and more particularly a clear direction for future research in precision irrigation, and
- development of a series of case studies where precision irrigation is being implemented in whole or part.

1.3 Case Studies

The review has suggested that there are no examples of what might truly be considered as a precision irrigation system in commercial use in Australia. However most of the essential tools and technologies are either available or are the subject of current research and development. The case studies included in this review are some of the best examples of these tools and technologies and serve to illustrate the requirements for a precision irrigation system.

2 DEFINING PRECISION IRRIGATION

2.1 Precision Agriculture

Precision agriculture or farming has been defined as farming with preciseness (Kitchen *et al.*, 1996) or as targeting the inputs of arable crop production according to crop requirement on a localised basis (Stafford, 1996). Various other terms have been employed to describe precision farming, including: site specific, spatially variable, prescription, and variable rate. All of these terms mean essentially the same thing although some people infer slightly different meanings. For example, Rawlins (1996) drew an interesting distinction between precision and prescription farming. He defined precision farming as having the capability to apply inputs precisely when and where they are needed, but identified that prescription farming requires a real-time knowledge regarding the processes which are limiting production at any time in all areas of the field.

Schueller (1997) identified five types of management response to the spatial variability of soil and crop properties within a field. Of these two are particularly important, viz:

- automatic – in which a real time response follows immediately that some variable quantity is measured; and
- temporally separate – in which the appropriate action occurs some time (possibly next season) after the measurement and recording.

In each case there are four essential steps in the process and technologies required (Kitchen *et al.*, 1996): (i) data acquisition; (ii) interpretation; (iii) control; and (iv) evaluation.

Most work on precision farming appears to have been directed toward the application of temporally separate responses, driven apparently by the disciples of GPS/GIS and yield mapping technology. Rawlins (1996) suggested that these and other technologies have made it possible for farmers to apply spatially variable inputs such as variable seeding and fertiliser application rates. However, prescriptions to apply these inputs are typically empirical, based on grid sampling of soil properties. This works reasonably well for P, K, lime and other inputs that don't leach or volatilise. However, Rawlins (1996) further suggested that the variables controlling crop yield are more often water, nitrogen, pests and diseases or other factors that require within season management, in other words an automatic response or at least a very rapid temporally separate response.

In a similar vein, Moore (1998) concluded that varying crop nutrient supply is not necessarily the best management practice in precision agriculture and speculated on how variables associated with crop water and energy supply might be manipulated in the precision agriculture context. To reach this conclusion it is assumed that temporal variations (within and between seasons) are greater than the spatial variability that the variable rate technologies attempt to address.

Although research on spatially varied or precision irrigation is currently being undertaken (this is reviewed in later section of this paper), irrigation is rarely mentioned in the context of precision agriculture. This is despite the fact that irrigation removes one of the

main limitations to crop production. Exceptions are Rawlins (1996) and Buchleiter *et al.* (1997), the latter study being one of the few long-term projects researching the application of precision farming technology to an irrigated crop. Even though the Buchleiter *et al.* study made no attempt to vary the irrigation applications spatially, the results are interesting because intuition suggests that the practice of precision agriculture might be far more effective when applied in irrigated rather than dry-land agricultural systems. It might also be possible that other spatially varied inputs to production will be less necessary for irrigated crops as the improved water management reduces the significance of other input interactions. The role of irrigation as a spatially varied input to production is a natural extension of its present and primary role of minimising the temporal variation in crop water supply.

2.2 What is Precision Irrigation

Irrigation aspires to be and should be a precision activity involving both the accurate assessment of the crop water requirements and the precise application of this volume at the required time. The prevailing wisdom is that precision irrigation should meet the needs of the crop in a timely manner and as efficiently and as spatially uniformly as possible. To achieve this, accuracy is required in irrigation scheduling, and in particular the estimation of how much water to apply, and precision is required in:

- the control of the applications so that only the amount needed to be applied is applied, that is, high volumetric efficiencies; and
- the design of the applications so that each plant or area of the field receive the same amount of water, that is, spatially uniform applications.

An historical hierarchy of irrigation is suggested that parallel the development and adoption of improved water application technologies, viz:

1. Irrigation (the past practice) – simply the application of water to crops;
2. Precise irrigation (the present objective) – ensuring the efficient and uniform application of water to meet the spatial average requirements of the crop; and
3. Prescription irrigation (the future direction) – the accurate, precise and possibly spatially variable application of water to meet the specific requirements of individual plants.

The concept of a Precision Irrigation system as defined in this report differs from the traditional meaning of precision irrigation, that is: applying precise amounts of water to crops; or applying water at precise locations (eg. within the soil profile); or at precise times. This traditional meaning connotes a precise amount of water applied at the correct time, but uniformly across the field. High application efficiencies are a key measure in the traditional definition of precision irrigation.

However for this project, we are defining Precision Irrigation within the context of Precision Agriculture principles. A Precision Irrigation system utilizes a systems approach to achieve 'differential irrigation' treatment of field variation (spatial and temporal) as opposed to the 'uniform irrigation' treatment that underlies traditional management systems. A number of terms are used throughout the literature including precision irrigation, prescriptive/prescription irrigation, site-specific irrigation, variable-rate irrigation and precision differential irrigation. For the purposes of this report, the

term Precision Irrigation has been adopted.

A review of the Precision Irrigation literature brings up a range of definitions, including:

Precision Irrigation involves the accurate and precise application of water to meet the specific requirements of individual plants or management units and minimize adverse environmental impact (Misra et al., 2005; Raine et al., 2007).

The application of water to a given site in a volume and at a time needed for optimum crop production, profitability or other management objective at the site (Camp et al., 2006).

Applying water in the right place with the right amount (Al-Karadsheh et al., 2002).

Irrigation management (depth, timing) based on crop need to defined sub-areas of a field referred to as management zones (King et al., 2006).

There are some common elements to all of these definitions, including:

- Precision Irrigation involves the optimal management of the spatial and temporal components of water and irrigation.
- Precision Irrigation is holistic. It should combine seamlessly the optimal performance of the application system with the crop, water and solute management.
- Precision Irrigation is not a specific technology. It's a way of thinking, a systems approach. Crop yields are optimised through systematic gathering and handling of information about the crop and the field. A range of irrigation management and application technology, sensing, modelling and control technologies are suitable for use in a Precision Irrigation system.
- Precision Irrigation is applicable to all irrigation application methods and for all crops at appropriate spatial and temporal scales.
- Site specific objectives need to be determined. Precision irrigation systems have the potential to fundamentally alter on-farm decision making and to simultaneously achieve the multiple objectives of enhancing input use efficiency, reduce environmental impacts, increase farm profits and product quality.
- A Precision Irrigation system is a continual learning system. Measurement of the engineering, agronomic and economic performance are essential in providing feedback and improvement for the next cycle, ie. 'closing the loop'.

This definition of precision Irrigation is broad and inclusive and reflects that the use of high technology is not essential to the implementation of a Precision Irrigation system. However, it needs to be recognized that an ideal Precision Irrigation system will utilise advanced irrigation management & application technology combined with sophisticated sensing, modelling and control technologies to achieve the best possible performance. An ideal Precision Irrigation system is likely to incorporate:

- Application technology capable of spatially and temporally variable applications;
- Automation;
- Informatics (information and communication technologies); and
- Real time control.

2.3 Key Steps in a Precision Irrigation System

Precision irrigation is best viewed as a management approach defined by the Precision Farming cycle. There are four essential steps in the process and technologies required: (i) data acquisition; (ii) interpretation; (iii) control; and (iv) evaluation.

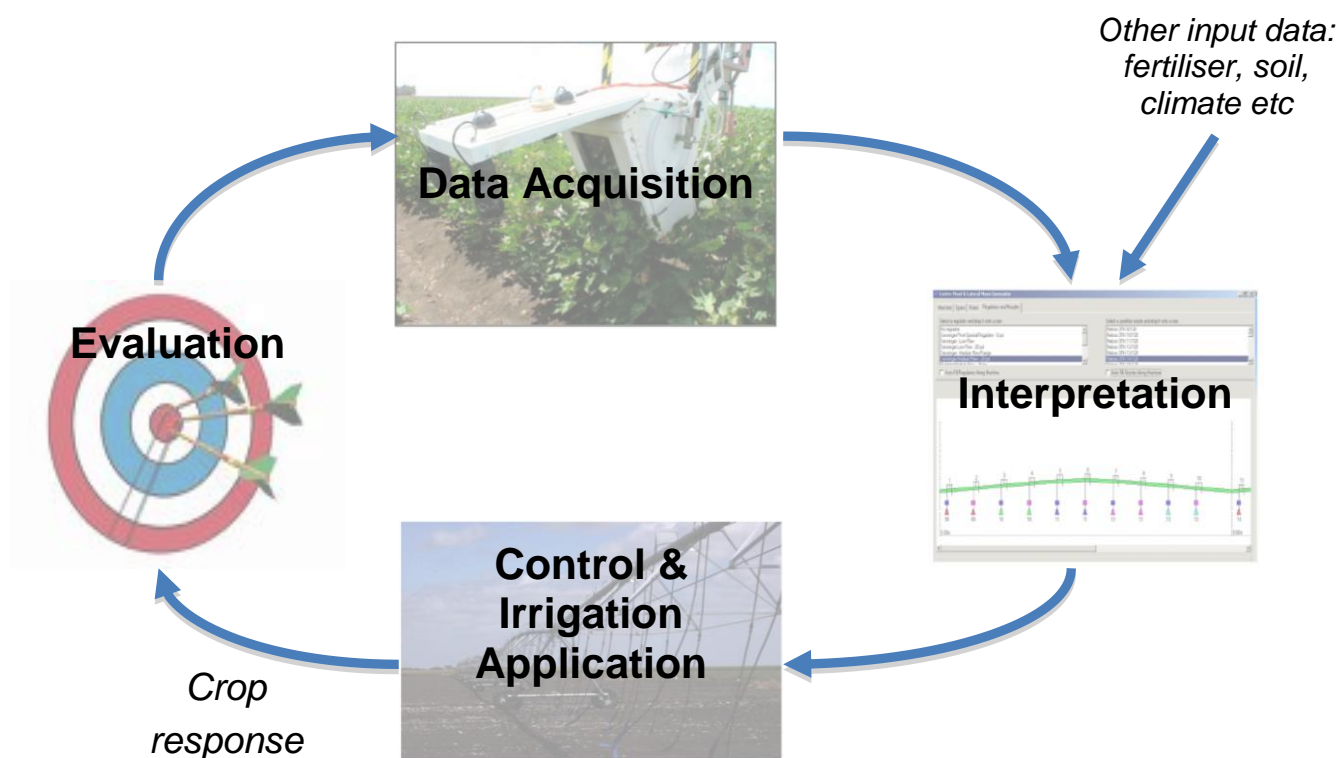


Figure 1 Precision Irrigation Cycle: (i) Data acquisition, (ii) Interpretation, (iii) Control and (iv) Evaluation

Data Acquisition

A Precision Irrigation system requires clear evidence of significant spatial and/or temporal variability in soil and crop conditions within a field and between fields and the ability to identify and quantify such variability.

Existing technology is available to measure the various components of the soil-crop-atmosphere continuum (soil based monitoring, weather based monitoring, plant sensing), many in real-time and at sub-metre scales, and to provide precise and/or real-time control of irrigation applications. A practical limitation will be the density of sensing required.

Interpretation

Data has to be collected, interpreted and analysed at an appropriate scale and frequency.

The inadequate development of control and decision support systems for implementing precision agriculture decisions has been identified as a major stumbling block to the adoption of precision agriculture (McBratney *et al.*, 2005). Appropriate multi-

dimensional simulation tools (incorporating crop response, system constraints etc.) are essential for irrigation optimization.

Control

The ability to reallocate inputs and adjust irrigation management at appropriate temporal and spatial scales is an essential component of a Precision Irrigation system.

Applying differential depths of water over a field will be dependent on the nature of the irrigation system but can be achieved in two ways that is: by varying the application rate or by varying the application time.

Automatic controllers with real time data from on-the-go sensors, should provide the most reliable and potentially accurate means of controlling irrigation applications.

Evaluation

Evaluation or ‘closing the loop’ is an important step in the Precision Irrigation process. Measurement of the engineering, agronomic and economic performance of the irrigation system is essential to providing feedback and improvement for the next cycle in the PI system.

3 RESPONDING TO SPATIAL & TEMPORAL VARIABILITY

3.1 Spatial and Temporal Variability of Crop Performance

Spatial and temporal variability of crop factors within a field can have a significant influence on agricultural production (Zhang *et al.*, 2002) by reducing yield and quality of produce (Raine *et al.*, 2007). For example, there is typically a ten fold variation in wine grape yield across vineyards in any given year (Bramley & Hamilton, 2004). Spatial and temporal variability has also been reported in cotton (Meredith, 1996; Wilkerson & Hart, 1996; and Elms *et al.*, 2001), corn (Chen *et al.*, 2000; Krachenko *et al.*, 2005; and Saddler *et al.*, 2002), wheat (Ciha, 1984; Jin & Jiang, 2002; and Kelly *et al.*, 2004), and vegetables (Barber & Raine, 2002).

The spatial factors responsible for yield variability include irrigation non-uniformity, field topography, fertilizer non-uniformity, genetic variation, soil hydraulic and nutritional properties, microclimate differences as well as pest and disease infestation (Zhang *et al.*, 2002). Climatic factors such as rainfall, temperature and radiation also vary temporally (Zhang *et al.*, 2002). Water commonly plays a leading role among the factors responsible for spatial and temporal yield variability and is a major input resource for precision management (Saddler *et al.*, 2000; Warrick & Gardner, 1983).

Soil properties that are spatially variable within fields include fertility, texture, physical properties, chemical properties and depth (Zhang *et al.*, 2002). Variability of these properties within a field has been found to affect the crop yield. For example, Cox *et al.* (2003) reported that areas in a soybean field with high clay content had higher yield than areas with lower clay content. Similarly, when the application of water or water quality (salinity) is non-uniform in the field, the resulting soil moisture properties may be an important factor in causing spatial variations in crop yield (Sadler *et al.*, 2000).

Yield variability within surface-irrigated fields has been related to the spatial variability of available soil water due to non-uniform irrigation (Palmer, 2005). In this method of irrigation the soil infiltration characteristic and its spatial and temporal variability is the single greatest factor in determining the irrigation performance (Gillies, 2008). The only form of water which can be beneficially utilised by the crops is the soil water (Zhang *et al.*, 1994), and soil water relations have been shown to explain more than 50% of infield yield variability (Irmak *et al.*, 2001). Temporal and spatial management of soil water can significantly increase water use efficiency (Jin *et al.*, 1999).

Meteorological conditions (e.g. rainfall, temperature and sunlight) can affect the crop yield. For example, the climatic conditions during the pre-harvest and drilling stages of the season may significantly alter soil structure and thus affect the crop yield (Landers & Steel, 1994). Wind damage, and infestations of weeds, insects and disease, are also spatially variable and often have a significant effect on agricultural production (Zhang *et al.*, 2002).

In-field spatial variability is dynamic within each growing season and between growing

seasons. Temporal variability occurs both intra-seasonally (that is, time dependent in day steps) and inter- seasonally (that is, time dependent in year steps), respectively. An example of intra-seasonal temporal variability is the day-to-day change in climatic parameters, whereas an example of inter- seasonal temporal variability is the change in weed infestation patterns between growing seasons (Zhang *et al.*, 2002).

3.2 Spatial & Temporal Scales Associated with Irrigation Management

Precision irrigation may be viewed at a range of scales from the "tactical" or day-to-day management level to the "strategic" or seasonal management level. Strategic precision irrigation is the result of longer term decision making processes involving the use of broad scale (i.e. field or farm level) data over long time frames (i.e. monthly, seasonal or yearly data). It should be used to identify broad scale strategies in relation to irrigation management based on variations in a range of operating variables including crop/variety selection, planting area, planting dates, expected weather conditions, field layout, equipment constraints and expected economic returns.

However, tactical precision irrigation requires a much smaller areal and temporal focus and, in its most precise form, an ability to alter irrigation management in real-time and at the sub-metre scale. Where sensor, decision-making or control capability is limited in either temporal or spatial scale, the level of precision achievable is a function of the most limiting component in the process.

The spatial resolution of the precision irrigation system will be influenced by:

- spatial scales inherent in the irrigation application system used (eg. the wetted area of a single sprinkler or emitter, a single furrow etc);
- spatial limitations associated with data acquisition, decision making simulation capabilities etc; and
- the spatial scale associated with the variability in the crop water requirements.

The spatial and temporal yield variability within the whole field can be controlled by dividing the field into homogenous management zones, that is, areas within a field or irrigation system where crops respond somewhat uniformly to irrigation.

3.3 Spatial Scales Associated with Irrigation Application Systems

Determining the potential for spatially varied irrigation requires an understanding of the characteristics of the various application systems. In particular, there is a need to identify the spatial scales inherent in the irrigation application system used (Table 1) and the spatial scale associated with the variability in the crop water requirements. The feasibility further requires an ability to sense in real time the water requirements of the crop at the appropriate scale. Applying differential depths of water over a field will be dependent on the nature of the irrigation system but can be achieved in two ways viz: by varying the application rate or by varying the application time.

Table 1 Spatial scales of common irrigation systems

System	Spatial Unit	Order of magnitude of spatial scale (m ²)
Surface - furrow	single furrow	1000
Surface - furrow	set of furrows	50000
Surface – bay	bay	10000 to 50000
Sprinkler – solid set	wetted area of single sprinkler	100
Centre pivot, lateral move	wetted area of single sprinkler	100
LEPA [#] – bubbler	furrow dyke	1
Travelling irrigator	wetted area of single sprinkler	5000
Drip	wetted area of an emitter	1 to 10
Micro-spray	wetted area of a single spray	20

LEPA – low energy precision application

A further matter to be resolved is the minimum length (or area) scale of the actual variability in applications possible with the various application systems including lateral move or centre pivot machines and its relationship to the spatial variability of the crop response or crop water requirements, that is, to the crop management zones. The nature of sprinkler systems (particularly the spray diameter and overlap) means that the minimum area of spatially varied applications will probably be very much larger than the horizontal extent of the root zone of the crop being irrigated. The exception is LEPA machines where the area scale of applications will be similar to that of the crop but variability of applications at this scale will only be achievable at a very greatly increased sensing density.

3.4 Management Zones

An alternative to fully spatially varied applications is the use of management zones. This is common place in precision agriculture where a management zone is a sub-region of the field that expresses a relatively homogeneous combination of yield limiting factors for which a single rate of a specific crop input is appropriate (Doerge, 1998). In precision agriculture managing fields as zones is thought to improve the efficiency in applying inputs (Moore & Wolcott, 2000).

Either historical map-based or real-time sensor input based approaches may be used to delineate management zones. Field zoning for site-specific agriculture has been successfully achieved by frequency analysis of multi-year yield data (Diker *et al.*, 2004). Morphological and filtering tools can also be used in the delineation of management zones (Zhang & Taylor, 2000). Similarly, Fridgen *et al.* (2004) used a management zone analyst (MZA) software package (USDA, 2000). Long term yield data were also used by Boydell and McBratney (2002) along with a ‘*modified fuzzy k means*’ method of classification to define management zones in irrigated cotton.

The hypotheses underlying the use of spatially varied applications and management zones in precision irrigation are that:

- there is a significant variability in crop production responses within existing irrigation management units (fields), a substantial and manageable part of which is related to water supply and its management (for example, application uniformity and/or agronomic water use efficiency) and not other constraints;
- the variance in crop response to water within irrigation management units limits the productive capacity and profitability of the management units;
- the optimal size of the irrigation management unit will be a function of the irrigation application system characteristics, environmental factors (soil, topography, microclimate); and
- the crop response (for example, genetic) variances; and
- optimising the spatial scale and temporal interval of irrigation management will increase crop biological responses (yield/quality) to water application and reduce losses of inputs (such as, water and nutrients).

Doerge (1996) proposed a three step process for farmers wishing to move from a uniform rate to variable rate input strategy, focussing on the development of variable rate application maps for precision farming systems. The steps proposed, which are equally applicable to precision irrigation, are:

- “1. Start Simple. Use the spatial information that is the most readily available represents the best balance between cost and relationship to crop yield. In general, the best quality information is quantitative, densely or continuously sampled, and represents site characteristics that are stable over time, e.g. soil survey maps.
2. Fine-tune management zones. Over time, add information that further describes the patterns of yield variation within a field. This includes dynamic or qualitative spatial layers such as multiple-year yield maps, high-intensity soil survey maps, targeted soil sampling results, and landscape relationships, or ideally real-time information, e.g. crop canopy reflectance or temperature, soil moisture information.
3. Evaluate the effectiveness of management units. Evaluate the effectiveness of the management zone strategies, preferably over multiple seasons. It is crucial to maintain a sound agronomic perspective when evaluating the performance of different management zone strategies. Critically look for primary yield-limiting factors and for possible confounding effects. Be patient – remember that no single strategy will be perfect every year.”

Much of the early work using centre pivot machines to apply spatially varied applications (reviewed in Section 4.1) in fact used management zones in the form of maps based largely on differences in soils and this remains an obvious approach (e.g. Oliveira *et al.*, 2003). Alternatively the management units might be based on characteristics of the irrigation system, for example the individual bay in bay irrigation is potentially a management unit if managed differentially from neighbouring bays. For tree horticulture, Goodwin *et al.* (2008) based their management units on tree vigour as reflected in the degree of canopy cover and consumptive use of water. This is described in greater detail in Case Study 1. McClymont *et al.* (2009) took a similar approach in considering the degree of over- and under-irrigation occurring over the area of a vine block. Their Irrigation Management Units Decision Tree Framework aims to increase productivity in horticultural crops by better matching irrigation supply with the crop water requirement.

The challenge in determining management zones is to minimise the number of units and at the same time minimise the variability in irrigation depths and crop responses over each area. Oliveira *et al.* (2003) developed a procedure to aid delineation of irrigation management zones. Areas of the field are grouped into units which have the minimum variability in water holding capacity. These units are then evaluated using an economic response model which determines the optimum number and grouping of units. The procedure was tested for tomato production.

Feinerman and Voet (2000) evaluated the effect of imperfect information on the benefits from irrigation management units applied to sweet corn production. They concluded utilisation of site specific farming does not guarantee water saving. Similarly, Whelan and McBratney (2000) explained that spatial variability must be correctly characterised for effective site-specific management. If this is not possible, then the ‘null hypothesis’ of precision agriculture applies, i.e. uniform application is more appropriate than variable rate application.

Case Study 1: Irrigation management units in orchards

Water use in orchards is shown to be linearly related to tree size. Hence variation in tree size over an irrigation block will result in over-irrigation of the smaller trees and under irrigation of the larger trees. This case study from DPI, Tatura, shows that dividing a block into smaller irrigation management units according to tree size will result in water savings and increased yield.

Extracted with permission from: Ian Goodwin, Mark O’Connell and Des Whitfield (2008) Optimising irrigation management units in a nectarine orchard. *Australian Fruitgrower*, 2(11): 28-30.

The horticulture industries face serious challenges to improve water use efficiency. Recent low irrigation allocations and competition for water resources (urban demand and environmental flows) have resulted in significant increases in the cost of water. Community pressure to reduce environmental risk of nutrient, water and salt losses combined with the cost of water means that orchards cannot afford to be over-irrigated.

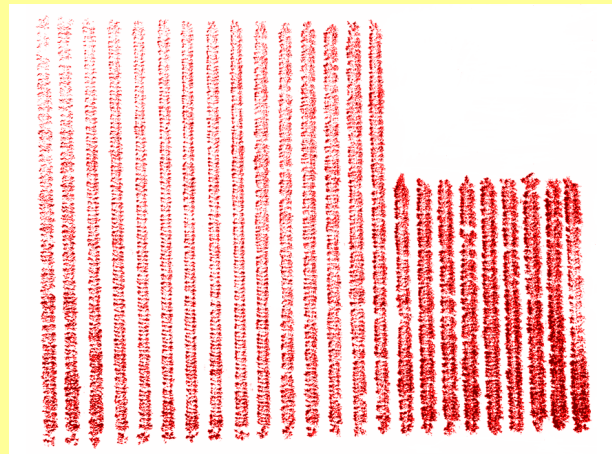
Nowadays the majority of orchards are micro-irrigated. Efficiency has improved dramatically compared with flood or sprinkler irrigation because similar amounts of water are applied to each tree with minimal non-productive water use such as soil evaporation and cover crop water use. Irrigation is directed to the tree root-zone when the trees need it. Such efficiency gains, however, can easily be lost if tree water use varies across an orchard block.

Previous studies have shown that tree size is linearly related to tree water use. Variation in tree size in an irrigation block will hence lead to over-irrigation of the smaller trees and/or under-irrigation of the larger trees. Yield is compromised by under-irrigation. For example, if a group of trees are small compared with the rest of the trees in a block, then irrigating the block to average water requirements will lead to over-irrigation of the small trees (resulting in substantial losses of water and nutrients below

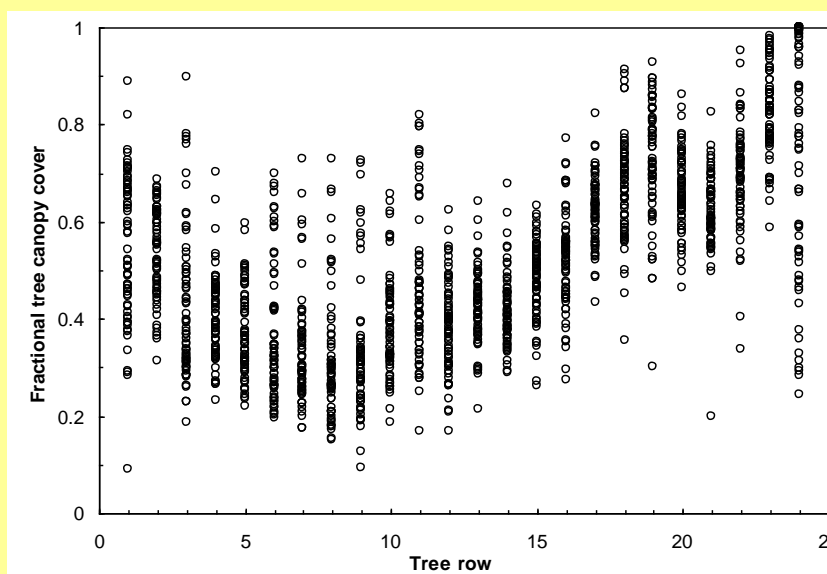
the root-zone) and under-irrigation of the larger trees (resulting in yield below tree capability).

Irrigating each tree to match ET_C obviously resulted in maximum efficiency. Such management is currently not feasible. In contrast, dividing the block into 24 row-based irrigation management units is feasible and resulted in substantial improvements in water use efficiency. A water saving of 1.7 ML/ha and a reduction in drainage from 4.9 to 3.2 ML/ha was estimated for this orchard assuming irrigation was applied to maximum canopy cover to avoid a yield penalty.

This type of analysis can be easily undertaken for any orchard and highlights the opportunity to improve water use efficiency by dividing existing irrigation blocks into smaller management units. Management units with similar irrigation requirements can then be grouped and irrigated identically.



Aerial photograph of the commercial nectarine orchard used in this study and the corresponding red pixel image (green and blue bands removed).



Spatial variation of tree-scale canopy cover showing the distribution of canopy cover within and between tree rows (n = 24).

4 REVIEW OF PRECISION IRRIGATION RESEARCH

4.1 Current Research: International

Research efforts into precision irrigation were initiated in the USA in the early 1990's. Initially this work largely centred on the modification of centre pivot and lateral move irrigation machines to give spatially varied applications of water and nitrogen (Evans *et al.*, 1996; King *et al.*, 1996; Sadler *et al.*, 1996; Duke *et al.*, 1997; Heermann *et al.*, 1997; Sadler *et al.*, 1997; Camp and Sadler, 1994, 1998; Camp *et al.*, 1998; and King and Wall, 1998; Sadler *et al.*, 2000), with the system control based on stored databases of spatially referenced data. A range of methods for implementing valve control to achieve the desired application rate have been trialled including programmable logic controllers and addressable solenoid valves. The variable rate water application systems employed include multiple sprinklers or groups of sprinklers for time-proportional pulsing, and a variable-aperture sprinkler with time-proportional control (Kincaid and Buchleiter, 2004; King and Kincaid, 2004). Readers are referred to Camp *et al.* (2006) for a comprehensive review of research undertaken in the USA since the early 1990's on precision irrigation with moving irrigation systems. Interest by European researchers grew through the 2000's and the emphasis shifted to the purpose and performance of spatially varied irrigations. Examples of this work include Al-Karadsheh *et al.* (2002); Camp *et al.* (2006); Chevaz *et al.* (2006); King *et al.* (2005); and Sadler *et al.* (2005b).

Recent work (Peters & Evett, 2004, 2007, 2008; O'Shaughnessy *et al.*, 2008) has expanded to include the use of infrared thermometers mounted on centre pivots to map soil and canopy temperatures to develop protocols for real time automatic irrigation scheduling and control. Other recent work at Washington State University (Camp *et al.*, 2006) has focused on the development and testing of digital control systems using on-board computer to implement radio based transmitted instructions and the installation of both sprays and LEPA (low-energy precision application) on the same machine for plot research in Montana.

Additional work has also been undertaken in Europe (Al-Karadsheh *et al.*, 2002) examining the yield response to non-uniform water applications under moving irrigation systems, and in New Zealand (Yule *et al.*, 2008; Hedley and Yule, 2009a&b) investigating the water savings and economic benefits of precision irrigation using centre pivots.

Clearly the ease and consistency with which the location of moving irrigation machines can be determined, the large number of nozzles and the presence of computer control offer a ready means of differential irrigation. Features common to many of these studies include:

- emphasis on the design and control of the machine to give spatially varied applications;
- variation achieved by multiple nozzles of different size controlled by solenoid valves and covering the same area as covered by a single nozzle on a conventional machine;

- the use of GPS to control irrigation applications according to pre-determined maps based on soil type differences; and
- differential irrigation of areas ranging from 40 to 100 m².

The justification for the early work was given by Sadler *et al.* (1997) as differences in yield observed on relatively light soils with poor water holding capacity and in the case of Evans *et al.* (1996) to also minimise the loss of nutrients through leaching following heavy rainfall. Only limited studies have been undertaken exploring the benefits of precision irrigation, notably studies have investigated the benefits in cotton (Booker *et al.*, 2006; Bronson *et al.*, 2006; Clouse, 2006), potatoes (King *et al.*, 2006) and soybeans (Paz *et al.*, 2001) and to date they have provided no significant evidence that investment in a precision irrigation system can provide sound financial returns to irrigators. Further, it has not been established that spatially variable irrigation will necessarily result in water savings, increased efficiency in fertiliser usage or improvements in yield. Much of the work in precision irrigation has been done so far because of the assumed potential for benefits that have not as yet been demonstrated. An interesting use of a system designed for spatially varied applications was provided by Chavez *et al.* (2010). In this case the spatially variable capacity was used to compensate for non-uniformity inherent in the irrigation applications from the machine and so give greater uniformity.

Research to date has resulted in the development of prototype systems for variable rate application. Appropriate decision support systems, particularly decision systems that could incorporate the output from real-time monitoring technologies have not been developed and as such, none of the above research groups have attempted to vary water applications in specific response to a measured crop water demand. Hence these systems do not yet meet the requirements of a precision irrigation system as defined in this report. Evans *et al.* (1996) acknowledged that the greatest difficulty faced in the implementation of precision irrigation is associated with determining appropriate prescriptions for the application of water and nutrients. Central to this will be the use of real-time on-the-go sensors.

There is no doubt that centre pivot, lateral move and low energy precision application (LEPA) machines can be modified to apply spatially variable irrigation. The common strategy employed by most irrigation researchers has been to vary the application rate and hence, depth applied in response to identified crop needs. This applies irrespective of whether it is in response to real time sensed crop needs or to some predetermined plan. However, as noted above, the factors most likely to delay significant commercial application of these systems are the need to develop the technology required to sense the water (and nutrient) requirements of the crop at an appropriate spatial scale and the need to develop decision support systems to identify appropriate management actions. No significant international research undertaken to address these gaps has been located.

4.2 Current Research: Australia

A diverse range of precision irrigation research projects are underway in Australia. Key groups involved in precision irrigation include the National Centre for Engineering in Agriculture at the University of Southern Queensland, the University of Melbourne and CSIRO.

Some of this research was co-ordinated through the CRC for Irrigation Futures with research effort directly addressing:

- Improved promotion of existing precision irrigation measurement technologies, including spatial evapo-transpiration (E_t) measurement systems that measure soil and plant evaporation from paddock to region and incorporate into web-available decision aids for irrigators and water managers.
- Improved soil water and water flow monitoring technology including solute signature analysis and soil water in the root zone to monitor and interpret salt and nitrogen distributions for precision irrigation decision making.
- Development and testing of improved irrigation application systems including adaptive irrigation control systems providing methods of real time monitoring of plant water status with direct control of water application at sub paddock level.

Work is being undertaken by the National Centre for Engineering in Agriculture (NCEA) at USQ toward the development of adaptive control systems for two very different irrigation application systems. A current project proposes an automated furrow irrigation system with intelligent real time control that uses data collected during the irrigation being managed to control that irrigation and can adapt to the current soil conditions (Koech, 2009). In parallel, the NCEA is investigating the use of adaptive control systems to improve the site-specific irrigation of cotton via lateral move and centre pivot irrigation machines. A simulation framework 'VARIwise' has been developed by McCarthy *et al.* (2010) to aid the development, evaluation and management of spatially and temporally varied site-specific irrigation control strategies.

The NCEA also has a broad program of work focusing on sensing technologies for precision irrigation. Plant-based sensors to improve irrigation management are being developed and a prototype vision sensor system has been developed, tested and patented for cotton by McCarthy *et al.* (2006a&b, 2007). Furthermore, stem diameter sensors have been evaluated in cotton (under a range of irrigation strategies and bollgard varieties) to compare plant stress predictions against soil moisture deficit and other measures of plant water status. A number of field trials (in cotton and vegetables) have been conducted to identify the spatial variability of crop response to irrigation application (Hussain, 2010; Padhi, 2010). Both low cost satellite imagery and camera based sensors are being used to quantify crop size and vigour and relate this to irrigation strategy.

UniWater, a joint initiative of the University of Melbourne and Monash University, is undertaking research to demonstrate wireless sensing control of various irrigation strategies in both viticulture and horticulture industries. This research funded through the STI, Victoria Government funding scheme and brings together the skills of control software scientists and engineers, with the agricultural scientists. The specific objective of the smarter irrigation project is to develop and evaluate the performance of fully automated, irrigation systems based on wireless sensing and actuation platforms in a range of agricultural enterprises including dairy pasture, horticulture and viticulture. The STI funded Smarter Irrigation Project successfully achieved proof of concept for smarter irrigation by successfully deploying leading edge wireless sensor and actuation technology enabling application of real-time closed-loop control to automate irrigation (Uniwat, 2008).

Additional work being undertaken by the University of Melbourne (Land and Food Resources, 2008) includes collaboration with the Department of Primary Industries,

Primary Industries Research Victoria investigating open hydroponics and real time ET irrigation scheduling on peaches and using thermography to assess the spatial and temporal patterns of water stress across grapevines canopies and whole vineyard blocks.

CSIRO (Hornbuckle *et al.*, 2008, 2009b) have been involved in the development of irrigation design and scheduling tools incorporating ground based and remote sensing methodologies and the use of informatics for irrigation decision support systems. Specific projects have developed techniques for providing low cost irrigation scheduling information over large areas using satellite and mobile phone SMS technology. Remote sensed indices (NDVI, RVI etc) from ground, airborne and satellite platforms have been used for determining crop coefficients and site specific irrigation water requirements.

4.3 Demonstrated Benefits

Precision irrigation has the potential to increase the economic efficiencies by optimally matching irrigation inputs to yields in each area of a field and thus reducing costs. The potential economic benefit of precision irrigation lies in reducing the cost of inputs or increasing yield for the same inputs.

The notion of spatially varied irrigation is predicated on the hypothesis that the crop is non-uniform and the water requirements are similarly non-uniform, probably as a result of differences in root zone conditions. It is also assumed that yield will be maximised if each plant is supplied with water exactly matching its individual requirements. However, evidence to support these hypotheses is not readily found in the literature.

The crop response to water has been studied extensively leading to the development of crop production functions for most crops. Also reasonable well known is the spatial variation in crop performance largely as a result of unintended spatial variations in the depths of irrigation applied (e.g. Mantovani *et al.*, 1995; Mateos *et al.*, 1997; Marques de Silva, 2006). Less well studied is the variation in crop response to water across a field, that is, variation in the crop production function across the field (Sadler *et al.*, 2002). It is the presence of this variation that provides the justification for spatially varied irrigation.

4.3.1 Water Savings

The primary goal of precision irrigation is to apply an optimum amount of irrigation throughout fields. This review does not see site specific or variable rate irrigation as a necessary or essential component of precision irrigation. However, it is a possible or even desirable component. It is also seen by many as the most likely means of achieving significant water savings (e.g. Kinkaid and Buchleiter, 2004; Evans and Sadler, 2008). While conditions could exist for which the aggregated optimum input for the entire field is greater than the amount usually applied in a conventional uniform application to the field, most researchers expect a reduction in water use on at least parts of fields, if not a reduction in the value aggregated over entire fields. Sadler *et al.* (2005b) have identified that this has only recently been achieved for precision irrigation and then only in a few instances.

Sadler *et al.* (2005b) reviewed much of the work prior to that date and suggested that opportunities for water savings accrue by not irrigating non-cropped areas, by reducing irrigation applications to adapt to specific problems, and by optimising the economic value of water applied through irrigation. Results from case studies of variable rate irrigation reviewed showed water savings in individual years ranging from zero to 50%, and savings averaged over a number of years from 8 to 20%, depending on the previous irrigation management. They concluded that variable rate irrigation could save 10 to 15% of water used in conventional irrigation practice.

While there are no Australian studies pointing to the potential water savings from precision irrigation, in New Zealand Yule *et al.* (2008) and Hedley and Yule (2009b) suggested water savings of around 25% are possible through improvements in application efficiency obtained by spatially varied irrigation applications adjusted to suit the available water holding capacity of the soils.

4.3.2 Yield and Profit

Studies specifically evaluating the yield and profit potential of precision or variable rate irrigation have involved both modelling and field experimental approaches.

Notable among the experimental studies is King *et al.* (2006) who measured the yield of potatoes under a centre pivot equipped for spatially varied applications. Yields per unit of water applied were greater (4 and 6%) in two consecutive years over those for uniform irrigation management. However the increase in income was only half the annual cost of a commercial site specific irrigation system.

For cotton (an indeterminate crop) the yield benefits of variable rate irrigation are yet to be demonstrated. Booker *et al.* (2006) analysed yields and water use efficiency for spatially varied irrigation over four years. They concluded that cotton seems too unpredictable to manage with spatially varied irrigation. This result is supported by the work of Bronson *et al.* (2006) who concluded that management zones for upland cotton based on landscape position were not justified, and by Clouse (2006) who in a modelling study obtained conflicting results between variable rate and uniform irrigation of cotton depending on the scheduling strategy employed.

Crop modelling has been shown to be an important and effective means of determining the value (yield and profitability) of variable rate strategies in precision farming (e.g. Paz *et al.*, 2001; Sadler *et al.* 2005a). The same is the case for spatially varied irrigation.

Nijbroek *et al.* (2003) investigated the economics of irrigation management zones for soybeans in the south-eastern USA. The model CROPGRO-Soybean was used to determine optimal irrigation strategies for each zone and the results compared to various uniform strategies applied to the whole field. Varying the irrigation strategies for the individual zones gave the highest return although the differences were small at US\$16/ha between the best and worst management.

DeJonge and Kaleita (2006) and DeJonge *et al.* (2007) used the model CERES-Maize to explore the feasibility of irrigation of corn in Iowa, USA. In doing so they also investigated the benefits of spatially varied irrigation. Irrigation was shown to reduce

both the spatial and temporal variability in yield and spatially varied irrigation gave higher yields than uniform irrigation. However irrigation only gave an economic return in three of 28 years.

The results from the above studies show that there is potential for yield improvements but that the benefits may not cover the costs of the technology required for spatially varied applications (Lu *et al.*, 2005). Heermann *et al.* (2002) similarly concluded that site specific irrigation management increased risk and that the potential economic benefit from it is small when the farmer's tolerance for risk is low. Almas *et al.* (2003) suggested that caution is required and that the benefit of changing to variable rate irrigation (VRI) from uniform application methods needs to be assessed before adoption. Their results indicate that substantial field variability and high crop prices are required for VRI to be profitable. It also depends heavily on the useful life of the equipment. This latter point was reinforced by Yule *et al.* (2008) who showed payback periods ranging from 5 to 20 years for adoption of VRI in dairy and cropping in New Zealand.

To date, there is a lack of significant evidence that investment in a precision irrigation system can provide sound financial returns to irrigators. It remains to be seen whether the costs can be reduced significantly or whether a simpler form of precision irrigation is needed that does not involve spatially varied applications.

5 IRRIGATION APPLICATION METHODS: TOOLS & TECHNOLOGIES

5.1 Surface Irrigation

5.1.1 Introduction

In the various forms of surface irrigation the furrows, bays or basins serve both as a means of conveying water across the field and as a surface through which infiltration occurs. The soil infiltration characteristics vary across the field and also from time to time (Walker, 1989; McClymont and Smith, 1996; Emilio *et al.*, 1997; Gillies, 2008). Khatri and Smith (2006) and Gillies (2008) identified this variability as a major physical constraint in achieving higher irrigation performance in furrow-irrigated fields. Precision irrigation systems have the potential to address the both the spatial and temporal variation in soil infiltration in these systems.

In surface irrigation, infiltration variability causes non-uniformity in water absorption rates and furrow stream advance rates (Trout, 1990). Furrow irrigation efficiency is further compounded by the furrow-to-furrow inflow variability in both gated pipes and siphon tubes (Trout and Mackey, 1988). In a typical field under furrow irrigation, it is difficult to identify one furrow that is accurately representative of the entire field. Therefore field evaluation of infiltration characteristics based on measurements from a single furrow is unlikely to give an accurate estimation of irrigation performance (Langat *et al.*, 2008; Gillies, 2008 & Schwankl *et al.*, 2000).

The management strategies and technologies required to implement precision irrigation systems in surface irrigation systems are available to achieve improved spatial and temporal management and are outlined below.

5.1.2 Simulation

Surface irrigation simulation models are developed to the point where they have the ability to simulate the depth of water applied over the field more precisely than is possible for sprinkler systems. Depths can be calculated at fine spacing along the length of the furrow or bay. Across the field the scale is determined by the width of the irrigation unit (furrow or bay). In either case the prediction scale is finer than the control scale.

In Australia, SIRMOD developed by Utah State University has been widely accepted as the standard for the evaluation and optimisation of furrow irrigation (Gillies, 2008). This is a comprehensive simulation software package for simulating surface irrigation hydraulics. The software is based on the solution of the full hydrodynamic equations and its accuracy is limited only by the accuracy of the input parameters, in particular the soil infiltration parameters and the resistance provided by the surface roughness (the Manning n). SIRMOD takes into account an average infiltration characteristic for the entire furrow

or bay, and this may lead to infiltration being under- and over- in many parts of the field (Emilio *et al.*, 1997) due to small scale variations in the infiltration characteristic.

SIRMOD typically uses current irrigation data to modify and optimise the management of future irrigation events. In this role the optimisation is a manual trial and error process.

Other similar models that are also readily available are WinSRFR (Bautista *et al.*, 2009) and AIM (Austin and Prendergast, 1997). Both of these models employ approximations to the hydrodynamic equations and their accuracy may be limited in some situations.

Improvement of furrow irrigation performance through the process of evaluation, simulation and optimisation with the IRRIMATE™ suite of tools developed by NCEA is now an accepted practice in the cotton industry. However, IRRIMATE™ and other similar tools are only useful for the modification of future irrigation events which in any case could be occurring under different soil conditions.

Significant limitations of the current simulation models are: (i) the need to use other modelling tools to determine the controlling soil parameters, for example, the use of IPARM (Gillies and Smith, 2005; Gillies *et al.*, 2007) to determine the infiltration from measurements of the irrigation advance, and (ii) the manual optimisation procedure. The Surface Irrigation Simulation Calibration and Optimisation (SISCO) model currently under development at USQ, and used recently in an evaluation of bay irrigation in the GMID (Smith *et al.*, 2009) removes these limitations. It is based on the simulation engine of McClymont *et al.* (1999) involves solution of the full hydrodynamic equations. As with SIRMOD it simulates the surface irrigation advance and recession and provides an estimate of the irrigation performance. However it also performs the inverse solution for the infiltration parameters from measured irrigation advance, runoff, recession, and/or depth data; and optimises the irrigation against a user defined objective function that will involve some combination of the usual performance measures. These late capabilities make it suitable for inclusion in a real-time control system for surface irrigation.

5.1.3 Automation and Control of Surface Irrigation

Automation and adaptive real-time control has been proposed for the management of temporal variability of infiltration characteristics (for example Emilio *et al.*, 1997; Mailhol & Gonzalez, 1993; Khatri & Smith, 2006; Turrall, 1996). It can provide an even higher level of irrigation performance than the traditional evaluation (as demonstrated by Raine *et al.*, 1997, Smith *et al.*, 2005, and Khatri & Smith, 2007) along with substantial labour savings.

Control systems used in surface irrigation can be implemented at diverse levels of sophistication and can be manual or automatic. Automation is not essential to the implementation of precision irrigation however it does provide the convenience and reduced labour requirements.

The use of irrigation evaluations to modify future irrigations is essentially an example of temporally separate feedback control. Real-time control as applied to surface irrigation implies that measurements taken during an irrigation event are processed and used for the modification and optimisation of the same irrigation event. The real-time control system

monitors the advance of water along the furrow or bay, determines the soil infiltration characteristics through a simulation process and modifies the management variables (flow rate and time to cut-off) accordingly before the end of that particular irrigation event. If the management variables are continually and automatically varied it is a form adaptive control.

Adaptive or real-time control of furrow irrigation leads to better irrigation efficiencies and water savings because of the use of 'current' or 'real-time' estimates of the soil infiltration characteristic.

Automated feedback control systems have been attempted for various configurations of surface irrigation (e.g. Clemmens, 1992; Hibbs *et al.*, 1992). In these cases the response being sensed was the water advance down the field, where the sensing was by contact (Humpherys and Fisher, 1995) or non-contact (Lam *et al.*, 2007) means.

Automation and control development in surface irrigation has to a large extent been biased towards border and basin irrigation systems. Humpherys (1969) observed that border and basin irrigation systems are generally better suited to automation and control than furrow irrigation because the inflow into the bay is more easily controlled.

Humpherys (1995a; 1995b; 1995c) has researched extensively on semi-automation of borders and basins by use of gates. He developed and tested both single function and dual function gates. The control of these devices was achieved by either a mechanical timer or electric solenoid. However, both types of gates require resetting prior to the next irrigation event. Niblack and Sanchez (2008) designed an automated basin irrigation using commercially available products. The flow of water into the border was controlled by jack gates powered by a battery and solar panel. The system applied both time-based and volume-based control methodology. The cut-off distance portion of the system used commercial radio transmitters placed along the border to transmit a signal to the gate to close and for the next gate to open. These transmitters were triggered by the advancing front of water. However, the major drawback of the use of water sensors is that they have to be removed before machinery is used on the basin.

AWMA Pty Ltd., a company based in Australia has developed the 'Aquator' system which combines the technology of radio telemetry, solar power and personal computers to automate and remotely control border and basin outlets. The Aquator software is installed in a personal computer stationed in the farm office (base station). The operation commands from the base station are sent out to the outlets to be controlled through a base transmitter connected to the computer and aerial installed on the roof. The outlets to be controlled have radio receivers, control electronics and aerials, and are mostly solar-powered (see Case Study 2).

Furrow irrigation has seen very little mechanisation and automatic control compared with other surface irrigation techniques. Some previous attempts at furrow irrigation automation and control include surge flow irrigation systems (Walker, 1989; Mostafadeh-Fard, 2006), and conventional continuous flow (Hibbs *et al.*, 1992 Lam *et al.*, 2007).

Two commercially available surge flow irrigation systems are described by Walker (1989). The 'dual line' system commonly used by irrigators who already have gated pipe system in place, uses an automated surge flow valve to switch the flow between the two

sides of the pipe system. In the 'single line' system, each outlet of the gated pipe is fitted with a valve. These valves are grouped into a suitable number and controlled from a central location to achieve a surge flow pattern. Mostafadeh-Fard (2006) designed an automatic surge flow irrigation system using wireless, cheap programmable surge valves installed in a gated pipe and use solar-powered batteries. The control mechanism consisted of an electronic board, motor and gear, and solar battery. Notwithstanding the merits of the surge system (overall, a smaller volume of water is required to complete the advance phase by surge flow than with continuous flow (Walker, 1989)), the method is generally seen as complex and the cost of implementation may be too high. The use of rigid gated pipes in surge flow systems is also unlikely to appeal to many irrigators because of transportation difficulties.

Hibbs *et al.* (1992) developed a furrow irrigation automation system utilising an adaptive control algorithm in which water is delivered to a block of furrows and the outflow is monitored using a flume and a depth sensor installed at the downstream end of the furrow. The infiltration characteristics are analysed by a microcomputer and the inflow is adjusted accordingly by using an automatic valve. The inflow system employs an adjustable pressure regulator and a diaphragm valve to supply equal inflow rate among a block of furrows. However, outflow is only monitored from selected representative furrows. While it might be infeasible to monitor outflow from each furrow, errors will inevitably be introduced into the system because of spatial variability of the infiltration characteristics across the field. Application efficiencies were found to be higher than those of conventional systems (Hibbs *et al.* 1992). However, the system is based on the outflow hydrograph, and it is not always practical to obtain accurate measurements of outflow using a flume.

A ground-based remote-sensing feedback control system was developed by Lam *et al.* (2007), as an alternative to contact-type sensors, to monitor the advance of water down a furrow, and allow automatic control of the water discharge at the furrow inlet during furrow irrigation of Californian row crops. A camera, located at the field boundary, captured images of water flowing down a furrow during an irrigation event. The images were analysed by a machine vision system to calculate the actual position of the leading edge of water. The feasibility of determining the position of the leading edge of water for row crop fields before and after crop emergence has been demonstrated for relatively short furrows. A similar system (McCarthy, 2004) was tested on the very much longer furrows on the Darling Downs, Qld and was unable to measure the position of the advance front with sufficient accuracy. Slight errors in the grading of the furrows were magnified substantially by the low camera height.

All of these cases can be considered a form of adaptive control where the response being sensed is the water advance down the field and the output is the depth of water applied (rather than crop yield) and the usual performance measures of efficiency and uniformity. The objective is typically a uniform application over the entire field. Systems such as these account for the temporal variation in soil moisture deficits and soil hydraulic properties. Varying the management to accommodate spatial variations in the soil infiltration characteristic is usually not considered.

Case Study 2: Automation of surface irrigation

Improving the performance (application efficiency and uniformity) of surface irrigation typically involves the application of higher flow rates and shorter irrigation on-times. Automation, while not an essential component of precision irrigation, provides the means to deliver this improved performance without increasing the labour required to shepherd the system. The Aquator system supplied by AWMA is an example of a commercially available system that has been widely applied in bay irrigation in southern Australia. Irrigation control for individual bays is time based and is 'adaptive' in the sense that the farmer can adjust the times for the remaining bays based on the observed time to completion of the first bays irrigated.

Extracted with permission from the AWMA Aquator sales literature.

The following example is a lucerne farm near Kerang in Northern Victoria.

The layout under automation is 400 acres and consists of:

- controlled and monitored Dethridge wheels
- 1 electric re-use pump
- channel stops/checks
- 89 bay outlets
- 11 channel level alarms
- 33 nodes in total
- Personal computer running the Aquator program at the home office

A 'node' consists of a raised enclosure containing a radio transceiver, battery, solar panel and relay cards. Usually there is one node per outlet, but in certain cases where outlets are located right next to each other, one node can be used to control up to three structures. In all cases each outlet is controlled totally independent of any other structure. Structures are opened and closed using 12 volt linear actuators. These units are totally maintenance free, very efficient and strong. Any type of outlet can be modified for automation including: slides, rubber flaps, pipe ends, over-centre locking, gravity flaps, pipe & risers and Dethridge wheels. ***Aquator also controls and monitors re-use pumps.***

All channels are protected by level alarms (high and low) located at crucial points (upstream of checks and end of channels). This provides an alarm should something occur to disrupt flow. The wheels are monitored for water flow and show both actual and total flow on the computer screen. The Adaptive Flow feature of Aquator allows allocated times of bays to automatically extend if the wheel slows down, effectively watering via volume rather than time.

Aquator monitors flows, channel level, communication and other functions. These are all connected to a dialler that will call up to six different telephone numbers and provide a voice message should a fault occur. Aquator has proven to be very reliable, easy to use and is saving many farmers a lot of time and water.



Actuator on bay inlet structure



Automated Dethridge meter wheel

5.1.4 Current Work

A recent project undertaken by UniWater, a joint initiative of University of Melbourne and Monash University, involved the development of four fully-automated measure and control irrigation systems that were integrated into wireless networks at two commercial dairies at Dookie and Kyabram (Uniwater, 2008). At the Dookie dairy a fully automated ‘measure and control’ irrigated pasture bay was compared with a manually irrigated

pasture bay whilst at Kyabram a fully automated ‘measure and control’ irrigated bay was compared with an existing time-based automatically irrigated bay. Results suggest that automated irrigation in response to soil moisture can significantly reduce irrigation volume, runoff and deep drainage losses while maintaining similar dry matter yields compared to irrigation at regular intervals. Furthermore, combined outcomes from field investigations and simulation modelling indicate that the automation of border-check irrigation using closed loop control systems can increase water productivity by upwards of 25% annually compared to manual operations.

In this trial case the simulation and optimisation used the analytic solution of the kinematic equations provided by Austin and Prendergast (2007). The limitation of this work is determined by the limitations of the simulation model which is applicable only to cracking clay soils and is less accurate than simulation models based on solution of the full hydrodynamic equations.

Recent research at NCEA (Khatri, 2007; Khatri & Smith, 2006; 2007) has established the basis for the practical real time control of furrow irrigation. It is similar in conception to the University of Melbourne system but very different in its execution using the NCEA developed simulation tools and commercially available control hardware.

The proposed system involves:

1. automatic commencement of the furrow inflow and measurement of that inflow,
2. measurement of the advance down the furrows mid way through each irrigation,
3. real time estimation of the soil infiltration characteristic and moisture deficit,
4. real time simulation and optimisation of the irrigation for selection of the time to cut-off that will give maximum performance for that irrigation, and
5. automatic cut off of the inflow at the designated time.

All of this is done without user intervention. The system proposed has been kept simple, by using a fixed inflow and varying only cut-off time, to encourage implementation of the system. The system will be field tested over the coming irrigation seasons

Decision support software is an essential part of the system and includes the following:

- continuous inflow measurement through inference from pressure measurements of pressure in the supply system (for example, for gated pipe supply using the program Gpipe of Smith *et al.* (1986) and Smith (1990)),
- pre-characterisation of the field by determining a generic soil infiltration characteristic from detailed measurements of single irrigation events using the program IPARM (Gillies & Smith (2005) and Gillies *et al.* (2007)),
- real-time prediction of the current infiltration parameters from a single observation of the irrigation advance during the irrigation event being controlled, as proposed by Khatri & Smith (2006) and described in Case Study 3, and
- simulation of the irrigation and optimisation to determine the preferred time to cut off the inflow to the field using an appropriate solution of the full hydrodynamic equations such as Sisco (Smith *et al.*, 2009) and taking into account the current soil moisture deficit or in the case of furrow irrigation the IrriPROB model (Gillies *et al.*,

2008) which also accounts for the variation in the infiltration characteristic across the set of furrows (Case Study 3).

In both of the above systems the focus is on the control of the individual irrigation event. While this is an important aspect of a precision irrigation system it is not sufficient. Both lack the overarching crop modelling and adaptive control that will deliver maximum seasonal water use efficiency. This aspect will be discussed in greater detail in Sections 6 and 7.

Case Study 3: Optimum management of furrow irrigated fields – The Irriprob model

Understanding and accommodating spatial and temporal variability is an essential feature of precision irrigation. The Irriprob model is a decision support tool for managing variability in furrow irrigation. It allows selection of the management variables (flow rate and time to cut-off) that give the best overall irrigation performance for a furrow irrigated field or set of furrows, taking in to account the spatial and temporal variability of the furrow infiltration characteristics.

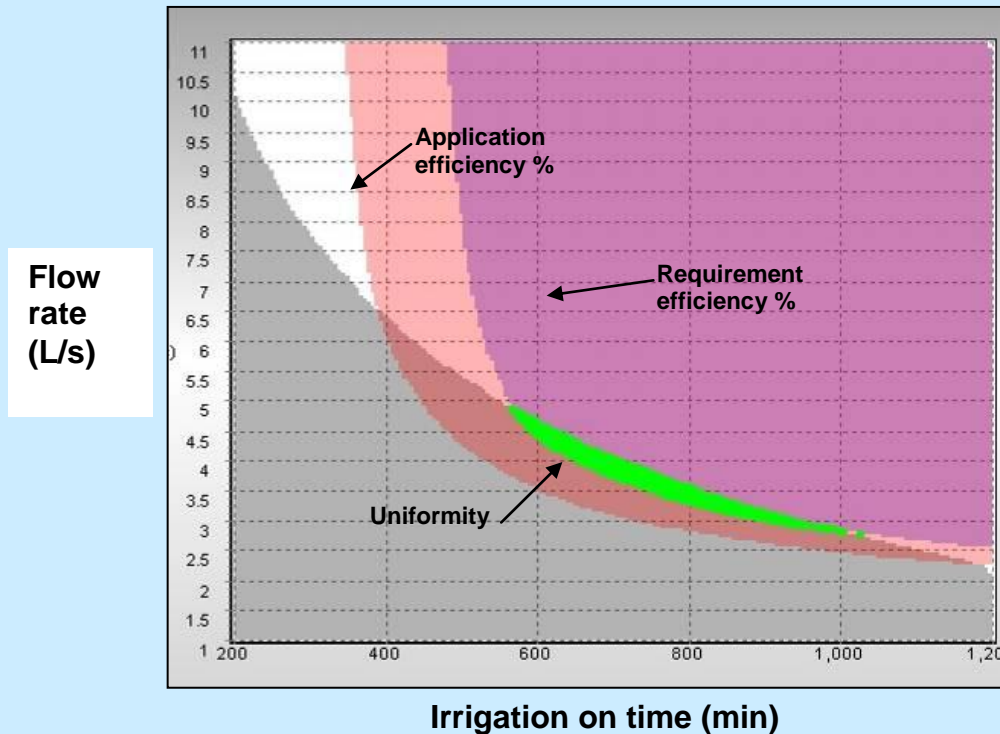
Reference: Gillies, M.H., Smith, R.J. and Raine, S.R. (2008) Measurement and management of furrow irrigation at the field scale. Irrigation Australia 2008 – National Conference and Exhibition, 20-22 May, Melbourne.

Generally, the measurement, evaluation and optimisation of furrow irrigation is restricted to a single furrow or small number of adjacent furrows. The measurement process is too intensive to be applied at the full field scale. Consequently it is necessary to assume that the infiltration characteristics and inflow rates of the measured furrow(s) represent the remainder of the field. Many have observed or speculated upon the significance of spatial variability but few outline potential strategies to deal with the issue. Research conducted by the authors and others at the NCEA has investigated and developed potential tools and techniques to better evaluate surface irrigation accounting for spatial and temporal variability.

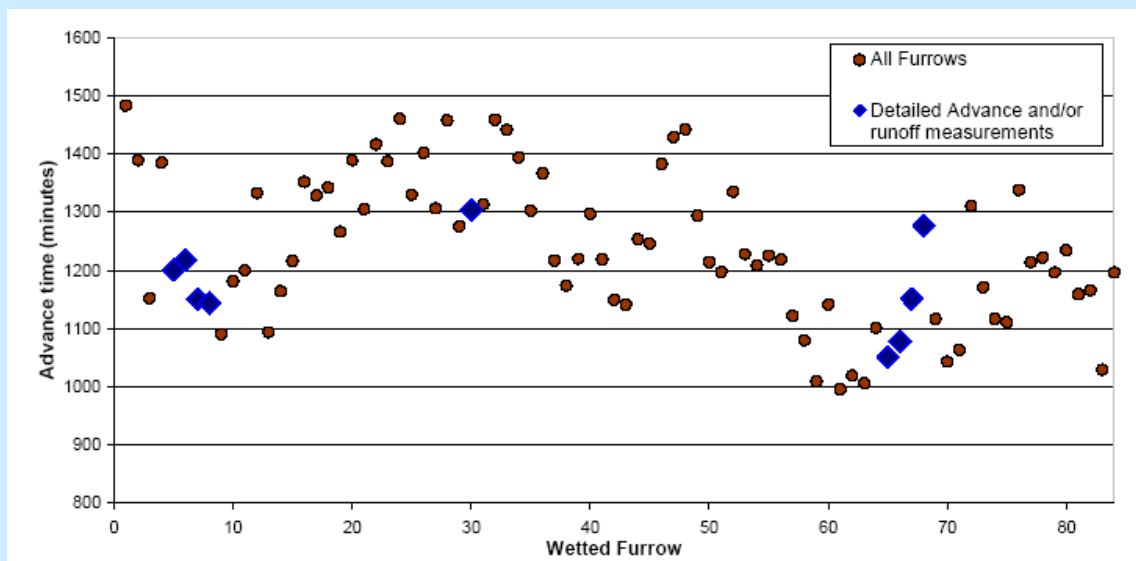
The computer package IrriProb was developed to extend hydraulic modelling from the single furrow to the whole field scale. The simulation within IrriProb applies the hydrodynamic equations to describe the flow of water along a single furrow. The model runs multiple simultaneous simulations on each furrow in the field or set and combines the results to create a two-dimensional grid of applied depths. It can then be used to determine the flow rate and time to cut-off for maximum performance for the field or set. IrriProb accommodates in-field variability by allowing each furrow to have individual infiltration characteristics, inflow rates and times and soil moisture deficits.

A trial was conducted in a typical commercial cotton field to showcase the tools and techniques to evaluate and optimise irrigation performance at the field scale. The resulting data also provided an insight into the nature of spatial variability. Complete inflow, advance and runoff measurements were used to accurately determine soil infiltration rates for a small number of furrows. Single advance points were then used to predict the infiltration characteristics across the remainder of the field (84 furrows). Combined with the whole field simulation model IrriProb this data enabled evaluation of

the true irrigation performance taking into account the inter-furrow variability in infiltration and advance rates. The use of the optimisation component of IrriProb demonstrated the ability to identify the optimal field management to maximise irrigation performance.



Example of the optimisation screen for IrriProb showing the interaction of the performance parameters for multiple furrows across a whole field – the green area indicates the zone of optimum performance



Advance (completion) times for the 84 furrows showing the furrow to furrow variation.

Case Study 4: Real time control of furrow irrigation

This on-going work is an initial step toward the realisation of surface irrigation as a precision system. It will involve automation of the system and the advance measurement, simulation, optimisation and control in real-time. The automation provides substantial labour savings and the control system the water savings. The real-time aspect accommodates the differences that occur in the soil infiltration characteristic and the soil moisture deficit from one irrigation event to the next.

References:

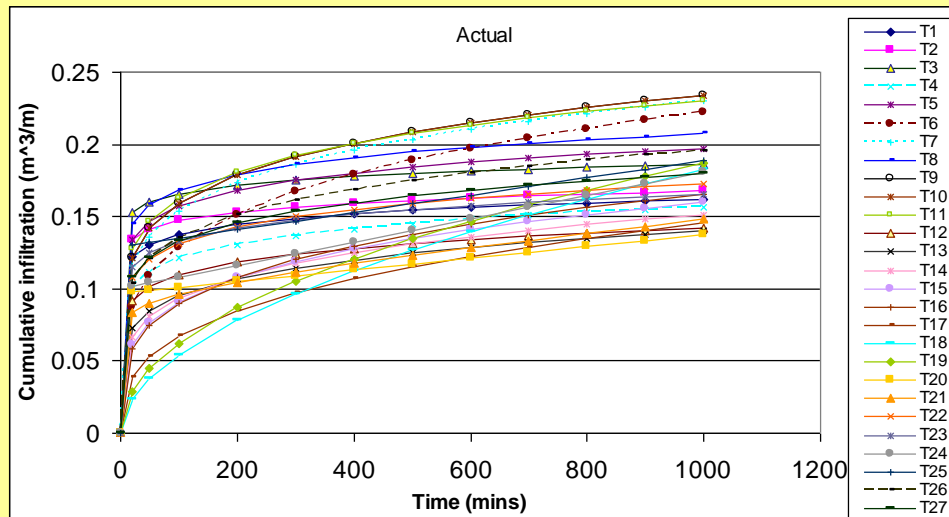
Khatri, K.L. and Smith, R.J. (2006) Real-time prediction of soil infiltration characteristics for the management of furrow irrigation. *Irrigation Science*, 25(1): 33-43.
Khatri, KL and Smith, RJ (2007) Toward a simple real-time control system for efficient management of furrow irrigation. *Irrigation and Drainage*, 56: 463-475.

A simple real-time control system for furrow irrigation is proposed that: predicts the infiltration characteristic of the soil in real time using data measured during an irrigation event, simulates the irrigation, and determines the optimum time to cut-off for that irrigation. The basis of the system is a new method for estimating the soil infiltration characteristic under furrow irrigation that uses a model infiltration curve, and a scaling process to predict the infiltration characteristic for each furrow and each irrigation event.

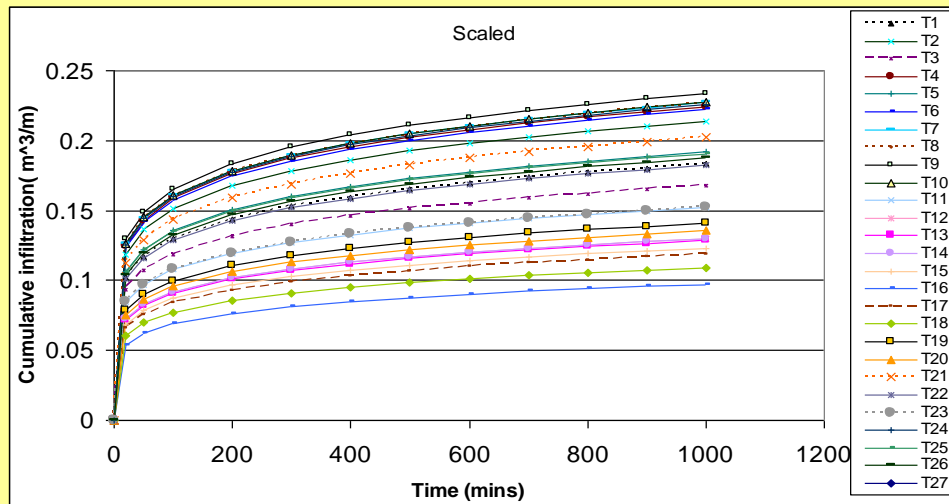
The proposed real-time control system involves:

- measurement or estimation of the inflow to each furrow or group of furrows,
- measurement of the advance at one point approximately mid way down the furrow,
- estimation of the infiltration characteristic for the furrow or group of furrows using the model curve and scaling technique,
- simulation of the irrigation and optimization to determine the time to cut off the inflow.

Data from 44 furrow irrigation events from two different fields were used to evaluate the proposed system. Infiltration characteristics calculated using the proposed method were compared to values calculated from the full advance data using the INFILT computer model. The infiltration curves calculated by the proposed method were of similar shape to the INFILT curves and gave similar values for the cumulative infiltration up to the irrigation advance time for each furrow. More importantly the statistical properties of the two sets of infiltration characteristics were similar.



(a) Actual infiltration curves from INFILT infiltration parameters



(b) Scaled infiltration curves

Cumulative infiltration curves for field T

The SIRMOD model was used to simulate the irrigation performance for two fields, for a range of irrigation strategies using both the scaled and the actual infiltration parameters. One of the strategies included in the simulations was the proposed real-time control strategy. It is shown that:

- the measured advance curves and measured irrigation performance were able to be reproduced with sufficient accuracy using the scaled infiltration parameters, and
- the simple real-time control strategy is feasible and has the potential to bring significant improvements in irrigation performance (application efficiency) over that achieved under simple recipe management or current farmer management.

5.2 Sprinkler Systems

5.2.1 Simulation Models

Prediction of how adjacent sprinklers overlap to give the pattern of applications is essential for the efficient design of sprinkler irrigation systems. In its simplest form it involves the overlapping of known patterns such as in the package SpacePro (Cape, 1998) for the purpose of selecting nozzle size and spacing for a given application. Here the objective is to maximise the uniformity of applied depths. It relies on knowledge of the sprinkler patterns for the given nozzle, pressure and height above ground. Wind effects are typically ignored and the answer is relatively insensitive to uncertainties in the individual sprinkler pattern used in the analysis (Christiansen, 1941).

Simulation of sprinkler distribution patterns provides the potential for powerful and effective decision support models for sprinkler systems that will assist in the development and application of optimum irrigation management strategies. Central to an accurate simulation of sprinkler distribution patterns is the prediction of the impact of wind on the pattern. In general, wind lengthens the sprinkler distribution pattern downwind, shortens the distribution pattern upwind and narrows the distribution pattern normal to the wind direction (Shull and Dylla, 1976). Greater overlap of adjacent sprinkler patterns is thus required to obtain acceptable uniformity.

Simulation of sprinkler irrigation distribution patterns in windy conditions has evolved significantly over the past two decades. Two major approaches have been used, a deterministic approach, which applies traditional ballistic theory to calculate the flight trajectories of individual water droplets, and empirical methods, which involve extrapolation from measured sprinkler distribution patterns for various wind speeds and directions for the same nozzle, pressure and trajectory angle.

A recent example of the empirical approach is the TRAVGUN model of Smith *et al.* (2008) which uses field measured transects of applied depths to firstly calculate the no wind sprinkler pattern and secondly to determine the six factors used to adjust the pattern for the effect of the wind. Output from the model is an estimate of the uniformity of applications for any selected wetted sector angle, lane spacing, travel direction, and wind speed and direction. The model does not predict depths applied at specific points in the field.

The SIRIAS model (Carrion *et al.*, 2001; Montero *et al.*, 2001) reflects the latest thinking in simulation using sprinkler droplet ballistics. To simulate the wind affected pattern for a single sprinkler, SIRIAS requires a radial leg pattern for the given sprinkler, nozzle height and pressure, measured in still air. The model uses an inverse solution to determine the drop size distribution that would give that sprinkler pattern and then uses that distribution in the prediction of the wind affected pattern. It has been validated for a wide range of nozzles and configurations (eg, Montero *et al.*, 2001). The patterns predicted by SIRIAS can then be used in packages such as SpacePro to determine the overlap patterns for whole systems.

For the large mobile centre pivot and lateral move systems, models that use droplet ballistics to predict the uniformity of applications along the machine are a sensible alternative to field trials using large numbers of catch cans. Examples of this type of model are those of Smith (1989) and Thompson *et al.* (2000). Both used a similar statistical description of the droplet size distribution and combined the ballistic model with the overlap along the machine and the aggregation of the pattern in the travel direction. An alternative approach was used in the mBOSS model (Smith *et al.*, 2003; Foley, 2010) which applied the overlap and aggregation to wind affected patterns imported from SIRIAS.

In all of the above models, the purpose was estimation of the uniformity of applications and the selection of appropriate nozzles and nozzle spacing. None of the models are sufficiently accurate to predict applications at particular points in an irrigated field and hence are not suitable for use in a decision support system for precision irrigation. They are limited by:

1. The accuracy of the ballistic models;
2. The sprinkler pattern or droplet size data required; and
3. The use of time averaged wind speeds and directions.

Ballistic models typically assume that the jet from the nozzle breaks up into the assumed drop size distribution instantaneously or at some defined distance from the nozzle. In either case drag coefficients are modified in a calibration process designed to make the measured and predicted sprinkler patterns match. In an attempt to overcome this deficiency, Grose *et al.* (1998) used a three-dimensional two-phase plume, which consisted of modelling the interaction of the jet with the surrounding air, simulating the separation of the jet into individual droplets and determining the ballistics of the individual droplets after their separation from the plume. However this approach has not gained any traction.

Unless the breakup of the stream can be predicted from the fundamental fluid mechanics as attempted by Grose *et al.*, then any ballistic model requires a drop size distribution for the particular nozzle type and size, and pressure to be used in the simulation. Obtaining these data is both time consuming and expensive.

Finally, all current models use only time averaged wind speeds and directions. This is perfectly acceptable if the objective is an estimate of the uniformity of applications. However if the objective is a truly deterministic model that can accurately predict the depth of water applied at any point in a field, then actual instantaneous wind speeds and directions will be required.

5.2.2 Centre Pivot and Lateral Move Machines

The development of mobile sprinkler systems has provided more than convenient irrigation methods. Of all the irrigation systems, these machines offer the greatest potential for uniform applications as well as being readily adaptable for adaptive control of spatially varied applications. Significant progress has been made in hardware development for the control of centre pivots and lateral moves to deliver a precision irrigation system, with much of this work conducted in USA. Recent research in Australia (McCarthy *et al.*, 2010) has addressed the need to develop appropriate decision

making tools to significantly extend the potential of centre pivots and lateral moves to provide optimal precision irrigation.

The following sections provide a brief overview of current components including variable rate application devices, system control hardware, and decision making systems. An overview has also been provided of auxiliary components such as location technology and variable rate water supply pumps. Key management considerations, for example, management zone conflicts with irrigation application uniformity and integrated nutrient and pesticide applications are discussed.

Irrigation Application Devices and System Control

A range of technologies have been developed to deliver variable rate irrigation applications that were classified according to Camp *et al.* (2006) as:

- Multiple discrete fixed-rate application devices operated in combination to provide a range of application depths (see McCann *et al.*, 1997; Camp & Sadler, 1994);
- Flow interruption to fixed-rate devices to provide a range of application depths that depend upon pulse frequency (see Evans & Harting, 1999); or
- Variable-aperture sprinkler with time-proportional control (see King & Kincaid, 1996; King *et al.*, 1997).

Each of these examples also involved development of an appropriate control system, to control both the speed of the machine and the variable rate of applications from the different nozzle arrangements.

Key criteria in the development of these technologies included:

- Ease of retrofit to existing commercial irrigation systems;
- Good water application uniformity within and between management zones;
- Robust electronics;
- Compatibility with existing irrigation system equipment;
- Bi-directional communication; and
- Flexible expansion for future development and functional requirements.

The precise location of all elements of the application system needs to be known at all times during operation if accurate site specific water applications are required. Various approaches have been used to accurately locate the multiple segments or spans. Approaches for centre pivots have included:

- Use of multiple electronic compasses to continuously measure the misalignment along the length of the system.
- Use of Global Positioning Systems (GPS) at one or more locations along the site (e.g. Peters and Evett, 2005). GPS units are progressively getting cheaper and this is becoming an increasingly viable option (Camp *et al.*, 2006). Most lateral move systems utilise one or more GPS sensors to determine location.

The Farmscan 7000VRI system described in Case Study 5 is an example of a commercial system, developed in Australia, for control of variable applications from centre pivot machines. The case study which is taken from the sales literature of the company describes the operation of the system. A similar system has been developed in New Zealand by Precision Irrigation (<http://www.precisionirrigation.co.nz>). The first system was installed on a dairy farm in 2008 and since then 12 VRI systems have been installed.

Case Study 5: Control of centre pivot machines for site-specific irrigation

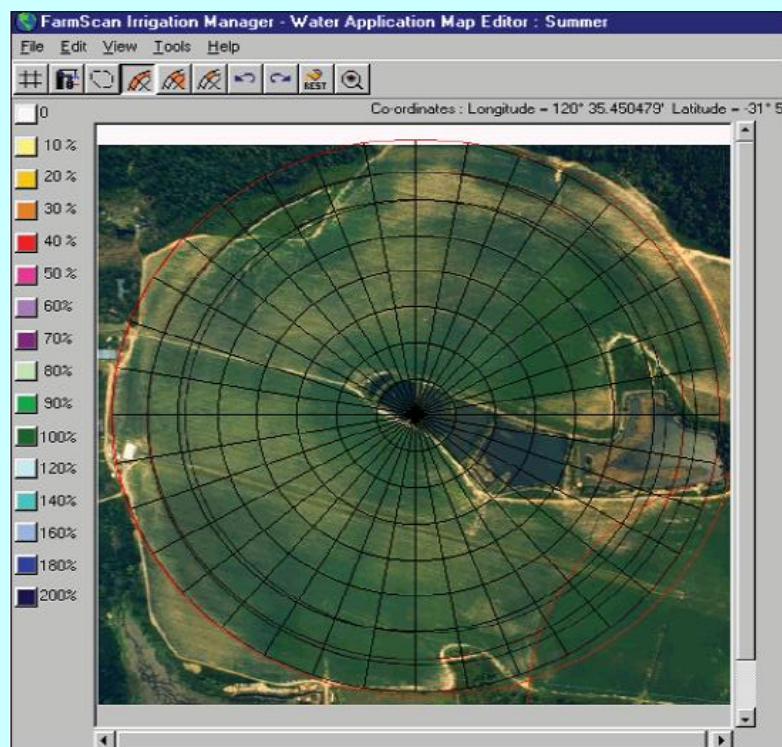
Configuring centre pivot machines to apply variable rate irrigation to predetermined maps is now a commercially available technology. An example is the Farmscan 7000 VRI. This is an important step toward centre pivots becoming precision systems, in that it provides one of the four stages required for a true precision system.

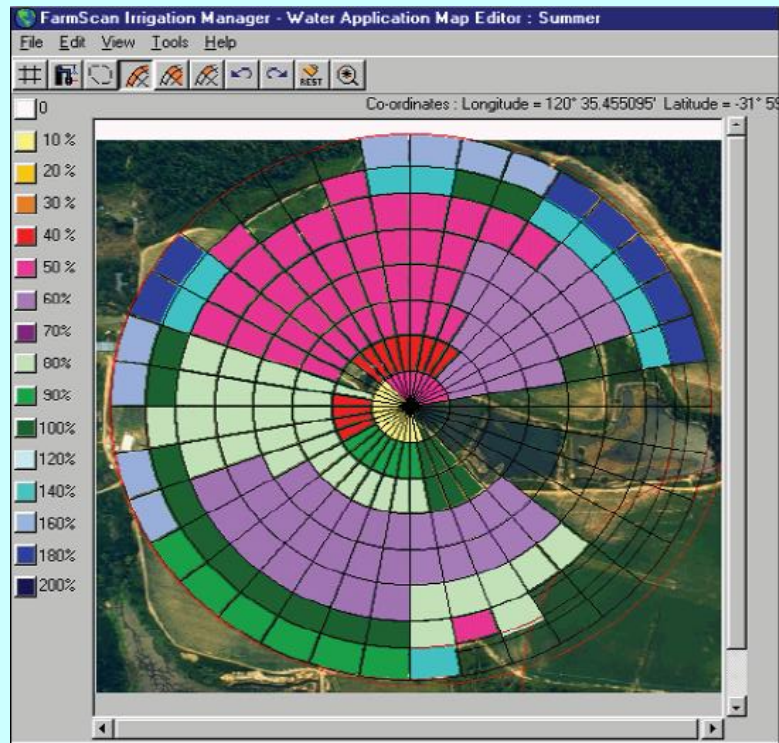
Extracted from the Farmscan sales literature:

Prescription maps are created using PC desktop software. The application map divides the circular area covered by the pivot into 2-10° pie slices and every slice is divided into segments. Rates can be assigned to as many or as few of these segments as required. Maps are then transferred to the 7000 controller via a USB stick. The GPS at the end of the pivot monitors actual position. If watering rates need to increase above 100%, the pivot will be slowed down. Similarly, if less than 100% is required in zones, the pivot will walk faster, saving energy and wear and tear.

The 7000 master node can control five zones plus end gun in stand alone mode. By adding 7001 slave nodes placed along the boom on a simple shared communication system, up to 48 watering zones plus end gun can be controlled. Options for wireless communication are also offered. Sprinklers are grouped into banks and these banks are controlled by either an air or a water pilot line that turns the water off.

The Farmscan 7000 system enables variable water application rates. Using GPS, banks of sprinklers are cycled on / off according to a predetermined prescription. Additionally, it controls pivot travel speed and end gun function for optimal efficiency. The system controls watering to compensate for spatial variability in the field.





Because soils have different textures, water holding capacities and infiltration rates etc, irrigation requirements may differ between different zones in one field. Application rates can be pre-determined for automatic rate control on different soil types. Low lying and boggy areas can be excluded from watering.

With multiple crops under production, harvest timing and watering regimes are often different. Pivots can be programmed to automatically shut-off to avoid overlap and non-crop inclusions in the field.

Decision Making Systems

The development of decision making frameworks to control variable rate irrigation for CPLMs in real time lags behind the development of the hardware components (Camp *et al.*, 2006). Much of the early work on spatially varied irrigation use map-based (historical) data rather than real-time data from on-the-go sensors (Smith *et al.*, 2000). Sensor-based irrigation systems are potentially more accurate than map-based systems due to the real-time nature of the data. Typically the existing control systems utilise a digital map or file of predetermined spatially referenced data for managing site specific applications of water. Research is underway to develop management systems that respond dynamically to real time data collected by remote or local sensors mounted on the irrigation system (e.g. Peters & Evett, 2008; O'Shaughnessy *et al.*, 2008).

Automated site-specific sensor-based irrigation control systems have been reported in the literature for lateral move and centre pivot irrigation machines (e.g. Moore & Chen, 2006; Evans *et al.*, 2007). These control strategies are one-dimensional (using only soil properties for scheduling) and they aim for crop uniformity across the field rather than attempting to optimise production in different parts of the field. However, local

microclimate, plant genetics and pest infestations in the crop may result in one area having a different optimal yield relative to another area of the field, and if the control strategy aims for uniform yield across the field then the yield cannot be maximised. The system developed by Evans *et al.*, (2007) forms a soil map based on soil moisture data calibrated with neutron probes and a weather station: irrigation and fertiliser amounts determined by the soil map are then transmitted to the sprinklers.

Another controller for variable-rate centre pivot irrigation using soil moisture data feedback was conceptualised by Moore and Chen (2006). In this case, a learning controller adjusted the irrigation application flow rate to control the water or concentration of nutrients in the soil. The application flow rate of the centre pivot system would be adjusted based on data from sensors buried in the soil in each management zone. The control of the irrigation was solely dependent on the concentration of crop input (e.g. moisture content) in the soil and did not involve evaluating the input sensor data, when in fact the soil moisture content alone may not accurately indicate the health of the crop as it only optimises one variable. This controller of Moore & Chen (2006) is only conceptual and has not been tested on an actual irrigation machine to verify the performance of the controller.

Work at the National Centre for Engineering in Agriculture (NCEA) at USQ, directed toward the adaptive control of spatially varied applications from centre pivot and lateral move machines is progressing on three fronts.

First is the development of simulation models of the machine hydraulic performance and of the depths of water applied by the machines (Smith, 1989; Smith *et al.*, 2003). These models were originally conceived as diagnostic tools but will be an essential component of the decision support for the adaptive control system. The models have also been used to determine the minimum size of management zone possible with these machines, expressed as a function of the sprinkler spacing, wetted diameter of the sprinklers and the machine speed.

Sensing of the crop response to the water applied is currently seen as the preferred feed back to the machine controller. Recent work by McCarthy *et al.* (2006a&b, 2007) has used machine vision to monitor inter-node length of cotton. Measurements on the same plants on each pass of the irrigation machine offers the possibility of real-time measurement of crop production functions for different irrigation application regimes. Hence the machine controller will be able to select the most appropriate application for particular sub-areas of the field in real-time and at a spatial resolution limited only by the number of sensors deployed and the spatial resolution of the associated modelling. Finally, a project currently underway (McCarthy, 2010) is investigating control options for these machines as outlined in Case Study 6. Although developed for centre pivot systems, it has the ability to provide the decision making for any irrigation application method as discussed in Section 7 of this review.

Variable Water Supply

Most conventional moving irrigation systems are designed for and operate with a constant flow rate and pressure to the system in which all sprinklers operate all of the time (with the exception of end guns). The bulk of the precision irrigation research with centre pivots and lateral moves has focussed on delivering variable flow rates for predetermined

management zones, requiring water to be supplied to the system at a constant pressure but at a variable flow rate.

Possible solutions developed for variable supply include:

- Multiple pump plant, for example the system described in Camp *et al.* (1998) uses four pumps, each drawing from a reservoir and each connected to a discharge manifold to provide constant pressure at a range of flow rates; and
- Use of variable rate pump as used by Harting (1999).

Both options represent a significant additional expense compared with conventional irrigation systems (Camp *et al.*, 2006).

Management zone conflicts

There is a close relationship between the wetted diameter of the sprinklers and the need for overlap to achieve acceptable application uniformity, the allowable overspray into adjacent management zones and the desired management zones (based on plant and soil condition). Consequently, the system can be designed either for maximum application uniformity within the management zones, which means accepting overspray into adjacent zones, or for maximum management zone integrity (no overspray allowed), which means the desired water application depth will not be met evenly in the border areas.

Further improvements in the performance of these types of machine are occurring through the adoption of Low Energy Precision Application (LEPA) technology (Lyle and Bordovsky, 1981). The LEPA system involves use of very low pressure sprays or bubblers located just above the soil surface on the end of long drop tubes. Efficiency is improved through a reduction in spray drift and evaporation. Spatial uniformity is also very high and spatially varied applications are readily achievable.

Case Study 6: Adaptive control of centre pivot and lateral move machines for site-specific irrigation

Irrigation is traditionally undertaken with the objective of maximising the uniformity of applications, ie, applying the same depth of water to all parts of the field. However not all plants may require the same amount of water. With appropriate decision support and control systems, centre pivot and lateral move machines (CPLMs) can be configured to deliver spatially variable or site specific applications in a real-time response to plant requirements. This case study illustrates a possible framework (VARIwise) for the control of such a system and provides a direction for the future development of sensing and decision support tools that will be required. The study has shown how an adaptive self-optimising irrigation strategy could result in improved water use efficiency.

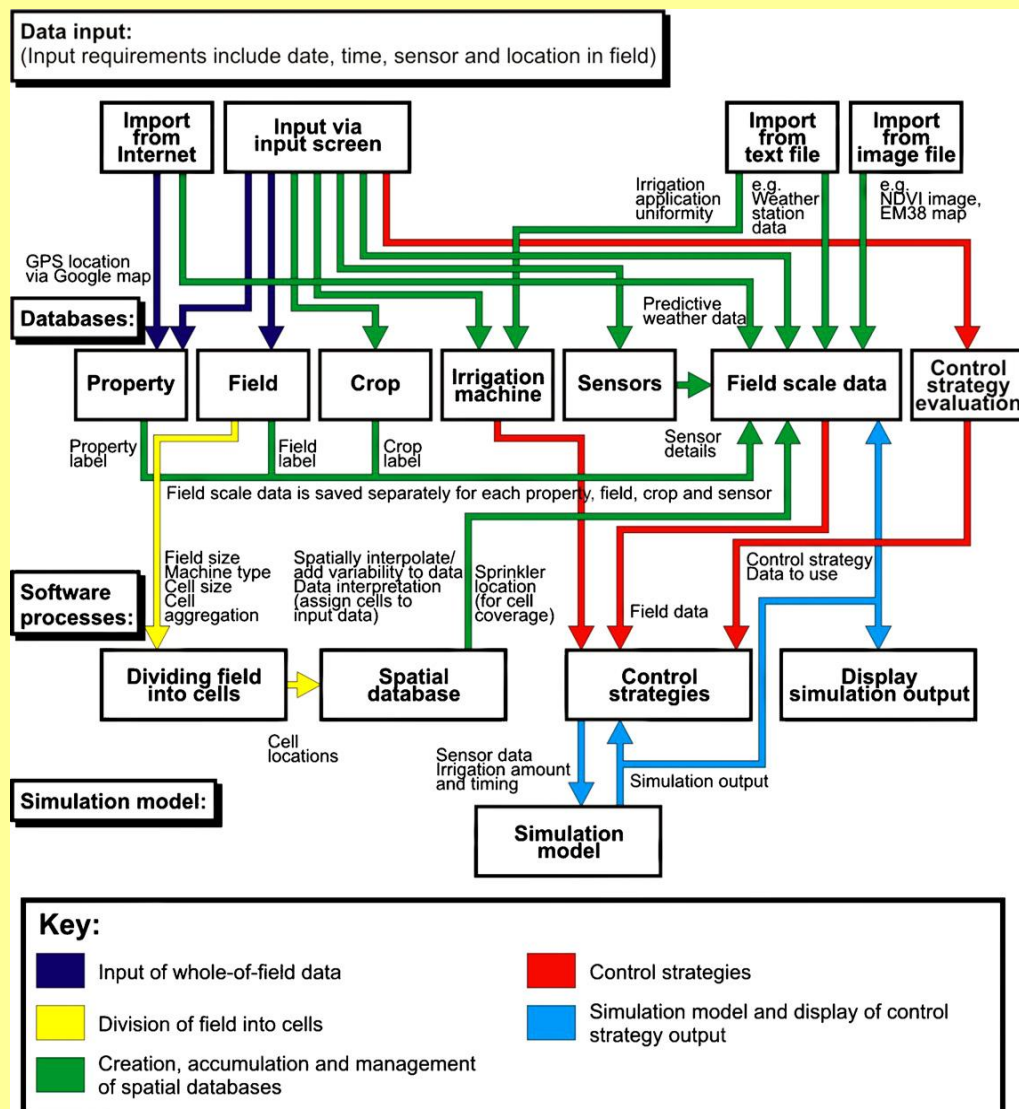
This work has demonstrated the potential benefits of site specific irrigation and has illustrated how VARIwise might be used as a core component of control systems on CPLMs designed for variable rate applications. Integration with commercially available control systems such as the Farmscan 7000VRI is a next step in its development. However, beyond this VARIwise has the potential to be a ‘holistic’ irrigation management tool that:

- is applicable to all irrigation application methods;
- can optimise the water management to give maximum yield or WUE (replacing the traditional stand alone irrigation scheduling);

- can optimise and control the application system; and
- is applicable irrespective of whether or not the system can apply spatially varied applications or is automated.

Reference: McCarthy, A.C., Hancock, N.H. and Raine, S.R. (2010) VARIwise: a general-purpose adaptive control simulation framework for spatially and temporally varied irrigation at sub-field scale. Computers and Electronics in Agriculture, 70: 117-128.

Irrigation control strategies may be used to improve the site-specific irrigation of cotton via lateral move and centre pivot irrigation machines. A simulation framework ‘VARIwise’ has been created to aid the development, evaluation and management of spatially and temporally varied site-specific irrigation control strategies. VARIwise accommodates sub-field scale variations in all input parameters using a 1 m² cell size, and permits application of differing control strategies within the field, as well as differing irrigation (and fertigation) amounts down to this scale.

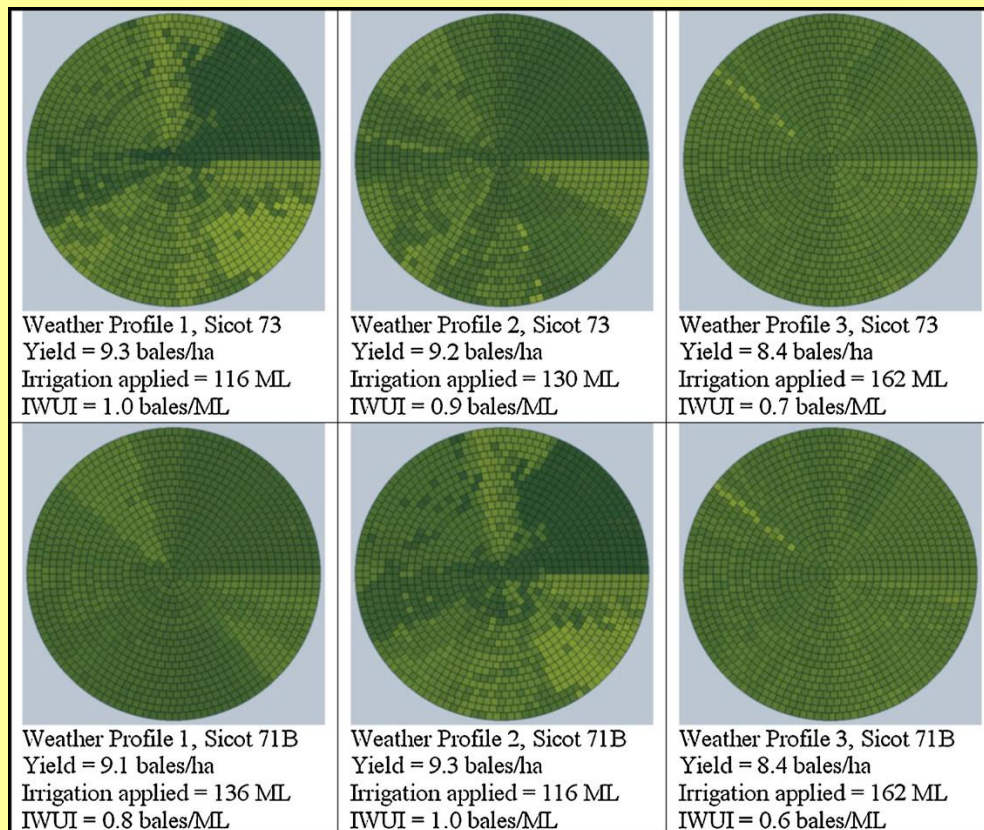


Flow chart for the VARIwise software

VARIwise has the following major functional characteristics:

- (1) the ability to input whole-of-field data and distribute sparse spatially varied data;
- (2) division of the field into variably sized cells (which may be grouped into zones);
- (3) creation, accumulation and management of spatial databases;
- (4) simulation of natural variability for sensitivity and robustness analyses;
- (5) incorporation of agronomic simulation model/s (e.g OZCOT);
- (6) implementation of control strategies;
- (7) display of control strategy output; and
- (8) real-time irrigation machine control.

A case study for the irrigation of cotton demonstrated that VARIwise accommodates field-scale variations in input parameters, a standard cotton plant model (OZCOT) and evaluation of adaptive control strategies which have the potential to improve yield and irrigation water use index. Further work in VARIwise will entail an analysis of the control strategy outputs and exploration of the strategies using input data with various spatial scales and time steps.



Output of the self-optimising irrigation strategy with variable-rate irrigation machine

5.2.3 Other Sprinkler Systems

The other sprinkler systems such as fixed systems and travelling gun systems, have received the least attention to date in irrigation research in general and precision irrigation research in particular.

For the fixed systems, the design and simulation tools mentioned in Section 5.2.1 are available and if used correctly should lead to acceptable irrigation performance. However anecdotal evidence suggests this is not the case and that incorrect nozzle spacing is resulting in less than acceptable application uniformities. Adaption of these systems to provide spatially variable applications has been achieved (e.g. Miranda *et al.*, 2005) although no information was provided regarding its irrigation performance.

Travelling gun irrigation is a popular form of irrigation in the Queensland dairy, sugar and horticultural industries. High uniformity of irrigation applications is essential to the efficient production of high yields from these irrigated crops. However, poor uniformity of applications is characteristic of travelling gun machines under commercial conditions, as supported by recent field measurements. For example, Smith *et al.* (2002) reported that only 25% of machines tested in sugar cane in the Bundaberg area of Queensland gave uniformities greater than the recommended Christiansen Coefficient of Uniformity (CU) of 80%. There are a variety of reasons for this poor performance, including excessive spacing between travel lanes, poor nozzle selection, sub-optimal gun sector angle, and the operation of machines in windy conditions.

The computer model, TRAVGUN (Smith *et al.*, 2009) was developed specifically to diagnose problems with the operation of these machines. Once calibrated it simulates the irrigation applications by a particular machine under different wind and operating conditions. A novel approach to calibration of the model was developed that uses simple field measurements of applied depths along transects perpendicular to the travel direction of the machine. The user can simulate the sprinkler patterns, transects, and applications over an entire field while changing various operating parameters such as the lane spacing and sector angle to identify the optimum values for those parameters.

A conventional travelling gun system is adversely affected by windy conditions. To counter this, Ozaki (1999) at Cranfield University, UK, developed a prototype robotic self-travelling sprinkler (STS) system. It controls the nozzle (head) and the water supply instantaneously in response to windy conditions to minimize the distortion of the sprinkler pattern by wind and the amount of the wasted water. The robotic STS sprinkler head has two degrees of freedom; sector and trajectory angles, driven by stepper motors to follow the control model, which are found by applying prediction models of water distribution. The robotic STS system offers several advantages, including:

1. The STS head is controlled instantaneously to correct the water distortion from the wind with relation to the wind speed and direction. In addition, the system is shut down when the wind becomes too strong for it to run efficiently.
2. Using the experimental and mathematical models of application patterns from sprinklers, the system enables water to be distributed to the required area, even up to irregular boundaries, for example, fence lines, corners of fields, and virtual field boundaries.
3. Treatment maps can be introduced to the models of the STS head which can be controlled by reckoning the position with either a DGPS or dead reckoning system.

In other words, it is possible to apply water or chemicals, which vary spatially in the regions of the field or temporally through the season.

This project demonstrates the potential of travelling gun irrigation systems and similarly configured sprinkler systems to be controlled to deliver spatially variable irrigation through a fully automated system.

A similar system was reported by Ghinassi (2010) where performance of a travelling gun sprinkler is maximised by real-time variation of pressure, travel speed, wetting angle and speed of rotation.

5.3 Micro-irrigation Systems

Micro-irrigation systems are typically designed to wet only the zone occupied by plant roots and to maintain this zone at or near an optimum moisture level. Obvious advantages of micro-irrigation include a smaller wetted surface area, minimal evaporation from the soil surface, reduced weed growth, and potentially improved water application uniformity within the crop root zone by better control over the location and volume of application.

A particular benefit of micro-irrigation is the ability to apply small amounts of water at short intervals. This provides the opportunity to maintain the soil moisture at a specified moisture deficit below field capacity for part or all of the season and hence the opportunity for increased effectiveness of rainfall during the irrigation season.

The potential efficiency of micro-irrigation systems is often quoted as greater than 90%. Losses of water in micro-irrigation systems occur principally through evaporation from the soil surface, surface run-off and deep drainage. Evaporation losses are generally small due to the limited wetted surface area and the absence of ponded surface water due to the low discharge rates. The application of water usually occurs beneath the crop canopy, either directly on to or beneath the soil surface, further reducing the potential for evaporative loss. Run-off losses are also usually small due to the low application rates. However, as with all irrigation systems the ability to achieve high levels of efficiency is more a function of the management of the system rather than some inherent property of the system. For example, Shannon *et al.* (1996) found that drip irrigation application efficiencies under commercial conditions in the Bundaberg area ranged from 30 to 90%. Given the nature of the system, these losses were most likely from over irrigation and deep percolation.

Placement of the drip lines is an important consideration in achieving high efficiencies. For example, Henderson *et al.* (2008) demonstrated a 25% gain in efficiency when drip lines were placed adjacent to each row of broccoli rather than between every second row.

Dominant causes of non-uniform applications from micro-irrigation systems are: pressure variations along the lateral pipelines, variability in the emitters occurring during manufacture, and blockage of the emitters. Extensive evaluations of the uniformities of applications from micro-irrigation systems have been conducted in the USA (eg. Hanson *et al.*, 1995) using mobile field laboratories. These have shown that emission uniformities are less than desirable with commercial systems commonly operating with an Emission Uniformity (E_u) of less than 80%. This is supported by local data from

McClymont *et al.* (2009) and Hornbuckle *et al.* (2009a) who reported Distribution Uniformities (*DU*) as low as 32% from a sample of drip irrigated vineyards in Southern Australia. These data point to the need for field evaluation, diagnosis and correction of all micro-irrigation systems if the potential of these systems for precise applications is to be realised.

Systems for recording and reporting the results of performance evaluations of micro-irrigation systems are available, for example Hornbuckle *et al.* (2006, 2008, 2009b). However these systems do not provide any diagnostic capability and cannot be readily integrated with the software used for system management.

Micro-systems have greater potential for precision irrigation than other systems. They are easily controlled and are commonly automated on a time, soil moisture or time-temperature basis (e.g. Phene & Howell, 1984; Meron *et al.*, 1996; Dukes and Scholberg, 2004; Wanjura *et al.*, 2004; Evatt *et al.*, 2006). They also lend themselves to adaptive control and have the potential to apply spatially variable applications at a range of scales from individual laterals to individual emitters. Variable rate-controllers that respond to real-time sensing and decision making, are particularly applicable to micro-irrigation systems.

Research into precision irrigation for micro-irrigation systems has been undertaken primarily in horticultural crops including viticulture (Ooi *et al.*, 2008; Capraro *et al.*, 2008a&b) and fruit tree orchards (Coates *et al.*, 2004; Uniwater, 2008; Adhikari, 2008).

Research by Capraro *et al.* (2008a&b) in viticulture utilised closed loop irrigation control systems with moisture measurements in the root zones to maintain the soil moisture level around a set value. The controller determines when and how much to irrigate as a function of the current difference between soil moisture measurements and the reference values. Both projects incorporated regulated deficit irrigation strategies within the irrigation control system to achieve particular quality targets, that is, the enological quality in the grapes.

Coates *et al.* (2004, 2005, 2006) focused their efforts on the development of a spatially variable micro-sprinkler system that will allow for management of individual trees in an orchard. More specifically, the focus was to differentially supply water and dissolved chemical fertilizers to one or more individual trees fed by a single micro-sprinkler drip line. In particular, the project focused on:

- Designing an intelligent micro-sprinkler node that can be individually addressed from a drip line controller.
- Developing a physical network and serial data protocol for power distribution and communication between a drip line controller and individual sprinkler nodes along a drip irrigation line.
- Developing software to operate the master controller, drip line controller, and individual micro-sprinkler nodes.
- Experimentally evaluating the system performance.

Their work has resulted in demonstration and testing of a four node prototype spatially variable micro-sprinkler system. A total of 50 micro-sprinkler nodes were deployed. Each micro-sprinkler node consists of a low cost microcontroller and electronic circuitry. Simple latching solenoid valves individually control water flow at each micro-sprinkler.

A pressure sensor is used to monitor drip line pressures. A drip line controller provides adequate memory to store irrigation schedules and sensor data. A master laptop computer is used to transmit schedules and access sensor data on the drip line controller. Preliminary results show that spatially variable management is possible. The focus of this work has been on hardware development. The decision making tools required to support and optimize the system responses have not been developed.

Torre-Neto *et al.*, (2000) provided another example of sensor based control of spatially varied applications from a micro-sprinkler system.

The University of Melbourne recently completed a project to develop and test automated irrigation systems for micro-irrigation (Ooi *et al.*, 2008; Uniwater, 2008). Two irrigation controllers, a soil-moisture based controller and an ET-based controller were developed and integrated into wirelessly networked irrigation control systems in a Pink Lady apple orchard at Dookie and a block of Shiraz wine grapes within a large commercial vineyard at Corop. Results from the Dookie orchard showed that automated irrigation using closed loop control systems improved water productivity compared with manual irrigation by 73% (Uniwater, 2008). These results demonstrate the potential of closed-loop irrigation control for irrigators at the lower end of the spectrum to rapidly ‘leapfrog’ to the upper end of the efficiency spectrum. For those irrigators already at the upper end of the spectrum, adoption of the technology would lead to substantial labour and time savings without any attendant loss of irrigation expertise.

6 EXISTING AND EMERGING TOOLS & TECHNOLOGIES

6.1 Data Collection: Tools & Technologies

A precision irrigation system requires clear evidence of significant spatial and/or temporal variability in soil and crop conditions within a field and between fields and the ability to identify and quantify such variability in order to implement an appropriate irrigation response. Existing technology is available to measure the various components of the soil-crop-atmosphere continuum (soil moisture content, crop water requirement or crop response), many in real-time and at sub-metre scales, and to provide precise and/or real-time control of irrigation applications.

Data collection to measure spatial and /or temporal variability for use in a precision irrigation system might include plant based sensing, soil-water sensing, weather based sensing or any combination of these. Field spatial variability can be measured:

1. Continuously (e.g. on-the-go monitoring using a thermal camera mounted to a centre pivot);
2. Discretely (e.g. point sampling of soil-water content using soil moisture probes); or
3. Remotely from a sufficiently high altitude such that a single measurement encompasses most or all of a field.

6.1.1 Weather Based Sensing

High quality, local meteorological data are needed for the purpose irrigation scheduling and for the operation of the various crop simulation and water balance models used in agricultural and irrigation management. These data can be obtained from automatic weather stations installed for a specific farm or project or more inexpensively from networks operated by a central agency.

An example of the latter is the Texas High Plains ET Network (Texas A & M University Agricultural Program, 2005) which was established in the 1990's to provide convenient and timely access to meteorological data for use by producers, agricultural researchers, and others interested in agriculturally relevant meteorological data. The TXHPET operated 18 meteorological stations with regional coverage estimated at four million irrigated acres. The network disseminated meteorological data, including ET-based crop water use information on a daily basis. These data were disseminated primarily through fax and/or on-line web access to over 825 data users per day. Data included daily values of reference crop ET, air and soil temperatures, precipitation and growing degree days (heat units) for the 3 days prior to the current date. Daily water demand, on a daily, 3-day, 7-day, and seasonal basis, were calculated for some key crops in the region. Water use estimates and accumulated growing degree days were presented for several planting dates for each crop. This service now operates as TexasET (<http://texaset.tamu.edu/>).

Weather station information for determining reference evapo-transpiration (E_{TO}) is commonly available through nearly all of the irrigation regions in Australia (Hornbuckle *et al.*, 2008). In addition daily E_{TO} values calculated using the modified Penman-

Monteith equation as described in FAO 56 (Allen et al., 1998) are available from the Bureau of Meteorology (<http://www.bom.gov.au/watl/eto/>).

Weather based E_{TO} data is now commonly used in conjunction with remotely sensed crop data as discussed in Section 6.1.3 to value-add to this traditional information source.

6.1.2 Plant Based Sensing - Overview

There are a wide range of plant based sensing technologies available to identify the onset and severity of plant stress. This section has been drawn largely from White & Raine (2008) and readers are referred to this report for a comprehensive overview of plant based sensing methods, details on the method of operation, maintenance requirements, typical purchase costs, and the advantages and disadvantages of each method and their use for commercial irrigation scheduling.

Plant based sensing technologies can be broadly categorised into those requiring direct contact with the plant and those non-contact sensors that are proximally (e.g. hand-held or machine mounted) or remotely (e.g. airborne, satellite) mounted. The contact sensors provide detailed time-series data for individual plants, useful for understanding diurnal fluctuations. The proximal and remote sensors are more appropriate for collecting spatial data across field, farm or regional levels and hence, are more appropriate for assessing spatial variations in plant stress and application in a precision irrigation system.

Plant based sensors for irrigation typically measure plant responses that are related to moisture uptake (e.g. plant water status, sap flow), transpiration (e.g. canopy temperature, reflectance) or growth rate. Variations in these measures indicate crop stress which can be used to infer when to apply irrigation. However, plant based sensors do not provide any indication of the volume of irrigation water that is required to be applied. Hence these techniques should be used in conjunction with either soil moisture measurements or simulation to confirm the irrigation requirements. It should also be noted that the level of crop stress observed is a complex function of soil, plant and atmospheric conditions. Hence the user needs to ensure that the crop stress observed is due to a root zone soil moisture deficit and not disease, pest or exceptional atmospheric conditions.

Plant based sensing for irrigation requires the identification of well tested/validated crop stress threshold values. Hence, a critical factor in choosing a particular sensor is the level of crop response knowledge that is available under alternative soil moisture and evaporative conditions for the various sensor options. Threshold values for plant based sensors can be developed by:

- (i) correlating the observed sensor outputs with established industry practices (e.g. what are the plant sensor readings when irrigation is applied based on accepted soil-moisture or atmospheric triggers?),
- (ii) conducting replicated trials where irrigation treatments have been ‘triggered’ over a range of sensor values to identify desirable agronomic crop growth, lint quality, yield or other crop characteristics, or
- (iii) evaluating trends in the sensor data and arbitrarily defining critical levels (i.e. if rate of growth shows a marked slowing then irrigations should be applied).

However, care should be taken when assessing the physiological responses (e.g. photosynthetic rate and assimilate production) to water availability as a reduction in the

photosynthetic rate may not necessarily inhibit the yield potential of the crop. For example, in the case of deficit irrigation of cotton, mild soil moisture stress may increase yields, reduce water use and increase crop water use efficiency.

It is the plant which is being managed to maximise production and profitability. It is also the plant which is the integrator of the environmental (e.g. soil, weather) conditions and farm management factors. Hence, it is appropriate to monitor plant stress and use this information to target improvements in crop and water management. However, as the range of plant sensing options increases, it will be increasingly important to identify which plant based sensors are appropriate for specific crops and to ensure that the appropriate sensor threshold values for irrigation application are defined.

Many proximal and remote sensing tools, which were previously only used by researchers, are now accessible for commercial use. Proximal units are typically handheld, trailed or vehicle mounted. They typically come with logging and GPS capability to enable maps of the field measurements produced. There is also a wide range of satellite based sensors from which data can be obtained for agricultural use. The number of product suppliers is increasing and the cost of these products has also been decreasing making these technologies more affordable for routine use. White and Raine (2008) suggested that with the then current use of remote sensor platforms (e.g. unmanned aerial vehicles, planes or satellites) for regional irrigation evaluations, commercial applications at the farm and field scales for precision irrigation are not far away.

6.1.3 Plant Based Sensing – Recent Applications

Radiometric sensors

Bastiaanssen *et al.* (2002) reviewed the sensing tools available for soil-vegetation-atmosphere-transfer processes and sought to identify the practical applications for these tools. A wide range of sensors are available which can be used proximally or remotely, and which measure the electromagnetic reflectance from a surface across a particular band width or a number of band widths. McBratney *et al.* (2003) provided an illustration of the parts of the electromagnetic spectrum that can be used for sensing environmental and soil variables (Figure 2).

A now common application in irrigation is to use remote sensing to evaluate crop factors for use in irrigation scheduling. In this case, the data have usually been processed to highlight differences in crop condition using a Normalised Difference Vegetation Index (NDVI) (see Figure 3). Various researchers have found relationships between NDVI and crop coefficients for a broad range of crops (e.g. Hunsaker *et al.*, 2003; Belmonte *et al.*, 2005; Johnson *et al.*, 2006; Trout and Johnson, 2007; D'Urso *et al.*, 2008; Hornbuckle *et al.*, 2009b). An alternative to the use of NDVI is the prediction of actual crop evaporation using remote sensing of the energy balance (e.g. Gowda *et al.*, 2008a&b; Chavez *et al.*, 2009). Both approaches offer the means to obtain large scale, low cost, site specific crop evaporation data to assist in site specific irrigation management. The energy balance approach is still in the development stage whereas systems using NDVI are in use in various parts of the world.

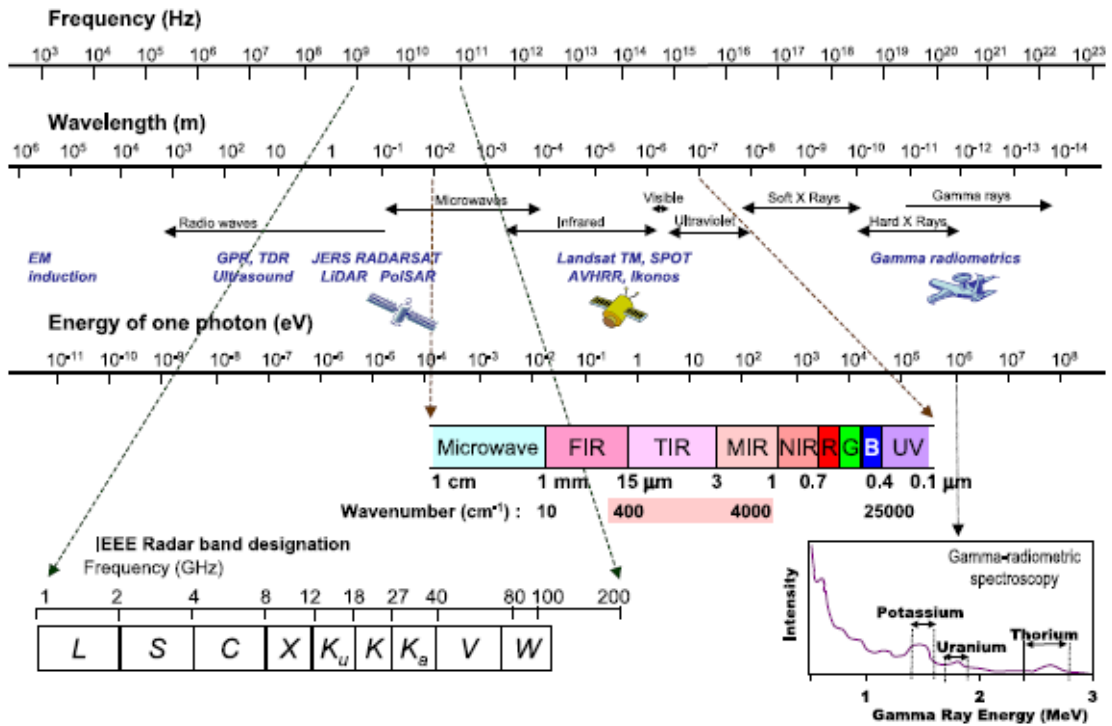


Figure 2 The electromagnetic spectrum and the frequencies useful for proximal and remote sensing (McBratney *et al.*, 2003) showing the frequencies for the EM, radar, infra-red, visible and ultra-violet wave bands

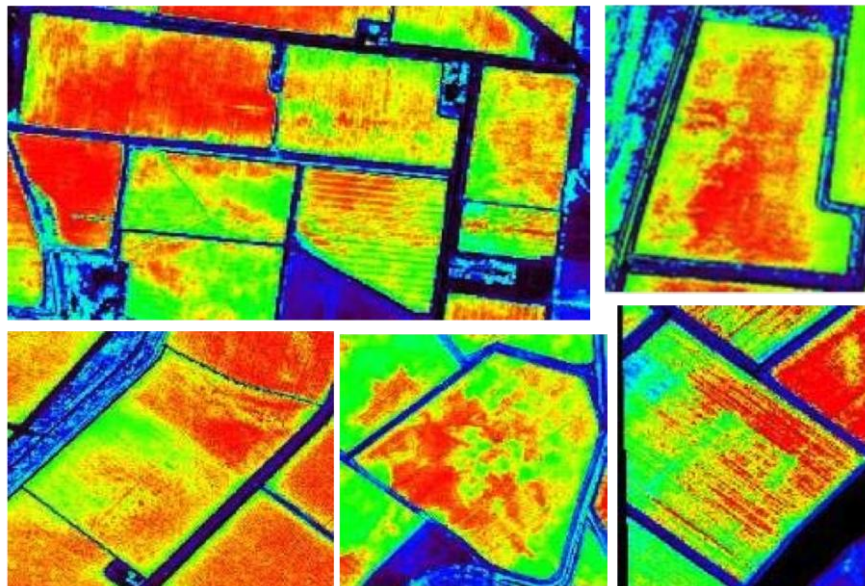


Figure 3 Example NDVI images of cotton fields in the Dawson Valley Irrigation Area (2003-04)

By way of example, during the 2005 irrigation season in California, a system for providing ‘nowcasts’ and forecasts of irrigation critical information using a combination of satellite images with a 4 × 4 m resolution and ground based E_{T0} reference station networks (Johnson *et al.*, 2006). These were combined with a soil water balance model and used to generate critical irrigation information such as soil water content, crop water stress and irrigation demand.

The automated system streamlines data retrieval from the various information sources, pre-processing, integration, and soil water balance modelling and produces daily spatial values of leaf area index (LAI), soil water content, leaf water potential, cumulative applied irrigation and cumulative water stress. Weather forecast information could also be used in the system to specify irrigation recommendations based on water stress levels of the vine. The information system provided daily spatial coverage (such as those shown in Figure 4) to irrigators. These were available for viewing on the web by 9:00am each morning.

A similar approach, relating crop coefficients to NDVI which, when combined with traditional on-ground E_{T0} reference stations was used for estimating water use of irrigated crops spatially as part of the DEMETER (DEMONstration of Earth observation TEchnologies in Routine irrigation advisory services) project in Europe (Belmonte *et al.*, 2005). This information was then delivered to irrigators through multimedia message service features on mobile phones.

Locally, a project undertaken by the CRC for Irrigation Futures (Hornbuckle *et al.*, 2008) likewise used satellite derived NDVI values using the Landsat Thematic Mapper satellite as a low cost means of determining site specific crop coefficient information. When converted to a crop factor it is then used with reference evapo-transpiration from weather stations to provide paddock specific scheduling information. A basic water balance model is run using the weather station information in conjunction with the irrigators’ specific crop and management situation. This data is then converted into an actual pump/dripper run time to replace the previous day’s evapo-transpiration and is sent directly to the irrigator on a daily basis via the mobile phone SMS (see Case Study 10).

The focus of the system at this stage has been on delivering this irrigation scheduling information for irrigated horticultural crops on pressurised systems. The system was trialled with a number of wine-grape irrigators in the Murrumbidgee Irrigation Area during the 2007/08 irrigation season. Coupling of the Landsat satellite-derived crop coefficients and the SMS delivery service offers the potential to provide low cost, personalised (for crop type and management condition) irrigation scheduling information to individual irrigators across an irrigation district. Other benefits also include high spatial resolution of scheduling information (approx. 30 m × 30 m) which offers potential applications within a precision irrigation system to manage spatial variability within individual fields.

The use of satellite imagery in this way for slowly varying parameters such as NDVI or LAI is not prejudiced by the occasional cloudiness that occurs in the more humid irrigated areas.

All of the above studies used the remotely sensed data in conjunction with a soil water balance model. Barnes *et al.* (2000) suggested that the synergy between remote sensing

and crop simulation modelling was the future for management irrigations in precision agriculture. They demonstrated the capability by integration of the remotely sensed crop water stress index with the CERES-Wheat model to provide data on within-field variability in plant water requirements and yield response.

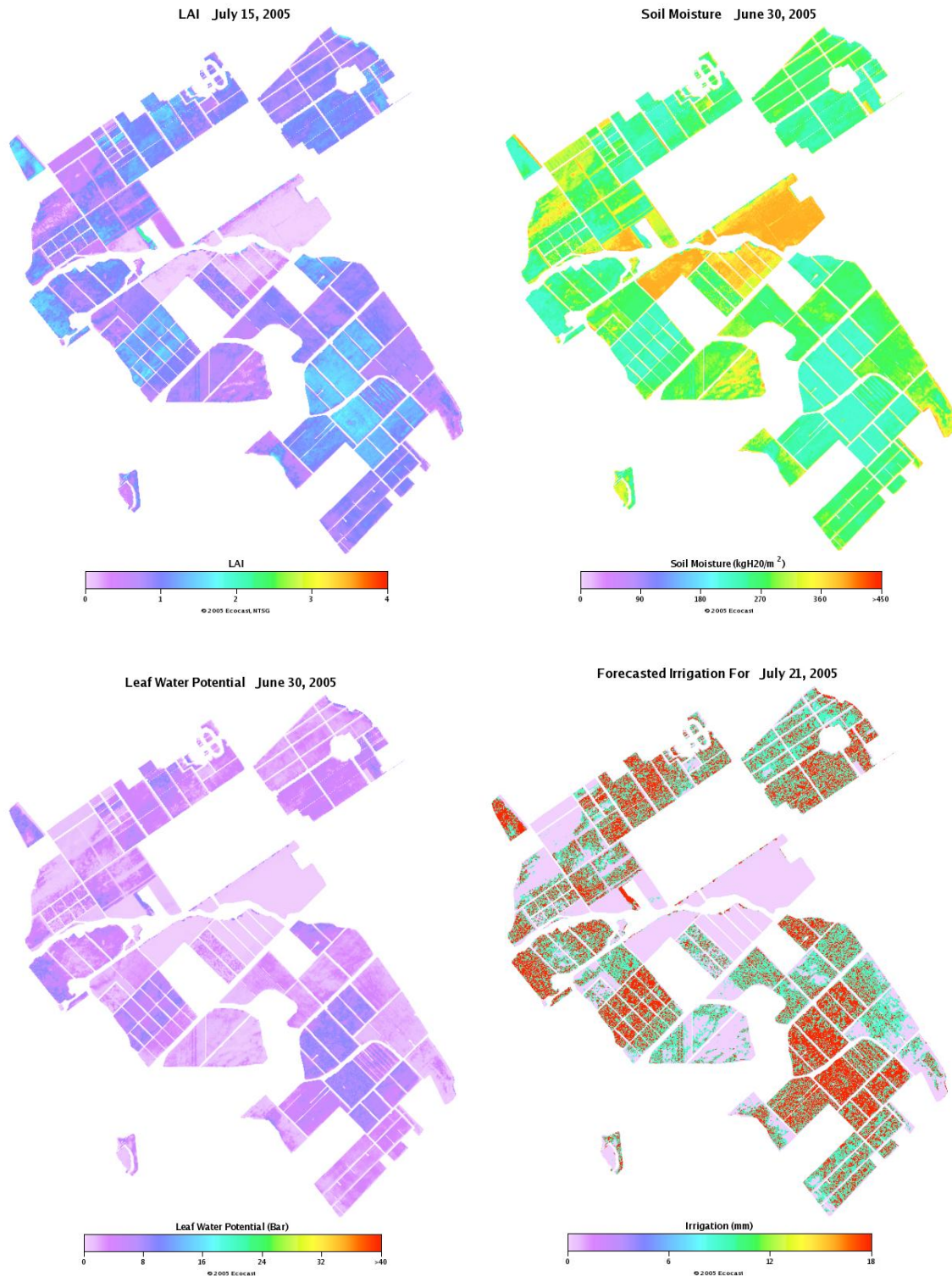


Figure 4 Soil water, crop variables and forecast irrigation for a 400 ha Napa Valley irrigated vineyard (reproduced from Johnson *et al.*, 2006).

An example of work in the visible range to sense plant characteristics is that of McCarthy *et al.* (2007) at the University of Southern Queensland. They developed a prototype machine vision system for the purpose of determining real-time cotton plant irrigation requirement. The unit relies on plant geometrical parameters such as internode length (i.e. the distance between successive branches on the main stem) as an indicator for water stress in cotton. The process for measuring the internode length is illustrated in Case Study 7.

Case Study 7: Vision sensing of crop responses

Sensing, of a host of climate, soil and crop variables, at appropriate spatial and temporal scales, is an essential component of precision irrigation. This example of vision sensing of plant structure and components illustrates an innovative method of determining the response of individual plants to irrigation.

Reproduced from: McCarthy, C.L., Hancock, N.H. and Raine, S.R. (2007) Field measurement of plant geometry using machine vision. Fifth International Workshop on Functional Structural Plant Models (SFPM07), Napier, New Zealand, November, pp 19.1-19.3.

An imaging system has been constructed that features a camera mounted in an enclosure with a transparent glass panel that forms the camera's field of view. The enclosure continuously traverses the crop canopy and makes use of the flexible upper main stem of the cotton plants to force individual plants against the glass window, and then smoothly and non-destructively guide each plant under the curved bottom surface of the enclosure. By forcing the plant against the glass window, the glass window becomes a fixed object plane which enables derivation of reliable geometrical data without the need for binocular vision.



Moving image-capture apparatus

The possibility for automatic, real-time, single-camera plant geometric measurement has been demonstrated. A camera enclosure that moves within the crop canopy is an effective and non-destructive method of collecting images suitable for analysis of plant geometry. For the dataset presented, the described image processing approach was effective at

identifying the main stem but further work is required to improve node detection before fully-automated inter-node length measurement is achieved. However, with the aid of some not-yet-automated procedures based on visual inspection, measurement of inter-node lengths to 3% standard error has been demonstrated.

Thermal Sensing

The crop canopy temperature provides a relative measure of transpiration rate and an indication of crop stress. Non-contact infrared thermometers and cameras measure the radiant energy (i.e. temperature) of an object within the thermal infrared electromagnetic wavebands. Canopy temperature measurements are compared to those obtained from a non-water stressed and a non-transpiring crop, and most commonly expressed as a crop water stress index (CWSI) (see for example, Irmak *et al.*, 2000). Baseline values are required to be identified for crops under local conditions.

The main advantages of thermal sensing for commercial applications in precision irrigation systems can be attributed to the non-contact real-time capacity of the devices. IR cameras and multipoint measurements using IR thermometers provide the capacity to map spatial variations across a field. Research systems which autonomously schedule variable rate irrigations using thermal sensing are currently being evaluated, including work currently being undertaken in the USA (e.g. Peters and Evett, 2007, 2008) and University of Melbourne (Land and Food Resources, 2008).

Peters and Evett (2007, 2008) scheduled irrigations and controlled centre pivot and drip systems using a temperature-time threshold (TTT). The TTT method involves using infrared thermocouples to continuously and remotely sense crop canopy temperatures. If a threshold canopy temperature is exceeded for a predetermined threshold time, an irrigation is scheduled. Their work has shown the TTT method to be a viable alternative to traditional irrigation scheduling. Mounting an array of sensors on a centre pivot provides the means to manage spatially varied irrigations.

A collaborative project (Land and Food Resources, 2008) between the University of Melbourne Dookie Campus and the Department of Primary Industries Tatura commenced during the 2007/2008 growing season investigating the application of remotely sensed thermal imagery to irrigation management. Researchers are utilizing a 6 metre long tethered blimp, with optical and thermal cameras attached, to collect images from up to 90 metres above the ground in order to monitor variation in plant water stress across vineyard and orchard blocks, and irrigated dairy paddocks (Figure 5).

6.1.4 Soil-Water Sensing

Readers are referred to (Charlesworth, 2005) for information on current soil water monitoring equipment and techniques, their use in traditional irrigation scheduling, extending to their use as controllers in automated irrigation systems. Other useful reviews are provided by Evett (2007) and Evett *et al.* (2007).

Soil moisture content in the crop root zone varies both spatially and temporally. Moisture in this zone is critical to plant development and health, so understanding the variability and dynamics of moisture distribution in this zone is crucial for optimal irrigation and crop management. Consequently, the purpose of this section is to consider the use of soil

moisture monitoring in a precision irrigation context and in particular the work toward inexpensive non-invasive techniques capable of mapping of soil moisture at relevant spatial scales.

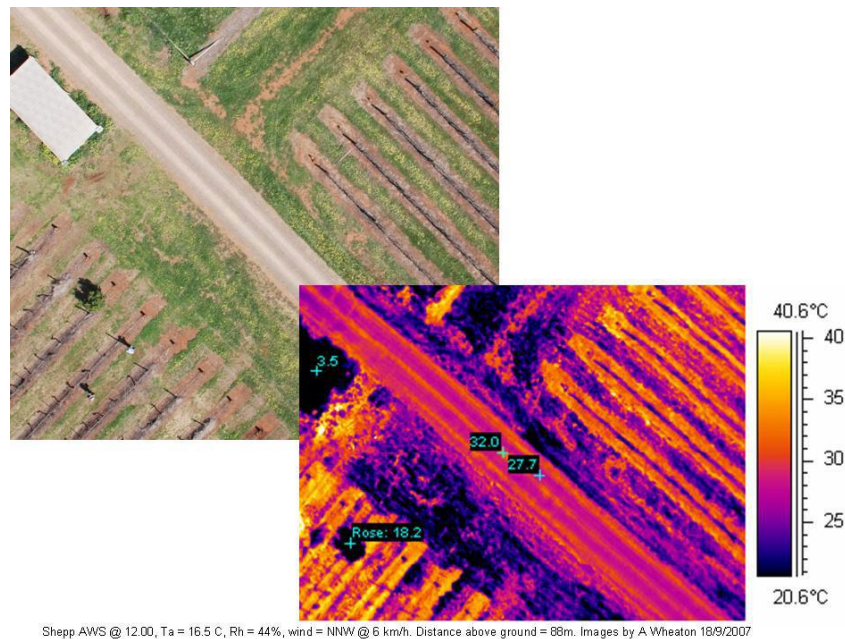


Figure 5 Remotely sensed optical and thermal imagery across a vineyard (reproduced from Land and Food Resources, 2008)

Many have recognised the ground based EM38 and ground penetrating radar as likely candidate techniques.

The EM38 electromagnetic induction sensor is a tool for measuring apparent electrical conductivity in soils. It can be used to infer a range of soil properties, including soil moisture, providing the other soil properties that influence the electrical conductivity, such as texture and electrolyte concentration remain relatively constant. Due to its ease of use, robustness, rapidity, large data capture and large volume of soil measured compared to other soil moisture sensors, EM38 has potential for use in irrigation management. The ability to configure an EM38 for on-the-go sensing and mapping of soil apparent electrical conductivity (EC_a), means high resolution soil maps can be produced that may significantly aid in the management of agricultural fields (Hossain, 2008; Hossain *et al.*, 2008).

In a recent local study by the CRC for Irrigation Futures, Hossain (2008) and Hossain *et al.* (2008) used EM38 to measure and map soil moisture content in the root zone of an irrigated cracking clay soil. This study was deliberately confined to a small study area with uniform soil, both spatially and at depth, to minimize the influence of factors other than soil moisture on EM38. They concluded that the apparent electrical conductivity (EC_a) data produced by the commercially-available EM38 unit can be used with calibration to imply soil moisture in the root zone of agricultural crops. They also suggested that the EM38 proved to be a useful technique for understanding paddock scale soil moisture variability in the root zone. Padhi and Misra (2009) concluded similarly. Despite the optimistic conclusions by the above authors, a more dispassionate assessment

of the results suggests that EM38 can give a spatial picture of soil moisture variation but must be supported by accurate spot measurements of soil moisture content.

Collaborative research in New Zealand between the Centre for Precision Agriculture at Massey University and Landcare Research applied electromagnetic induction techniques for mapping soil water status and managing variable rate irrigation (Hedley, 2008; Hedley & Yule, 2009a&b). The EM38 sensor was used to map soil variability and from this information management zones are identified. The plant available water-holding capacity of each management zone was measured by taking soil samples between very wet and very dry. Aquaflex TDR soil moisture sensors were used to monitor soil moisture to 60cm soil depth, on an hourly basis in each management zone. This enabled the calibration of an EM map for plant available water-holding characteristics, so that a soil moisture map could be produced. A daily time step was then added to this soil moisture map so that as soils dried out, the zones which dried fastest, and therefore reached the trigger point for irrigation, were identified.

The use of ground penetrating radar (GPR) for spatial mapping of soil moisture has received some attention internationally but little so far in Australia. For example, Huisman *et al.* (2003a&b) have reviewed the role of GPR and compared it to the traditional time domain reflectometry. They concluded that GPR provides the means to accurately and consistently monitor the development of spatial water content variation with time, sufficient to warrant further work on this technique. A review of the use of geophysics for the Australian irrigation sector (Allen, 2007) made mention of the possible uses of GPR but could point to no local applications.

6.1.5 Other Sensing Applications

Rainfall

Rainfall is a significant component of the water balance and its intensity and magnitude is known to vary substantially over relatively short distances. Spatially variable irrigation applications only make sense if the soil moisture deficit can be predicted at the same spatial scale as the applications. This will only be possible if the rainfall can be measured or estimated at the same spatial scale. The use of short range radar to measure rainfall intensity and amount at hydrologic scales has been demonstrated by the Danish Hydrological Institute (DHI), for example, Jensen and Pedersen (2005). Case Study 8 describes this work in more detail and poses the question of whether the scale can be reduced sufficiently for use in management of spatially varied irrigation.

Salinity

There has been significant research and educational inputs into improving water use efficiency over the past 20 years. Highly efficient irrigation with moderately saline water often results in insufficient leaching of residual salts, which in-turn threatens the sustainability of irrigated enterprises. Many Australian grape growers in south eastern Australia have reported elevated levels of sodium and chloride in leaves and berries. It is now very critical to put effort into managing root-zone salinity (Misra *et al.*, 2005).

Leaching flows required for maintenance of desired root zone salinities will in some situations will dictate the upper limit of irrigation application efficiencies that can be achieved by precision irrigation. In those situations monitoring of root zone salinity will be required on an on-going basis. Case Study 9 provides an example of an inexpensive simple salinity meter that can be used to measure root zone salinity in a wide range of soil types and moisture conditions.

Case Study 8: Measurement of the spatial variability of rainfall using local area radar

This case study shows that it is possible to use radar to estimate the depth of rainfall at scales down to 10,000 m² for use in catchment management and estimation of runoff. It remains to be seen if the spatial scale of measurements can be reduced to the sub-field scale required for irrigation purposes.

Source: DHI Water & Environment. "Weather radar and rainfall forecasting."
<http://www.dhigroup.com/Solutions/WaterAndEnvironmentalManagement/Radar.aspx>
(Accessed November 2008)

One of the most important parameters in the forecasting system is timely knowledge about the amount and distribution of precipitation over the catchment. By the introduction of the LAWR (Local Area Weather Rader) it is now possible to gain information on this information with a time resolution of 5 minutes and a space resolution of 500 by 500 m down to 100 by 100 m.

The high resolution of 100 by 100 m can be obtained up to a maximum distance of 6 to 10 km from the radar (this is true for ANY weather radar having a horizontal beam width on one degree, since the beam width exceeds 100 m in a distance of 5.7 km from the radar). Although the LAWR radar emits only a tenth (25 kW) of the power emitted from conventional weather radars (250 kW) is capable (within its range of operation, 60 km radius) to penetrate high intensity rainfall.



Short range radar installation

The radar only “see” falling rain, and the measured reflection is converted via an empirical form into rainfall intensity. A procedure has been developed to calibrate the radar using rain-gauge measurements. The resolution given by most rain gauges (0.2 mm) is insufficient for calibration of the radar since substantial time lack can occur between the rain event and the actual registration (timing) of rain. DHI has therefore developed a rain gauge with a resolution of 0.01 mm. Using this information a linear calibration function can be established having a correlation $R^2 = 0.83$. A rain gauge of this type (resolution) is required for this more precise calibration.

Case Study 9: Monitoring rootzone salinity – the SoluSAMPLER™

Leaching flows required for maintenance of desired root zone salinities will in some situations will dictate the upper limit of irrigation application efficiencies that can be achieved by precision irrigation. In those situations monitoring of root zone salinity will be required on an on-going basis. The SoluSAMPLER™ is an example of a new technology that may fill an important role given resolution of the uncertainties relating to the placement of the sensors especially under systems such as drip irrigation that exhibit strong 2 or 3-D salinity gradients. The development of the SoluSAMPLER™ was partly funded by NPSI.

Extracted from:

Biswas, TK, Schrale, G and McCarthy, M (2008) Real-time vineyard root zone salinity monitoring with a modified suction cup. Proc 2nd Intl Salinity Conf, Adelaide Convention Centre, 31 Mar – 3 Apr.

and:

SARDI Irrigation and Salinity Fact Sheet Number 1, August 2008

The SoluSAMPLER™ is a modified porous suction cup designed to extract a soil pore water sample of up to 70 mL at 60-70 kPa suction created by using a plastic syringe. The soil water samples can be analysed in-situ for electrical conductivity (EC_{sw}) as well as other parameters such as pH and nutrient composition. It is recommended that the SoluSAMPLER™ be installed in nests of three, positioned at depths of 0.3 m, 0.6 m and 0.9 m within 0.15 m of a dripper (assuming dripper spacing of 0.6 m) or at a representative site within the wetting zone of a sprinkler. Replication of depths across a vineyard will enhance the accuracy of data produced. Installing at multiple depths permits the tracking of salts as they move through the profile over time. EC_{sw} values can then be averaged to estimate the average annual soil water salinity encountered by the crop at each depth. This device also permits the tracking of nutrient status in the profile during the growing season. Whilst there are other devices and techniques available to monitor root zone salinity, the permanently installed SoluSAMPLER™ provides real-time EC_{sw} with minimal effort, expense or disturbance to the root zone. Such information will assist irrigators in make informed decisions on the requirement for and effect of leaching irrigations.

The greatest advantages of the SoluSAMPLER™ are its convenience to install and that the results are instantly available to the irrigators. They can extract the soil water sample and, with the aid of a simple hand held EC meter, measure its salinity in the field. Analysing soil water samples and plotting the results on a timeline allows the irrigator to view trends in salt and nutrient transport through the profile.



SoluSAMPLER™ - a grower tool for monitoring root zone salinity

6.1.6 Research Opportunities in Monitoring Tools and Technologies

Further development of low cost measuring technologies (e.g. soil moisture and crop measurement tools) allowing a shift from point to field and farm decisions, at a density that captures the spatial variability within the field to facilitate precision irrigation is necessary to support the implementation of precision irrigation on Australian farms.

A report by Misra *et al.* (2005) identified priority opportunities to refine and/or develop new tools and technology to increase on-farm measuring and monitoring capability. The technology gaps and research opportunities identified in soil water and plant use measuring and monitoring technologies (Tables 2 and 3) are still relevant and provide a useful overview of where further work is required.

Table 2 Technology gaps and research opportunities in soil water measuring and monitoring technology (Reproduced from: Misra *et al.*, 2005).

Technology gap	Research opportunities
Root zone is assessed from manual measurement of rooting depth or from soil water depletion data.	Reliable method or technique is needed to define root zone of an actively growing crop.
Safe, easy to use soil moisture instruments with a wide measurement sphere (radius ~ 20 cm) are not available. Inexpensive sensors are needed to allow sensing of soil moisture at many locations in the field. Low cost communication networks are needed to link multiple soil moisture sensors for reporting to single point. Easier and better methods are needed to calibrate and validate sensors.	Need to develop safe, easy to use, low cost soil moisture instruments with a wide measurement sphere (radius ~ 20 cm) to enable many installations in the field. Low cost communication networks are needed to link multiple sensors for reporting to single point Improved calibration and smart software needed for volume measurements as well as for soil moisture trend analysis and irrigation scheduling.
Least Limiting Water Range (LLWR) and Integral Water Capacity (IWC) are more recent concepts similar to plant water availability which have not been evaluated in irrigated soils.	Easier, more reliable, accurate and less expensive method using current or new concept of plant available water (PAW) estimate should be evaluated using more realistic water potential thresholds.
Low cost deep drainage metering equipment is not available.	Deep drainage may be occurring in wide areas in irrigated fields. Alternative, simple and low cost techniques and/or models needed to quantify this loss.

Table 3 Technology gaps and research opportunities in plant water use measuring and monitoring techniques (Reproduced from: Misra *et al.*, 2005).

Technology gap	Research opportunities
There are few tools and techniques that use measurement on plants or plant parts which could be used to schedule irrigation.	There is little plant based technology available that could be directly used by a grower or consultant to advise time or quantity to irrigate. Thus, new tool or technology is required to integrate with current irrigation system.
Need more testing to determine critical values of stem water potential for important crops. Need more testing of IR thermography and similar mobile technology.	Stem water potential, IR thermography and mobile sensing technology need further testing along with standard measurements to establish critical values and times of plant water stress.
Mobile, low altitude sensors may provide better resolution and improve application than conventional satellite imagery and remote sensing to measure crop water stress.	New mobile technology is needed to determine irrigation requirement that integrates well with irrigation system.
Estimation of ET is uncertain without adequate evaluation of resistance and crop factors.	More information on aerodynamic and canopy resistance and crop factors is needed.

6.2 Decision Making: Tools & Technologies

6.2.1 Management Objectives

The inadequate development of control and decision support systems for implementing precision agriculture decisions has been identified as a major stumbling block to the adoption of precision agriculture (McBratney *et al.*, 2005). This is likely to also be the case for precision irrigation where the scope of irrigation control systems reported in the current literature is limited.

Current irrigation management (whether manual or using controllers) generally involves irrigating the crop on preset days and apply a predefined irrigation volume (e.g. Evett *et al.*, 2006) or a volume corresponding to the crop's needs as indicated by climate or soil moisture data (e.g. van Bavel *et al.*, 1996) and without considering spatial variability. The most common approach is to apply a fixed volume of water at regular time intervals, conditional upon prevailing weather forecasts. The duration of the irrigation event is either a fixed period of time (e.g. Dukes & Scholberg, 2004 for drip irrigation; and Evett *et al.*, 2006 for centre pivot irrigation) or a calculated period of time corresponding to the crop's needs (e.g. van Bavel *et al.*, 1996 for drip irrigation). 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).

Optimal control strategies implied by the notion of precision irrigation must consider multidimensional issues (e.g. crop response, crop age, target yield and management constraints). One of the key challenges in developing suitable decision support systems or more particularly decision making systems is that they must support the goals (yield, quality, water, environmental) specific to the particular enterprise. They must take into account crop physiology, soils, irrigation system limitations, water supply limitations and economic requirements. They also need to be responsive to current weather and crop conditions.

6.2.2 Current Delivery of Irrigation Management Decision Support Systems

The decision making tools in the previous section are all designed to operate with automated irrigation systems with the data collection, decision making and irrigation control integrated into the one precision irrigation system. As an alternative to this approach, two different Australian projects (WaterSense and IrriSatSMS) have explored centralized methods for providing irrigation decision making tools to a large number of irrigators.

Adoption of decision support services (DSS) based on crop growth models has been poor and yet the concept of transferring an increasing body of scientific knowledge via DSSs remains attractive (Inman-Bamber *et al.*, 2000). In response to this, WaterSense, a web based irrigation scheduling service was developed for the sugarcane industry.

WaterSense (Inman-Bamber *et al.*, 2007) was developed to help growers with limited

water to plan irrigation through the season with these uncertainties by working out the most likely yield achievable with a given allocation, soil type, planting or ratoon date and past rainfall and irrigation. WaterSense then schedules irrigation to meet this yield target, which can change as actual rainfall deviates from historical records and with changing allocation. WaterSense combines up-to-date weather data, entry of paddock details, crop growth simulations, routines to identify optimal irrigation strategies to deliver a plan or schedule for irrigations for the remainder of the season. Irrigators are also able to compare their own soil moisture measurements with those predicted by WaterSense and are able to adjust irrigations accordingly.

A key difference between WaterSense and many other irrigation scheduling systems is the optimization of irrigation scheduling throughout the entire season and the ability to readjust this schedule throughout the season. This moves the DSS from an exploratory simulation tool to a tactical irrigation tool. It should be noted that WaterSense operates at the paddock scale only so it is unable to address within field spatial variability.

In contrast, IrriSatSMS (Hornbuckle *et al.*, 2009) uses a basic water balance model run using the weather station information and NDVI satellite information in conjunction with the irrigator's specific crop and management situation. This data is then converted into an actual pump/dripper run time to replace the previous day's evapotranspiration and is sent directly to the irrigator on a daily basis via the mobile phone SMS system (see Case Study 10). The scale of the data collection is such that spatial variability could be addressed (down to 30m × 30m). However, IrriSatSMS essentially manages systems at the current soil moisture and does not allow for the temporal optimisation of irrigations, particularly where water supplies may be limited.

Case Study 10: SMS Irrigation scheduling service

A decision support system for water management (this term is preferred over the somewhat limiting term irrigation scheduling) is an essential component of any precision irrigation system. The following example is the latest of the many scheduling services that have been offered to growers (and often later rejected). Like its predecessors it is separated from the other aspects of irrigation management (such as optimisation of the application system) which are required if the full benefits of scheduling are to be realised. Further, like its predecessors it has the potential for integration into precision systems.

Extracted from: Hornbuckle, J.W., Car, N.J., Christen E.W. & Smith, D.J. (2008) Large scale, low cost irrigation scheduling – making use of satellite and ET₀ weather station information. Irrigation Australia 2008, National Conference and Exhibition, 20-22 May, Melbourne.

Irrigation scheduling is an important aspect in maximising yields and improving water use efficiency but many irrigators still do not utilise quantitative tools for irrigation scheduling. This is due to a number of reasons related to cost and ease of use of equipment along with social aspects. At the last census only 20% of growers used some form of soil moisture monitoring device for irrigation scheduling with many still relying on 'gut feel' or non-quantitative measures.

This paper outlines an irrigation scheduling approach using the reference evaporation (from weather stations) with crop coefficient approach which has existed for the past 30 years and shown to be robust scientifically, but has been difficult to apply practically. While weather station determinations of reference evapo-transpiration (ET_0) are practical and easy to access in most irrigated regions, the difficulty has been in determining localised crop coefficient (K_c) information. Crop coefficients are affected by management (irrigation, fertiliser etc), soil type and varietal differences and often show variation even within crops in the same region due to these factors. This has proven a major limitation to applying a reference evaporation with crop coefficient approach for providing practical scheduling information on a per paddock basis.

Recent advances in remote sensing have seen the use of visible and near infrared light wavelengths used for determining vegetation indexes. These indexes, particularly the Normalised Difference Vegetation Index (NDVI) have the potential to be used for providing site specific crop coefficient information. A number of authors have found linear relationships between NDVI and crop coefficients for a broad range of crops. These relationships allow a practical method which can be used to gain large scale, low cost, site specific crop coefficient information which can then be used with reference evapo-transpiration from weather stations to provide paddock specific scheduling information. This crop coefficient derivation process is described in this paper together with a description of a Short Message Service (SMS) used to provide this information through a simple mobile phone text message to irrigators on a daily basis.

6.2.3 Adaptive Control

An irrigation control strategy can use historical data and/or quantitative measurements of crop status, weather and soil, either singularly or in combination, to automatically adjust the irrigation application. In contrast, an 'adaptive' control strategy uses these data to locally 'modify' the control, as required, to account for temporal and spatial variability in the field.

A control system is a system that controls the operation of a process. Control systems consist of the process being controlled, a controller, and measurement system for feedback control. It may also include simulation or decision support software.

Two major configurations of control systems are open-loop and closed-loop control systems. An open-loop control system uses known relationships between the process input and output to adjust the controller parameters. It does not monitor the output of the process. Many existing control strategies for irrigation described in the literature (particularly for surface irrigation) simply initiate an irrigation event, rather than decide an irrigation amount. The systems rarely account for spatial and temporal variability, and are usually open-loop, i.e. they do not monitor the response of the crop to the irrigation. A closed-loop control system measures the output of the system and adjusts the controller parameters based on the difference between the input and the measured output. This difference is called the error signal. A closed-loop irrigation control system would monitor the plant or soil moisture response output and aim to reduce the magnitude of the error by feeding the error signal to the controller.

Much of the control theory presented in the literature assumes that the system never varies with time once identified (Warwick, 1993). However, the characteristics of many real world systems vary with time. For example, characteristics of an irrigation system (crop growth, soil type and climate) vary within and between crop seasons, altering the optimal amount of irrigation to be applied to the crop. To achieve this it is necessary to automatically and continuously retune the control system to retain the desired performance of the system. A control system with such an adaptive structure is called an adaptive control system (Warwick, 1993). The generally accepted definition of adaptive control is a system that adjusts its controller parameters based on sensor feedback from the process such that the controlled process behaves in a desirable way. A generalised block diagram of an adaptive irrigation control system is given in Figure 6.

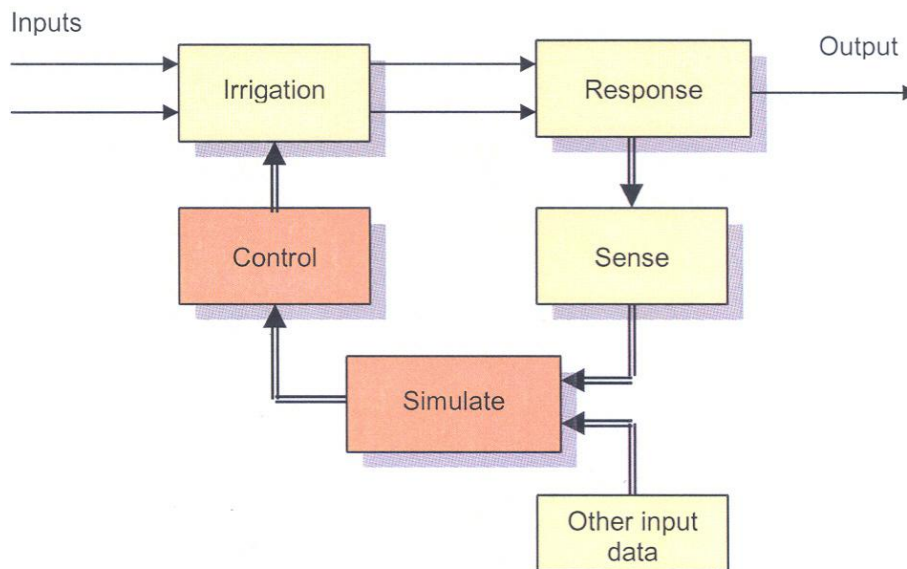


Figure 6 Conceptual model of a real-time adaptive control system for irrigation applications

While most literature focuses on the design of automatic control devices that 'learn', that is, to improve their performance based upon experience, it is important to recognise that adaptive systems can be human based as well as machine based as illustrated in Case Study 11. The authors of the present report would argue that the term 'adaptive control' should not be seen as an engineering term and should not imply that the learning or adaptation is machine based. All irrigation systems must be controlled and the control may be manual with the adaptive learning being provided by the irrigator. Additionally, we would argue that the perception that machine based irrigation control is not holistic is as a result of the current limitations of decision making systems. Many of those currently used in irrigation are essentially automated systems combined with irrigation scheduling (eg. Uniwater, 2008), and have no learning capability. This represents a significant gap in current precision irrigation research.

Case Study 11 : Adaptive learning through combined information

This case study illustrates that adaptive systems can be human based as well as machine based. The various strands of knowledge considered in this case study are essential components of precision irrigation and apply irrespective of whom or what is doing the ‘learning’. The term ‘adaptive control’ should not be seen as an engineering term and should not imply that the learning or adaptation is machine based. All irrigation systems must be controlled and the control may be manual with the adaptive learning being provided by the irrigator.

Reproduced from: Irrigation Update, Vol 9, Irrigation and the Rootzone, NPSI, December 2008.

Individual research projects often focus on just one factor and may tend to view a particular management issue in engineering terms with a focus on the associated command and control strategies for that single factor in isolation from all the others.

Richard Stirzaker, of the Cooperative Research Centre for Irrigation Futures, believes it is necessary to incorporate a more holistic “adaptive learning” approach that brings together various strands of information, including “local knowledge”, about what is happening in the root zone.

“If we think of irrigation management as an engineering problem, then we will think in terms of command and control strategies. If we think of irrigation management as but one part of the complex business of running a profitable farm, then we should think in terms of adaptive learning,” Dr Stirzaker said.

His research project aims to demonstrate how the collection of five independent strands of irrigation data via a novel sensor and logging platform will link irrigator experience with measured data, link atmospheric scheduling with soil-based monitoring, and link water management with solute management. The project will be carried out in seven locations around the country together with expert practitioners from different sectors of the irrigation industry.



Collecting irrigation data via a sensor and logging platform

6.2.4 Data Complexity in Precision Irrigation

The simple block diagram, presented as Figure 6, shows sensing of only a single response (or variable) with some other input data also being provided. However, the control system required for precision irrigation will in all likelihood require the sensing of the multiple variables (i.e. plant, soil and weather data) and provision of other data from a range of sources. An expanded version (McCarthy *et al.*, 2008) of the block diagram is given in Figure 7 showing the extent of sensing required (although not all of the variables may be necessary for any particular irrigation control).

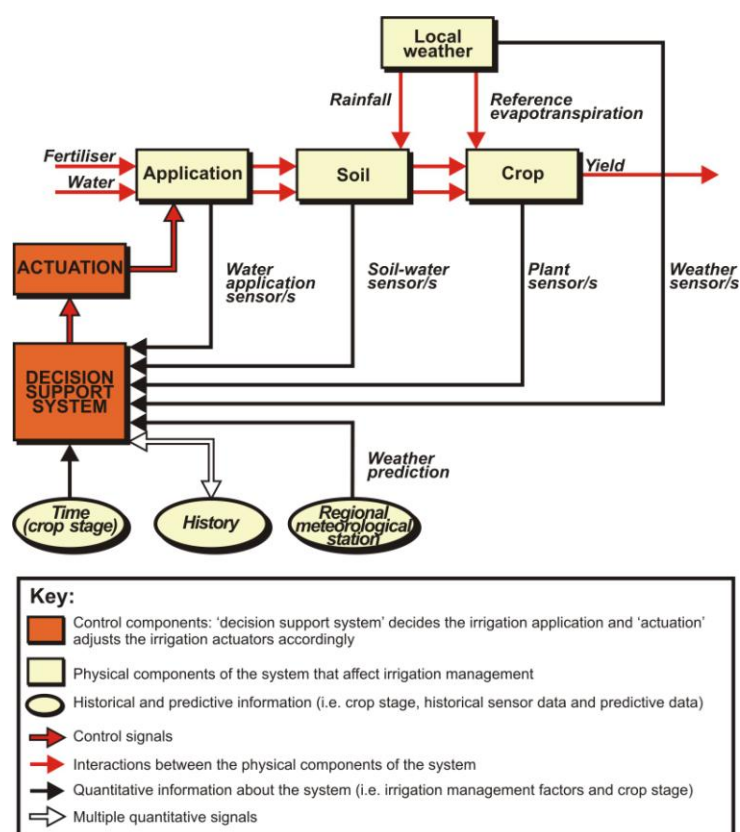


Figure 7 Conceptual adaptive control system for precision irrigation (McCarthy *et al.*, 2008)

The data includes manual measurements (e.g. a sensor reading or observation for a location in the field); websites (e.g. predicted meteorological data); bitmaps (e.g. NDVI image, aerial and in-field photos, EM38 maps); text files (e.g. Australian Bureau of Meteorology SILO point ET data); or sensors in real-time (e.g. weather station). Data may be collected spatially across the field (e.g. from an electromagnetic soil moisture (EM38) survey) at a high spatial resolution. Other data such as the spatial pattern of the depth of water applied in each irrigation may be provided either by direct measurement of by simulation of the performance of the application system. Some data may also be available only at a limited number of points in the field (e.g. from in-field soil moisture probes).

The system may need to interpolate sparse spatial data to estimate field data at a higher spatial resolution. For some sensor variables, only one data reading may be available for the whole field (e.g. rainfall) and the presumption that this value is constant across the field may be questionable. Therefore, the system may need to introduce additional variation (data 'noise') to the input variables to predict the effect of unmeasured variability.

Data will also be available at very different temporal scales, i.e. data may be available at a daily time step (e.g. from a soil moisture probe) or a weekly time step (e.g. for manual measurements).

McCarthy *et al.* (2008) summarised the various control alternatives based on the complexity of data used in the control system (Table 4). In agricultural environments, cost and practicality requirements commonly mean that some data may be unavailable. For example, it is common that only one soil moisture sensor is used in a field despite a range of soils being present. In this case, another method may be required for data deficient areas of the field. This may be use of a surrogate for the particular data which can be correlated with those data (e.g. EM38 for soil moisture) or use of a different variable which can be sensed over the particular area (e.g. evapo-transpiration and on-the-go plant sensors). Hence, to ensure the control system is robust to data availability, the ideal control system would employ data from plant, soil and weather sensors. Depending on the data available in different areas of the field, the system might use these data either singularly or in combination in different ways over the area of the field. Such a control system would be robust to data gaps and deficiencies, while maintaining a minimum level of control performance.

6.2.5 Decision Making Systems

By simulating and evaluating adaptive control strategies in a simulation framework, optimal adaptive control strategies to decide irrigation volume and timing may be identified. The simulation framework must allow for a range of field conditions in which data is available at various spatial and temporal scales. The various conditions and the capabilities of simulation software for adaptive irrigation control are discussed in Smith *et al.* (2009).

Many software tools are available to improve the precision of irrigation and water management. Readers are referred to Chapman *et al.* (2008) and Inman-Bamber and Attard (2005) for comprehensive reviews of available software including details of the technology, benefits, applications, limitations, barriers to adoption and promotion and further development needs.

However, there are very few crops where detailed information is available regarding production responses to variable inputs throughout the growing season. Hence, the major stumbling block to the introduction of effective prescription irrigation systems is the necessary understanding of the crop production systems and the ability to identify the interactions between the various crop inputs, productivity gains and operating constraints/costs.

Table 4 Dimensions of data complexity in conceptual adaptive control systems applied to irrigation (Source: McCarthy *et al.*, 2008)

Level of data complexity	Method	Possible sensors
History-based	This involves irrigating the crop at certain stages in the season as per previous irrigations.	Historical plant, soil and weather data
Soil-based	The soil water potential or soil moisture content can be used directly to determine the irrigation requirements.	Soil moisture content, soil water potential
Weather-based	This control strategy uses data from weather station/s and other regional sources (e.g. Bureau of Meteorology). For example, evapo-transpiration and solar radiation data from the weather station may be used in a water balance model (which involves balancing the water losses and uptakes of the plant root zone) to determine the irrigation schedule.	Weather station, predictive meteorological data
Soil- AND weather-based	Soil moisture data may be used to calibrate the water balance model and adjust the crop coefficient and readily available water values as required.	As for soil- and weather-based control
Plant-based	The current crop response is monitored. This control strategy would apply an irrigation amount based on the current crop response from plant-based sensing (e.g. McCarthy <i>et al.</i> 2007, 2008). This method involves applying an irrigation amount determined using a predefined relationship between the crop response and crop water requirement.	Plant size and shape (e.g. height, projected foliage cover, stem diameter, internode distance), plant stress (e.g. thermal, infrared or hyperspectral responses)
Iterative plant-based	The change in crop response since the previous irrigation is monitored. The previous irrigation amount applied is evaluated based on the current and previous crop response. The process is repeated for each irrigation until an optimum is reached.	As for plant-based control
Plant- AND weather-based	This control strategy may use the water balance model. Plant-based sensor data can be used to more accurately estimate the crop coefficient used in the crop evapo-transpiration calculation.	As for weather- and plant-based control
Soil- AND plant- AND weather-based	All of the components in Figure 4 are used to control the irrigation. The soil data may be used to validate a water balance model.	As for soil-, weather- and plant-based control

The relatively recent development of crop simulation models for the pasture (Johnson *et al.*, 2008), grain (Keating *et al.*, 2003), cotton (Hearn, 1994), and sugar (Keating *et al.*, 1999) sectors provide the basis for decision making models which may enable the identification of optimal strategies. While these models are currently suitable for identifying irrigation requirements at the tactical decision level, most do not have the ability to identify an optimal irrigation strategy.

Inman-Bamber and Attard (2005) identified that the majority of the models operate at the paddock or point scales even if they present data for the whole farm. They assume the paddock is represented by the processes operating at a point in the paddock for which soil, plant and atmospheric conditions have been defined. Several of the tools present a summary of all paddocks simulated or monitored but interactions between paddocks on the farm are not represented. For example, an irrigation schedule for a farm may not take into account the real limitation of irrigating more than one paddock (or bay or set of

furrows) at a time or the progressive irrigation of a single field as in the case of CPLMs. It almost certainly will not take into account the spatial variability in applied depths across a field.

Thorp *et al.* (2008) have demonstrated how the DSSAT family of crop models can be calibrated to simulate spatial variability of crop yield and be used to manage the spatially variable crop inputs in precision agriculture, including irrigation prescriptions. Other examples are the modelling studies (Nijbroek *et al.*, 2003; DeJonge and Kaleita, 2006; & DeJonge *et al.*, 2007) used in Section 4.3.2. Progress has also been made in this area in VARIwise (McCarthy *et al.*, 2010) and for pasture systems by Uniwater (2008) however further work is required to extend the range of crops under consideration and in some cases, to increase the spatial resolution at which these simulation tools operate.

Of particular importance is further development of decision making systems that account for multi-dimensional issues such as crop response, crop age and management constraints. Decision making systems need to incorporate both crop simulation (agronomic issues) and irrigation system constraints (engineering issues) to ensure the optimal irrigation strategy achieves agronomic goals and can be delivered by the intended irrigation system. An example of this integration is proposed in the following Section 7.3 with the coupling of the seasonal water management capability of the VARIwise model with the irrigation event optimisation and control for surface irrigation systems.

Decision making systems must possess the ability to determine the best irrigation strategy under conditions of less than adequate water supplies (e.g. Rao *et al.*, 1992; Inman-Bamber *et al.*, 2000 & 2008). They require knowledge of the available water supplies at start of season and updates as the season proceeds. They must be able to consider the risk of alternative strategies and plan the use of the available water accordingly.

The irrigation component of crop models is often insufficiently precise to model the effects of different application strategies such as frequent light irrigations versus the similar depth of water applied in less frequent applications (Joseph Foley, pers com). Another significant issue with the use of traditional crop models in automated systems is that of calibration (Thorp *et al.*, 2008). An alternative approach is to use self learning models. These may be traditional crop models redesigned to learn (or self calibrate) from the current year's data (e.g. Haverkort *et al.*, 2002) or models based on neural networks (e.g. Kaul *et al.*, 2005). These are obvious areas for future development and calibration of the models.

7 FUTURE DIRECTIONS: SYSTEM INTEGRATION

Precision irrigation is an emerging field and further research and development is required before optimal precision irrigation systems can be implemented. This section suggests further work that could be undertaken.

The overarching hypothesis of adaptive irrigation control is that crop production responses and profitability can be increased and environmental impacts minimised by the identification of irrigation management practices which optimise the spatial and temporal scale of irrigation applications. However, this infers a number of component hypotheses (all of which should be priority areas for research). These include:

- b. that a substantial and manageable part of the variability in crop production responses within existing irrigation management units (i.e. fields) is related to water supply and its management (e.g. application uniformity and/or agronomic water use efficiency), and not to other constraints;
- c. that the variance in crop response to water within irrigation management units limits the productive capacity and profitability of the management units;
- d. that the optimal size of the irrigation management unit will be a function of the irrigation application system characteristics, environmental factors (e.g. soil, topography, microclimate) and the crop response (e.g. genetic) variances; and
- e. that optimising the spatial scale and temporal interval of irrigation management will increase crop biological responses (i.e. yield and/or quality) to water application and reduce losses of inputs (e.g. water and nutrients).

Hence, it is likely that the specific adaptive irrigation control requirements will be specific to the irrigation application system employed. However, in all cases there will be a need to:

- sense the water application and crop response at a scale appropriate for management,
- make a decision for improved irrigation management using both historical (and possibly predictive) data, and
- control either the current (in real-time) or subsequent irrigation applications at an appropriate spatial scale.

This leads directly to the conceptualisation of a precision irrigation system as one that can:

5. Determine the timing, magnitude and spatial pattern of applications for the next irrigation to the best chance of meeting the seasonal objective (i.e. maximisation of yield, water use efficiency or profitability);
6. Be controlled to apply exactly (or as close as possible to) what is required;
7. Through simulation or direct measurement knows the magnitude and spatial pattern of the actual irrigation applications and the soil and crop responses to those applications; and
8. Utilise these responses to best plan the next irrigation.

In other words we have a system that:

5. Knows what to do;
6. Knows how to do it;

7. Knows what it has done; and
8. Learns from what it has done.

The following sections discuss how this conceptualisation can be applied to the more common surface and mechanised irrigation application systems.

7.1 Surface Irrigation Systems

The controlled (or optimised) outputs in past examples of automated surface systems have been the depth of water applied (rather than crop yield) and the usual performance measures of efficiency and uniformity. The objective was typically a traditional uniform application over the entire field. Systems such as these account for the temporal variation in soil moisture deficits and soil hydraulic properties. However, varying the management to accommodate spatial variations in the soil infiltration characteristic is usually not considered.

Automated adaptive real-time control of individual irrigations could be expected to provide the highest level of irrigation performance and the potential for spatially varied irrigation application (Raine *et al.*, 1997; Smith *et al.*, 2005; Khatri & Smith, 2007)

In any case the tools and systems only optimised and controlled individual irrigation events and even if irrigations were scheduled scientifically the system will not necessarily return the maximum water use efficiency.

To optimise WUE a further layer of decision support is required. The crop response to the irrigations needs to be monitored and modelled continuously through the season to determine the irrigation timing and amounts that give the desired crop response. It will also serve to determine the preferred target (optimisation function) for optimisation of the individual irrigation events and to manage the effects of spatial variability along the length of the furrows or bays. For example it will determine:

- whether the best strategy is to maximise application efficiency, or uniformity, or requirement efficiency, or some compromise combination of these measures,
- whether or not the strategy will differ from irrigation to irrigation, and
- whether the optimisation strategy will vary after rainfall.

The VARIwise system of McCarthy *et al.* (2010) can provide this layer of real-time decision support. Although developed originally for control of applications from centre pivot and lateral move machines it has the potential to be a holistic irrigation management tool applicable to all irrigation application methods.

Similarly, Uniwater (2008) coupled the surface irrigation simulation model WinSRFR (Bautista *et al.*, 2009) with the DairyMod pasture production model (Johnson *et al.*, 2008) to predict WUE under automated and manually controlled bay irrigation. The predictions were retrospective to the irrigation season and hence were not integrated into the control system. However as with VARIwise, integration is a possible next step in the development of that work.

The progression of surface irrigation from its traditional form to precision surface irrigation is illustrated in Figures 8, 9 and 10. In its current form (Figure 8) surface irrigation relies very substantially on the expertise of the irrigator. Some irrigators may

apply scientific scheduling of irrigations and evaluation of the application system but they would be in the minority. Some, particularly bay irrigators may utilise some degree of automation.

Application of smart automation (with real-time control of the applications) is an obvious first step toward precision irrigation (Figure 9). If combined with scientific scheduling it has most of the requirements of a precision system. This then is the type of system described in Section 5.1, as proposed by Uniwater (2008) and Khatri and Smith (2007).

The complete conceptualisation of surface irrigation as a precision system is provided in Figure 10. In this case the irrigation applications are managed or optimised at the usual relatively large scale of the irrigation bays or sets of furrows. However, the yield and WUE predictions occur at a much finer scale, equal to the scale that the event simulation model can predict the spatial variability of the actual applications. The overlying decision model will take into account this known variability in the applications and will plan the future applications to minimise the effect of those spatial variations.

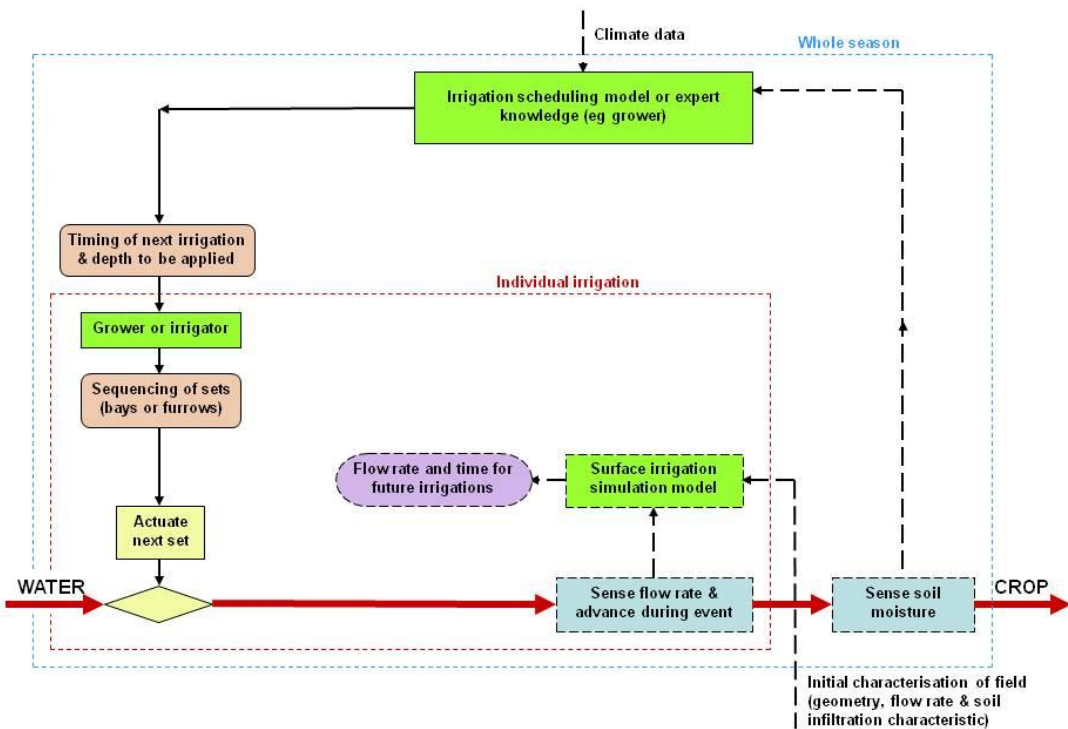


Figure 8 Traditional surface irrigation (automated or manual)

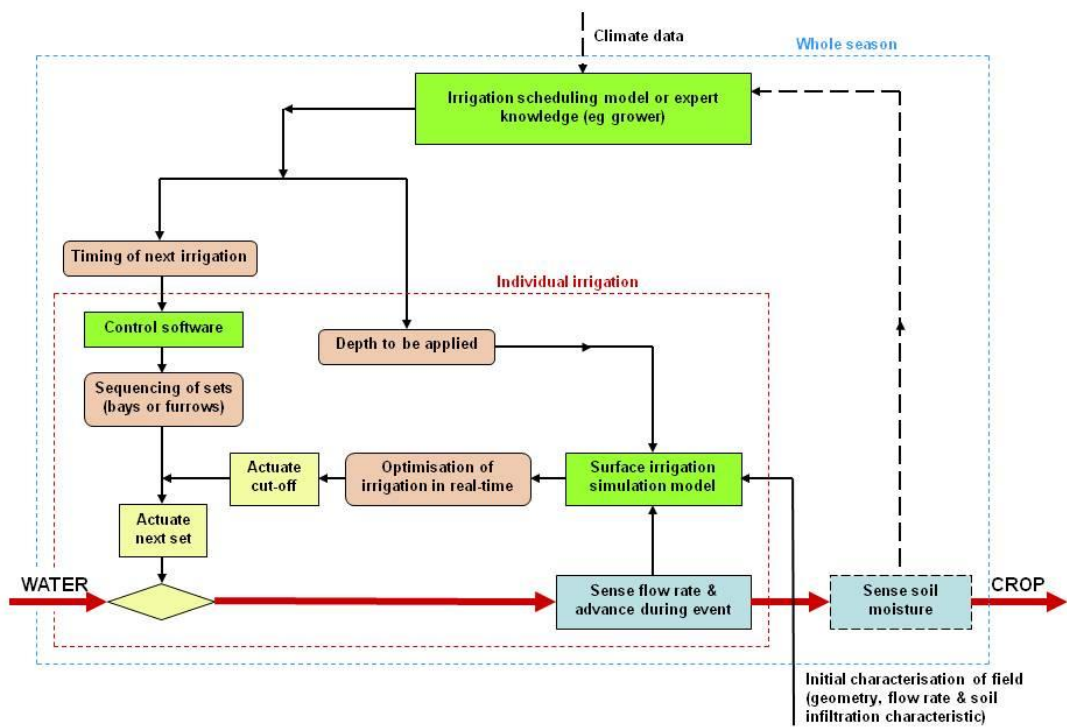


Figure 9 Smart automated surface irrigation

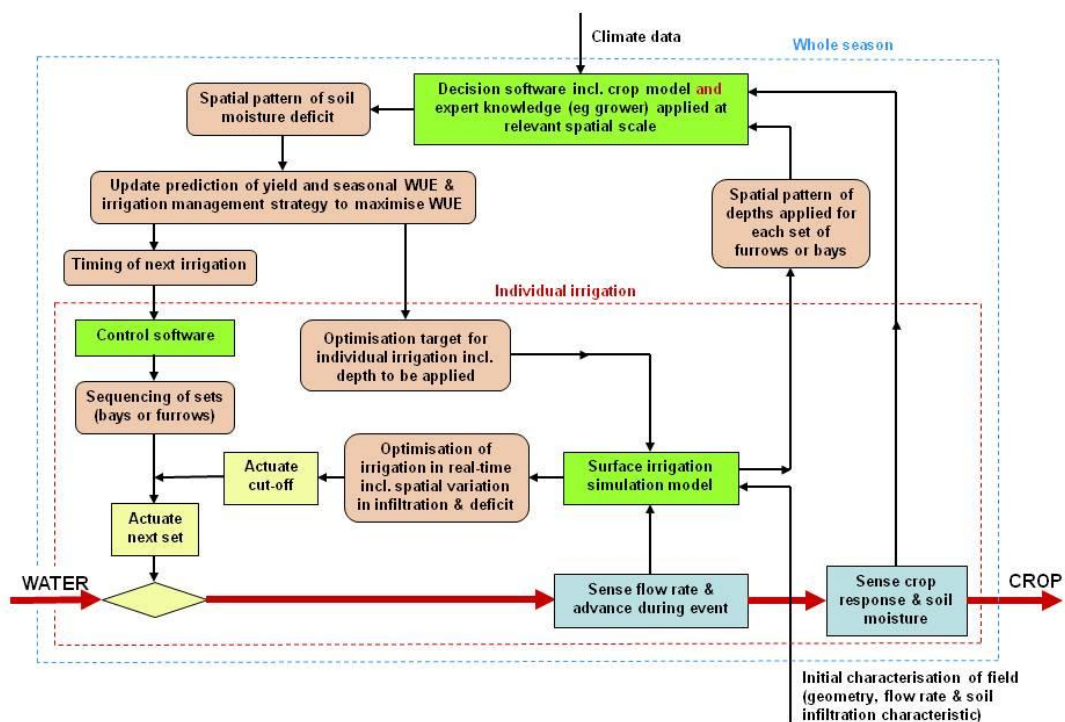


Figure 10 Surface irrigation as a precision irrigation method

7.2 Centre Pivots and Lateral Moves

The development of mobile sprinkler systems has provided more than convenient irrigation methods. Of all the irrigation systems, these machines offer the greatest potential for uniform applications as well as for adaptive control of spatially varied applications. The pseudo-continuous movement of the machines has conferred an improvement in uniformity at least in the direction of travel of the machine. Smith (1989) showed that these machines do not always perform up to their potential although other more recent studies (e.g. Hills and Barragan, 1998) have shown high uniformities from machines employing drop tube, boom and rotator sprayers. However, the problem of sprinkler overlap in the direction perpendicular to the travel direction remains. In the case of lateral move and centre pivot machines this can be solved by the use of very closely spaced nozzles and massive overlap of the spray patterns. LEPA technology (Lyle and Bordovsky, 1981, 1983), involving bubblers or socks discharging water just above the soil surface, also provides the opportunity to spatially vary applications at potentially small scales ($<1 \text{ m}^2$) to improve the performance of these machines.

The ability to spatially vary applications is an important component of adaptive control using centre pivots and lateral moves. Commercial irrigation controllers are able to vary the water application in the direction of machine travel but specialist controllers and actuators are also now able to be custom fitted to enable spatially varied irrigation applications based on historical or mapped inputs (e.g. Al-Kufaishi, 2005; Al-Kufaishi *et al.*, 2005, 2006; Dukes and Perry, 2006).

Simulation models of the machine hydraulic performance and of the depths of water applied by the machines are now available (Smith, 1989; Smith *et al.*, 2003). These models were originally conceived as diagnostic tools but will be an essential component of the decision support for the adaptive control system. These models may also be used to determine the minimum size of management zone possible with these machines, expressed as a function of the sprinkler spacing, wetted diameter of the sprinklers and the machine speed.

Sensing of the crop response to the water applied is currently seen as the preferred feed back to the machine controller. Recent work by McCarthy *et al.* (2006) has used machine vision to monitor internode length of cotton. There has also been much recent work (e.g. Falkenberg *et al.*, 2007; Peters and Evett, 2008) evaluating the potential to use proximal thermal infrared measurements for irrigation control. Hence, it seems that measurements on the same plants on each pass of the irrigation machine offers the possibility of real-time measurement of crop production functions for different irrigation application regimes.

The simulation framework 'VARIwise' was developed by McCarthy *et al.* (2010) to aid the development, evaluation and management of spatially and temporally varied site-specific irrigation control strategies under centre pivots and lateral move machines. VARIwise accommodates sub-field scale variations in input parameters using a 1m^2 cell size and permits application of differing control strategies within the field as well as differing irrigation amounts down to this scale. While VARIwise could be used to evaluate the costs and benefits of implementing variable rate control on centre pivots and

lateral moves, the components of the software are also suited for use in a real-time control system. Such a machine controller would be able to select the most appropriate application for particular sub-areas of the field in real-time and at a spatial resolution limited only by the number of sensors deployed and the spatial resolution of the associated modelling.

The future of development of the VARIwise system for these machines is twofold. First is integration with commercial systems for variable rate applications from CPLMs, for example, the Farmscan system described in Case Study 5. These systems typically vary applications to a fixed pattern. They lack the means to determine the optimum rate and timing of applications, to identify and react to crop responses, and to optimise WUE. VARIwise would provide them with this real-time control capability.

Second is the incorporation of hydraulic and sprinkler simulation models for simulation of the hydraulics of CPLMs and the pattern of depths applied by these machines. Varying applications spatially involves turning sprinklers on and off thus varying the discharge being delivered by the machine. This in turn causes fluctuations in pressure and in pump performance that can be predicted and controlled. Continuous monitoring of pressure at key points in the system using the will provide real time calibration of the hydraulic model. Further, knowledge of the depth of water being applied at any point in the field is essential. This is currently provided in VARIwise by a user entered pattern but can be provided more accurately by a sprinkler simulation model. The models developed by Foley (2010) are candidate models.

8 ADOPTION ISSUES

8.1 Lessons from the Adoption of Precision Agriculture

Precision Agriculture research started in the US, Canada, Australia, and Western Europe in mid-to-late 1980s (Zhang, 2002). Issues associated with the adoption of precision agriculture in the last two decades may provide some insight into the likely issues associated with the adoption of emerging precision irrigation systems.

Studies in Arkansas (Popp and Griffin, 2000) and Illinois, Indiana, Iowa, and Wisconsin (Khanna *et al.*, 1999) both identified that early adopters of precision agriculture tended to be younger, educated and operated larger sized farms. Both studies identified that farmers are waiting for research results on profitability of various PA technologies before increasing their investment significantly to adopt more technologies. In particular, Khanna *et al.*, 1999 identified that low rates of adoption are due to ‘uncertainty in returns due to adoption, high fixed costs of investment and information acquisition, and lack of demonstrated effects of these technologies on yields, input-use, and environmental performance’.

Cook *et al.* (2000) found that farmers in Australia are adopting precision agriculture technologies more slowly than expected. They attribute the slow adoption to four factors:

1. cost of adoption;
2. lack of perceived benefit from adoption;
3. unwillingness to be early adopters, and;
4. lack of technology delivery mechanism.

The problem in delivering the precision agriculture technologies to farmers has also been identified as the major obstacle due to the lack of knowledge and skills currently possessed by consulting agencies.

Zhang (2002) identified the following barriers that need to be overcome before PA technologies can be widely implemented in a fast pace:

1. Data overflow for farm management. This problem has to be overcome by developing data integration tools, expert systems, and decision support systems.
2. Lack of rational procedures and strategies for determining application requirements on a localized basis and a parallel lack of scientifically validated evidence for the benefits claimed for the precision agriculture concept.
3. Labor-intensive and costly data collection. Development of rapid sensing systems must take place before PA can be widely practiced.
4. Lack of technology-transfer channels and personnel. Educational programs involving researchers, industry, extension specialists, and consultants are urgently needed.

PA technology will likely gain more recognition when additional benefits, such as reduced environmental burdens and increased information flow, are recognized as a part of its rewards (Auernhammer, 2001).

8.2 Value in Precision Irrigation to Manage Risk

A study by Batte & Arnholdt (2003) of leading edge adopters of precision farming in Ohio identified that profitability concerns were the most important, however farmers also revealed that on-farm experimentation, improved information regarding within-field variability to support decisions, and the risk reduction potential were all motives for adoption. Lowenberg-Deboer (1999) identified that empirical evidence from on-farm tests of site-specific fertilizer management (SSF) supported the hypothesis that SSF can have risk-reducing benefits and that SSF can reduce the probability of profits falling into the lower profit distribution level. However, it was also recognized that SSF may increase some risks, including business, financial, human, and technological risks.

The acceptance and adoption of precision irrigation may be enhanced if it can be demonstrated to either reduce or manage risk. The management of risks associated with limited and variable water supplies may prove to be a key driver in the adoption of precision irrigation in Australia.

The use of technologies such as WaterSense provides opportunities for improved risk management. Experiments with sugarcane irrigators in Bundaberg and Childers (Inman-Bamber *et al.*, 2008) used WaterSense to schedule irrigations ahead for the entire irrigation season with management decisions modified in real time according to water availability. Used in this way WaterSense delivered results better than those achieved by good growers, particularly in unusual seasons.

8.3 Opportunities for Staged Adoption

Khanna *et al.* (1999) suggested that adoption of advanced precision farming systems is path dependent with 69% of the studied farmers choosing ‘a limited adoption strategy by adopting a diagnostic technology but preferring to wait before adopting a variable-rate application technology. Similarly, precision irrigation innovations that can be partially adopted, rather than an all or nothing approach may have greater adoption rates.

The ability to trial an innovation is important to adoption. Changes that can be trialled on smaller areas are more likely to be adopted (Vanclay and Lawrence, 1994). This allows the farmer to determine the likely result on their property without exposing themselves to excessive risk.

8.4 Experiences in Commercialisation

A recent program has extended the variable rate irrigation technology developed by the University of Georgia beyond the prototype stage and into commercialization. Federal NRCS Environmental Quality Incentives Program (EQIP) funding was used to provide a 75/25 cost-share opportunity for growers in the Flint River basin of Georgia to install variable rate irrigation on suitable pivots/fields (Perry and Milton, 2007).

With cost-share funding from NRCS EQIP and from a NRCS Conservation Innovation Grant (CIG) grant, 40 systems have been installed. Four systems have been purchased

without cost-share assistance. Current VRI systems are installed on farms that grow broadacre crops (peanuts, cotton, and corn) and turf farms. The CIG grant also provided funds to demonstrate the use, benefits, and effectiveness of VRI for irrigation management, water conservation, and optimal application efficiency through a series of workshops/field days.

A vendor was selected to provide the VRI hardware, installation, training, and support via a licensing agreement. This start-up company was created by the partnering of two experienced crop consultants with a keen interest in precision agriculture and technology. As expected with any first generation product, there were occasional problems that had to be resolved. Problem resolution often involved the in-field replacement of a controller, circuit board, or GPS unit.

This program provides an example of commercialisation of a complex precision irrigation technology supported by financial assistance with capital costs, an integrated extension program and support and involvement from experienced researchers.

8.5 Barriers to Adoption

The slow uptake and the low rate of adoption of improved irrigation practices has been the subject of many studies (e.g. Callen *et al.*, 2004). More specific to the present review, Stirzaker (2006) identified a range of obstacles to the adoption of many common irrigation technologies including:

- Irrigators do not see the importance of the technology. They commonly have limited data on the water they actually use, or should use, and there are few accessible champions that they can learn from;
- The entrenched culture is resistant to change, and inherited knowledge or the status quo is often seen as adequate;
- Little confidence that investing in new technologies actually pays off; the presence of structural barriers make it hard to change (e.g. schemes where water is not available on demand, limitations to farm layout, poor distribution uniformities and labour shortages); and
- Concern over the complexity of the technology and the uncertainty over which technologies are best suited to which applications.

These obstacles are likely to be as significant an issue in the adoption of complex precision irrigation systems.

Expertise required

Despite large investments in training packages, accredited courses and information material by many agencies, adoption levels of tools and techniques for improved irrigation are very low (Schmidt, 2005). Much knowledge is diffused across many organisations with information fragmented, incomplete, and outdated in terms of current understanding of learning processes and there is little continuity in delivery. Callan *et al.* (2004) proposed the development of an irrigation knowledge system that would overcome some of these knowledge issues but did not address the manpower limitations, the limited capacity and lack of continuity in delivery.

Precision irrigation is an emerging and poorly understood concept. Precision irrigation is by nature multidisciplinary requiring the integration of agronomic assessments, irrigation

application system assessments, data collection technologies, use of decision making tools and irrigation control technologies. A high level of expertise will be required to by irrigation professionals supporting the implementation of precision irrigation systems.

Lack of suitable decision making tools

A number of excellent tools have been developed for assisting with irrigation decision making however they have generally focused on one aspect i.e. soil water monitoring or E_{to} water balance scheduling, limiting the value and amount of information which is available for making decisions (Montagu *et al.*, 2006). However, precision irrigation requires the decision making tools that can manage for multiple objectives, using multiple information sources and address temporal and spatial variability as necessary. There is a lack of tools to perform this and it is a significant barrier to the implementation of precision irrigation systems.

As appropriate decision making tools are developed, their potential complexity is likely to be a further barrier to their adoption. The current poor uptake of existing Australian decision support systems, partly due to their perceived difficulty of use, provides an indication of the difficulties that may be faced in achieving adoption of decision making tools for precision irrigation. Although there are no direct statistics available on the usage of irrigation DSS, numbers are known to be very low with the most popular Australian DSS, such as the APSIM-derived Yield Prophet, only seeing usage in the order of a few hundred (Inman-Bamber and Attard, 2005).

Complexity of the innovation

The complexity of an innovation is likely to be a substantial barrier to adoption (Vanclay and Lawrence, 1994). The implementation of precision irrigation systems is likely to be complex and intellectually demanding and possibly involve large investments over the long term. On the other hand, the past low rates of adoption may be a direct result of the fact that most research and technology directed at improving irrigation performance has focussed on incremental improvements to the application systems and to the irrigation management. It might be hypothesised that a major step change in the technology such as precision irrigation, and one that delivers maximum performance, might lead to more rapid adoption.

8.6 Evaluation

Precision irrigation has the potential to maximise economic return by optimizing rates of yield-limiting irrigation inputs. However, the ‘Null Hypothesis’ of Whelan and McBratney (2000), that “given the large temporal variation evident in crop yield relative to the scale of a single field, then the optimum risk aversion strategy is uniform management”, is just as applicable to precision irrigation as it is to precision agriculture and should be tested continually. Consequently, irrigators implementing precision irrigation systems need an accurate means of evaluation to confirm or otherwise the value of a particular strategy adopted in a season. Precision irrigation strategies should be evaluated at the end of every season and can be evaluated at the scale of the whole field or whole farm or at the scale of the irrigation applications depending on the crop and the equipment available. Obviously the evaluation will consider the output of importance to the particular grower, be it yield, quality or profitability.

At the whole farm scale the yield or income levels attained with a particular variable rate or uniform rate input strategy can be compared to historical data for the same or different strategies. Historical evaluations are straightforward and essentially free. However, such comparisons are likely to be confounded by year-to-year fluctuations in yield, available water supply and resulting irrigation decisions. Because historical yield and income information is only likely to be at the individual field or farm level it will usually be too coarse to identify yield improvements within sections of the field in response to particular precision irrigation strategies.

Precision irrigation systems can follow the lead of precision agriculture and utilise differential global positioning system (DGPS) equipped yield monitoring will be able to make direct comparisons between multiple management zones and/or with predicted yields if available from the decision making tools used to determine irrigation strategies throughout the season (e.g. Seidl *et al.*, 2001). Direct evaluation of precision irrigation strategies with on-farm testing is quantitative, spatially robust, and requires no specialized equipment beyond a yield monitoring and mapping system.

9 RESEARCH AND DEVELOPMENT NEEDS AND OPPORTUNITIES

While many of the tools and technologies that will comprise precision irrigation systems are currently available, substantial research and development is required before a truly precision system is available for testing and adoption by the irrigation community. The R & D opportunities that emerge from the review fall into four categories. These are outlined below.

Integration of Precision Irrigation components

Examples of the integration required were discussed in Section 7. Combining the crop and soil sensing with appropriate crop growth simulation models to provide the seasonal decision making model (as has been done with the VARIwise system in cotton) is a necessary first step for all of the major crops. Combining that with the system for the control and optimisation of the particular irrigation application system completes the PI system. Given the dominant position in the irrigation sector occupied by the various forms of surface irrigation and the substantial gains possible in application efficiency and yield (and hence water use efficiency) this would seem the likely priority area.

Technical Feasibility of Precision Irrigation

The technical feasibility of precision irrigation needs to be established at two levels, conceptual and practical. At the conceptual level, simulation can establish the optimum spatial scales for the range of crops and application systems. This will account for the spatial limitations of the application system, the constraints imposed by the sensing needs and capability, and the ability of the simulation tools to accurately predict the effects on crop growth and yield of small variations in applied depths. This stage must also determine if the diagnostic tools needed to determine the causes of particular crop responses are available and sufficiently accurate. At the practical level, PI systems need to be proven and demonstrated in field trials across the breadth of the Australian irrigation sector.

Benefits of Precision Irrigation

Current and past work has established that there are benefits to be obtained from adoption of PI (including spatially varied irrigation applications). However it is far from clear if the benefits outweigh the costs by a sufficient margin to warrant the adoption. Work needs to be undertaken across a sufficient range of crops, soils and irrigation application systems to determine where the maximum benefit can be obtained and to direct the priorities for research investment. This will also establish the advantages of full versus staged or partial adoption.

Specifically, quantifying the costs/benefits of full automation of surface irrigation and the agronomic benefits of spatially varied applications for a range of crops appear to be of high priority. It also remains to be shown, via the mechanism of field trials rather than simulation, that adaptive systems can provide substantially greater benefits than simple automation and/or traditional irrigation scheduling.

Additional component tools and technologies

Development of improved tools and technologies will be on-going. However there are some clear immediate needs for particular sensing and simulation tools for the PI systems currently under development. These are:

- Low cost, spatially distributed, non-invasive sensing of soil moisture and crop response;
- Development of a fully deterministic sprinkler pattern model for CPLMs that can account accurately for varying sprinkler pressure and height, sprinkler pattern overlap, wind, and machine movement;
- Development of a hydraulic diagnostic model for drip irrigation systems capable of interaction with the system control;
- Improved crop models sensitive to small variations in irrigation management and with a self learning capability; and
- Verification of the use of short range radar for the measurement of the spatial distribution of rainfall at the sub-field scale.

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