MANAGING SPATIAL AND TEMPORAL VARIABILITY IN IRRIGATED AGRICULTURE THROUGH ADAPTIVE CONTROL

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ABSTRACT

Spatial variability in crop production occurs as a result of spatial and temporal variations in soil structure and fertility; soil physical, chemical and hydraulic properties; irrigation applications; pests and diseases; and plant genetics. It is argued that this variability can be managed and the efficiency of irrigation water use increased by spatially variable application of irrigation water to meet the specific needs of individual management zones (areas of crop whose properties are relatively homogenous). The prospects for spatially varied irrigation applications and the need for adaptive control of irrigation application systems are identified. Current work at USQ directed toward adaptive control of furrow irrigation and centre pivot and lateral move machines is described.

KEYWORDS

Real-time control, furrow irrigation, centre pivot machines, lateral move machines

INTRODUCTION

Practitioners of dry-land agriculture have embraced the concept and potential benefits of precision farming and substantial research has been undertaken on the yield mapping and variable rate technology that underlies the practice. Irrigation aspires to be a precision activity but one in which the traditional intention has been to deliver precisely the same quantity of water to each plant. The cost of any non-uniformity in irrigation applications is assumed to be reduced yield and lower efficiencies. However, this assumes that the requirements of each plant are exactly the same and ignores differences in crop water requirements due to spatial differences in soil hydraulic properties, fertility and other inputs. To counter the effects of this non-uniformity, irrigators are tempted apply larger water applications with a resultant reduction in volumetric and water use efficiencies.

The evaluation of commercial irrigation application systems of all types (sprinkler, surface and micro-irrigation) suggests that many systems operate with low uniformities and less than ideal volumetric efficiencies. Against this background, what are the prospects for irrigation to be a truly precision activity and what are the prospects for applying water automatically in a spatially variable manner to meet the specific requirements of individual plants or individual areas of the field?

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 spatially 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 (possible 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 is making no attempt to vary the irrigation applications spatially, the results will be 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. Both of these roles are discussed in the following sections.

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.*, 2005). For example, there is typically a ten fold wine grape yield variation across vineyards in any given year (Bramley & Hamilton, 2004). Spatial and temporal variability has also been reported in cotton (Elms *et al.*, 2001; Meredith, 1996; and Wilkerson & Hart, 1996), 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 uniformity, field topography, fertilizer 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 has 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 case the soil infiltration characteristic and its spatial and temporal variability is the single greatest factor in determining the irrigation performance (Gillies, 2007). 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 (Irmark *et al.*, 2002). 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).

The spatial and temporal yield variability within the whole field can be controlled by dividing the field into homogenous management zones. 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). Managing fields as zones improves 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).

IRRIGATION AS A PRECISE ACTIVITY

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.

Few published data are available on the performance (efficiency and uniformity) of Australian irrigation practices. However, the data that are available (for example, Raine & Bakker, 1996 and Smith *et al.,* 2005) for a limited range of irrigation methods, soils and regions, indicates that the level of precision being achieved is less than desirable. The obvious consequence of this lack of precision is both economic and environmental, and is manifest through low water use efficiencies and ultimately lower profits or the impact on groundwater and riverine flows. The economic and environmental benefits of improving the volumetric efficiency of irrigation are obvious, in both the value of the water saved and the additional production possible with this water. Less obvious are the benefits to be obtained through improved uniformity.

Strategies for improving the performance of irrigation are as numerous as there are different irrigators and irrigation systems. The various irrigation systems and the means for their improvement have been reviewed recently by Raine (1999) and need not be discussed further here.

SPATIALLY VARIED IRRIGATION

Spatially varied irrigation is the term used to describe those systems that are able to deliver differential amounts of water to different areas of the field. 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.

Work published to date has 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; Duke *et al.,* 1997; Heermann *et al.,* 1997; Sadler *et al.,* 1997; Camp & Sadler, 1998; Camp *et al.,* 1998; and King & Wall, 1998). Clearly the ease and consistency with which the location of these 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 m^2.

The justification for this 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. In no case has it been established that spatially variable irrigation will result in water savings, increased efficiency in fertiliser usage or improvements in yield. It must therefore be concluded that much of this work was being done because it can be done, just as variable rate technology was developed for dry-land precision farming.

So far none of the above research groups have attempted to vary water applications in specific response to a measured crop water demand. 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 (Stewart *et al.*, 2005). 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. However the practical limitation will be the density of sensing required. Camp *et al.* (1998) fitted infra-red thermometers at intervals along the length of their machines. The data from these thermometers demonstrated considerable variation in soil and canopy temperature over the field prior to irrigation, indicating similar considerable differences in plant stress. However, so far they have not reported any attempt to use these sensors (or any others) to provide real time control of the irrigations.

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 factor most likely to delay significant commercial application of these systems is the need to develop the technology required to sense the water (and nutrient) requirements of the crop at an appropriate spatial scale.

Quantification of the economic benefits of prescription irrigation taking into account water savings, yield improvements and the capital cost of the modified machines will also be necessary.

SPATIAL SCALE OF 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 sprinkler	5000
Drip	wetted area of an emitter	1 to 10
Micro-spray	wetted area of single spray	20

A further matter to be resolved is the minimum length (or area) scale of the variability in applications possible with sprinkler 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 these 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.

PRESCRIPTION IRRIGATION

The move from irrigation as a precise activity to prescription irrigation is significant as it recognises irrigation water as a significant input variable in the production process. It also highlights the importance of the interactions between the irrigation management practices, environmental conditions, the crop demands and other input variables. The use of prescription in this irrigation context is similar to that proposed by Rawlins (1996) for dry-land agriculture, and requires identification of the factor limiting production for each plant or sub-area of the field. Hoffman & Martin (1993) also preferred the term prescription irrigation and suggested that the design of a precision irrigation system must allow varying ratios of water application to parcels throughout the season. They further suggested that these parcels could be as small as 1000 m^2. However, we differ from Hoffman & Martin on the significant point that we view spatially varied irrigation as a non-essential component of prescription irrigation. Hence, prescription irrigation as a process should be equally applicable to all irrigation methods irrespective of whether the methods are able to apply spatially variable irrigations.

Prescription irrigation requires the identification of the appropriate volume and timing of the irrigation required. This implies that the operator has access to detailed data and response information regarding the crop, soil, weather, environment and other production inputs and that there is adequate knowledge regarding the interaction of these variables and the economic responses to variable inputs. In this case, prescription irrigation is used to maximise the value of the other crop inputs while minimising wastage and environmental impacts. Hence, effective prescription irrigation requires the same four management steps listed earlier in this paper, viz: an ability to measure, interpret, control, and evaluate. However, prescription irrigation requires this data, the relevant underlying knowledge and the level of technological control for the whole crop production system and not just the irrigation sub-component. This requires a holistic view of irrigation management that includes all of the factors needed to make irrigation a precise activity as well as those required in prescription agriculture.

Prescription 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 prescription irrigation is the result of longer term decision making processes involving the use of broad scale (ie. field or farm level) data over long time frames (ie. 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 prescription 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.

Further, 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. The relatively recent development of crop simulation models for the grain, cotton (eg. Hearn, 1994) and sugar (Keating *et al*., 1999) sectors provide the first steps towards a framework which may enable the identification of optimal strategies. These models are currently being used to identify fertiliser and irrigation requirements at the "strategic" decision level. They are also currently being used to quantify the effect of various irrigation scheduling strategies including the potential for deficit irrigation and partial root-zone drying during less sensitive periods of crop growth. However, stripped down versions of these and other models could also be used as part of the real-time decision support systems required for tactical prescription irrigation by incorporation into controllers on irrigation application systems.

CONTROL SYSTEMS

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. 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 control system monitors the plant output and aims 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 1.

Existing control strategies for irrigation described in the literature usually initiate an irrigation, 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 amount.

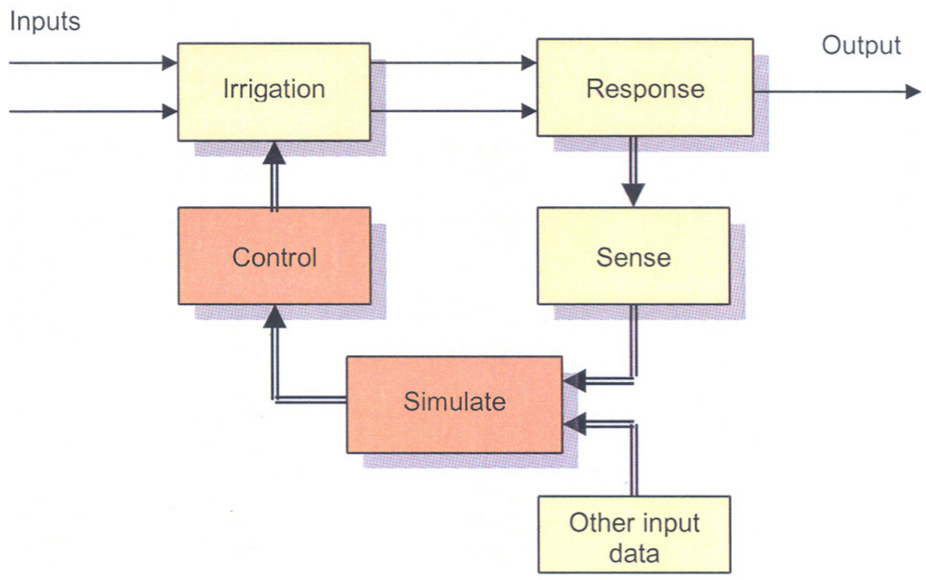

Figure 1 Conceptual model of a real-time adaptive control system for irrigation applications

An iterative learning controller conceptualised by Moore & Chen (2006) is the only automated sensor-based variable-rate application system designed for sprinkler systems to be found in the literature. This controller aims to control the concentration of a crop input (e.g. water or nutrients) at a depth 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. Optimal control strategies must consider multidimensional issues (e.g. crop response, crop age, target yield and management constraints). 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.

Adaptive control systems have been attempted for various configurations of surface irrigation (for example, Clemmens, 1992 and Hibbs *et al.*, 1992). In these cases the response being sensed is the water advance down the field, where the sensing may be by contact means (Humpherys & Fisher, 1995) or non-contact (Lam *et al.*, 2006). The outputs are depth of water applied (rather than crop yield) and the usual performance measures of efficiency and uniformity, and the objective is 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. Varying the management to accommodate spatial variations in the soil infiltration characteristic is usually not considered.

CASE STUDIES

The following case studies illustrate the work 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. The overarching hypothesis of the research currently underway at the NCEA is that irrigated 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. This research is based on the following component hypotheses 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).

Furrow Irrigation

The widely used surface irrigation methods of border check (or bay) and furrow irrigation are variously claimed to be as efficient as any other method or blamed for the perceived low efficiencies of Australian irrigation. However true these opposing claims may be, it is true that there is scope for improvement in both the efficiency and uniformity of surface irrigation applications and that the management strategies and technologies are available to achieve those improvements. Improvement of furrow irrigation performance through the process of evaluation, simulation and optimisation with the IRRIMATE^{TM} suite of tools developed by NCEA is now an accepted practice in the cotton industry. Automation and adaptive real-time control can provide an even higher level of irrigation performance (as demonstrated by Raine *et al.*, 1997, Smith *et al.*, 2005, and Khatri & Smith, 2007) along with substantial labour savings.

Recent research at NCEA has established the basis for the practical real time control of furrow irrigation. 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. All of the sensing, communication, software and control tools are available individually within NCEA but need to be assembled and a prototype system established for field validation.

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

- continuous inflow measurement through inference from measurement of pressure in the supply system, for example, for gated pipe supply using the program Gpipe of Smith *et al.* (1986) and Smith (1990),
- characterisation of the field by determining a soil infiltration characteristic from detailed measurements of one irrigation event using the program IPARM of Gillies & Smith (2005) and Gillies *et al*, (2007),
- prediction of the current infiltration parameters from one observation of the irrigation advance during the irrigation event being controlled (Khatri & Smith, 2006),
- simulation of the irrigation and optimisation to determine the preferred time to cut off the inflow to the field using the Irriprob model (McClymont *et al.*, 1999; and Gillies 2007) ,

taking into account the current soil moisture deficit and the variation in the infiltration characteristic across the set of furrows.

Centre Pivot and Lateral Move Machines

The development of mobile sprinkler systems has provided more than convenient irrigation methods. The pseudo-continuous movement of the machines has conferred an improvement in uniformity at least in the direction of travel of the machine. 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 was solved by use of very closely spaced nozzles and massive overlap of the spray patterns. Of all the irrigation systems, these machines offer the greatest potential for uniform applications as well as for adaptive control of spatially varied applications. Smith (1995) showed that these machines have not always performed up to their potential although recent studies such as Hills and Barragan (1998) showed high uniformities of applications from current generation machines employing drop tube, boom and rotator sprayers.

Further improvements in the performance of these types of machine are occurring through the adoption of Low Energy Precision Application (LEPA) technology (Fipps and New, 1990). 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.

Work at the NCEA directed toward the adaptive control of spatially varied applications from centre pivot and lateral move machines is less well advanced than the surface irrigation work but 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.* (2006) has used machine vision to monitor internode 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 commenced this year (McCarthy, 2007) that will investigate control options for these machines.

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