A PRESCRIPTIVE FUTURE FOR PRECISION AND SPATIALLY VARIED IRRIGATION

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ABSTRACT

Despite the widespread promotion and adoption of precision and prescription agriculture in dryland cropping systems, the concept of irrigation as a component of precision agricultural systems has not been widely canvassed. Irrigation application is commonly viewed as less than a precise activity and the potential for prescription irrigation is yet to be adequately evaluated. This paper reviews existing irrigation research into the use of precision application systems and the potential for prescription agriculture involving irrigation. 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.

INTRODUCTION

Practitioners of dryland agriculture have embraced the concept and potential benefits of precision farming and substantial research is underway on the yield mapping and variable rate technology that underlies the practice. Irrigation aspires to be a precision activity but one in which the intention is 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 commonly 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 in a spatially variable manner to meet the specific requirements of individual plants or individual areas of the field? This paper reviews recent work on precision irrigation, discusses strategies to apply water more precisely, and identifies those application systems where spatially varied applications are potentially feasible. It also looks towards the future and discusses the potential for the development of both strategic and tactical prescriptions for irrigation management.

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):

- data acquisition;
- mapping/interpretation;
- control/precise application; and
- 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 dryland agricultural systems. It might also be possible that 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.

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.

Little data is available on the performance (efficiency and uniformity) of Australian irrigation practices. However, the data that is available 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, 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) with some of the more important aspects discussed below.

Irrigation Scheduling

Volumetric inefficiencies in irrigation result largely from irrigating too often or applying too much water each irrigation. The first step in improving these efficiencies is the accurate assessment of how much water to apply and when to apply it, that is, scheduling the irrigations. Irrigation scheduling has traditionally been seen only in terms of determining when to irrigate. The assumption has been that the crop is fully irrigated and that irrigation is due when the soil moisture falls to some predetermined deficit. Various techniques have been used, commonly based on a calculated soil moisture balance and estimates of the crop evaporation. Most recently, scheduling employing soil moisture measurements have gained prominence using a range of sensors including the neutron probe (eg. Cull, 1981), enviroscan (eg. Harrison, 1996) and other systems. Despite the proven capability of these systems, irrigators are generally slow to adopt any form of scheduling and quick to reject it after a period of use (Raine *et al.*, 1996).

Soil moisture measurement based methods also allow scheduling under various non-traditional irrigation strategies, including: deficit irrigation, partial root zone drying, and supplemental or strategic irrigation. In each of these cases, the question is not when to irrigate, but how much to apply. This could be referred to as "temporally varied irrigation" where the objective is to match the time and volume of application to a specific crop and environmental requirement which would be expected to vary over the growing season. However, irrespective of the strategy employed, the benefits of scheduling will only be realised if the irrigation system can be controlled sufficiently well to apply only the exact amount required. Control is a necessary component of any irrigation system aiming to apply water in precise amounts (Hoffman and Martin, 1993).

Surface 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. Typical of the available technologies are the models that simulate the irrigation advance and allow field design or selection of the flow rate and time to cut-off to give optimal efficiency and/or uniformity of applications (McClymont *et al.*, 1996 & 1999; and Raine *et al.*, 1997 & 1998).

The benefits to be gained from the use of surface irrigation models are obvious to some in the research community. However, despite the fact that these models have been available for over a decade, they are not used routinely in design and only recently have attracted interest as extension tools. Hence, substantial work remains to be done. Firstly irrigators must be convinced that changing their practices will lead to economic gains that outweigh the cost and sometimes inconvenience experienced by, for example, cut-off times that do not fit comfortably with the shift hours of employed labour. Decision support tools must also be developed that will allow designers and irrigators to determine the irrigation management variables (in particular, flow rate and time to cut-off) that provide the best field and seasonal efficiencies under conditions of significant spatial and temporal variation in soil infiltration characteristics. Other management strategies that have been proven effective overseas but have not received significant interest in this country include cut back flows, blocked furrows, level basin irrigation and surge irrigation. All are worthy of further investigation in appropriate situations.

Further into the future are strategies such as manipulation of soil infiltration properties along the length of the field by selective compaction or amelioration, variation of the furrow slope or furrow shape along the length of the field and variation of the flow rate continuously during the irrigation. Simulation models have indicated that such strategies might be feasible but there are many practical problems to be solved before implementation will be possible.

Far more feasible is the application of real time control of irrigation where parameters measured during a particular irrigation are used to control that irrigation. The improvements in efficiency possible through real time control have been demonstrated by Smith *et al.* (1997). Real time control of surface irrigation is not blue sky dreaming. Certainly, automatic computer controlled irrigation may be many years away but a simple manual form of real time control is possible now. Firstly, models for the determination of soil infiltration parameters from measurements of the irrigation advance (McClymont and Smith, 1996) are available. Simple improvements to these models will allow prediction of the current infiltration parameters from one observation of the irrigation advance at say 50% distance. The parameters can then be used to determine the preferred time to cut off the inflow to the field.

The view of surface irrigation as a precise activity is heightened by the trend of some irrigators to apply lighter more frequent irrigations. What is certain is that alternative strategies (such as higher flow rates and irrigation of alternate furrows) and an increased level of irrigation management are required if lighter irrigations are to be applied with the same degree of efficiency.

Sprinkler Irrigation

The challenge for precise applications using any system of sprinklers or sprays is to overcome the inherent non-uniformity of circular spray patterns. The earliest work of Christiansen (1942) recognised that the uniformity of applications was directly related to the sprinkler and lateral spacings. Rules-of-thumb recipes for sprinkler spacing, developed by Christiansen, have been reproduced in most irrigation texts since that date and provide a useful first estimate. However these recipes should not be seen as a substitute for the proper design using sprinkler overlap packages such as SPRINKPAC or CATCH-3D (Allen, 1989).

The more recent 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. However with their greater complexity comes increased difficulty in the diagnosis of design and operational problems. 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 high with each crop row receiving much the same amount of water. One cost of this high precision is a very high application rate, very much greater than the infiltration capacity of the soil, necessitating the use of dyked furrows to prevent surface redistribution of the ponded water.

The performance of simpler machines such as single nozzle travelling irrigators and short boom machines is dependent very much on the selection of correct lane spacings. The little published evidence available (eg. John *et al.*, 1985) suggests that the operation of these machines is far from satisfactory. Application uniformities measured by John *et al.*, and expressed as a Christiansen Uniformity Coefficient, ranged from 19 to 96%, with only two of 11 machines giving satisfactory results. Other significant problems with these machines stem from the exceptionally high instantaneous application rates and the consequential difficulty of matching the rate to the infiltration characteristic of the soil.

Micro-Irrigation

Micro-irrigation covers a diverse range of systems that have the common feature of low flow rates and low application rates. It includes drip (or trickle) systems, micro-sprays, and porous pipe. 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 (James, 1988). 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 (Hoffman and Martin, 1993).

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%. 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.

Extensive evaluations of 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 E_u of less than 80%. The reasons for this poor performance are legion and 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.

SPATIALLY VARIED IRRIGATION

Review

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; Sadler *et al.,* 1996; Duke *et al.,* 1997; Heermann *et al.,* 1997; Sadler *et al.,* 1997; Camp and Sadler, 1998; Camp *et al.,* 1998; and King and 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 observed 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. The authors are led to conclude that much of this work has being done because it could be done, just as variable rate technology was developed for dryland precision farming.

So far none of the above research groups has 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 is the lack of techniques for sensing the crop water requirements at an appropriate spatial scale. 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.

Potential/Opportunities for Spatially Variable Irrigation Applications

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	furrow	1000
Surface - border	border	10000
Sprinkler – solid set	wetted area of single sprinkler	100
Centre pivot, lateral move	wetted area of single sprinkler	50
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	50

There is no doubt that centre pivot, lateral move and 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.

A further matter to be resolved is the minimum length (or area) scale of the variability in applications possible with lateral move or centre pivot machines and its relationship to the spatial variability of the crop water requirements. 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 this will only be achievable at a very greatly increased sensing requirement.

Fixed systems (sprinkler and micro) offer the potential for a different and very much simpler system for spatially varied applications. In this case, individual nozzles or emitters could simply be turned off when the area or plant they supply has received sufficient water. Relatively inexpensive wetting front detectors such as those described by Hutchinson and Stirzaker (2000) at this conference might provide the necessary sensing capability, with a sensor (wetting front detector) required for each emitter or group of emitters as appropriate. The sensors could be set at a level in the soil such that when the wetting front is detected, sufficient water has been applied to fill the root zone to the desired moisture content. This type of automated system would be particularly suitable for micro-irrigated orchard crops. In this case, individual emitters, or groups of emitters, could be turned off by solenoid valves linked to the moisture sensors. The only modification to the irrigation system would be the addition of the solenoid valves to each emitter with no change necessary in the application rates or scheduling techniques.

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 dryland agriculture, and requires identification of the factor limiting production for each plant or sub-area of the field. Hoffman and 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 and Martin on the significant point that spatially varied irrigation is viewed by the authors 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.

Existing technology is available to measure the various components of the soil-crop-atmosphere continuum (many in real-time and at sub-metre scales) and to provide precise and/or real-time control of irrigation applications. 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. 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 "blackbox" controllers on irrigation application systems. Hence, it seems likely that a convergence of sensing, decision support and controlling technologies will result in the future of precision irrigation being prescriptive.

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