

# ADVANCES IN INTELLIGENT AND AUTONOMOUS SYSTEMS TO IMPROVE IRRIGATION AND FERTILISER EFFICIENCY

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## **Abstract**

Water, nutrients, energy and labour are critical determinants of on-farm productivity and profitability. The National Centre for Engineering in Agriculture (NCEA) has a 20 year history of working with industry to improve the efficiency and productivity of irrigated farming systems. The NCEA has developed software tools and hardware technologies to improve the measurement, evaluation, optimisation and control of these key inputs for both manually operated and automated irrigation and fertiliser application systems. The tools are applicable to both uniform and spatially variable application systems. Spatial variability in crop water and nutrient requirements can occur as a result of spatial and temporal variations in soil structure, fertility and properties; or pests and diseases.

Two irrigation and fertiliser software frameworks that have been developed at the NCEA are 'KMSI' and 'VARIwise'. KMSI is a suite of online irrigation, nutrient and energy calculators and database tools which present sensed data, performance evaluations and recommendations for growers and consultants with manually operated irrigation and fertiliser application systems. Two tools in KMSI are IPART and NutriCalc, which provide performance auditing and reporting for irrigation and nutrient applications, respectively.

VARIwise steps toward autonomous irrigation and nutrient prescription and application by linking infield sensing, data processing and control actuation. 'VARIwise' is a software framework that implements and simulates control strategies on fields with sub-field-scale variations in all input parameters (including nutrients). Input parameters are measured using infield soil sensors and on-the-go crop monitoring cameras. The control systems can be implemented in VARIwise either in simulation through APSIM or in field implementations using irrigation and fertiliser actuators. Variants of the framework have been developed for centre pivots, lateral moves and surface irrigation systems. This paper will provide an overview of the irrigation and nutrient management tools developed by the NCEA along with a focus on current research investigating automated nutrient and water management control strategies for irrigation systems.

## **1. Introduction**

Grower tools and decision support systems have been a predominant approach in research for advising growers on systems for improved irrigation and fertiliser efficiency. Existing tools require manual sensor measurement and data input to the tool and then provide recommendations for the grower. However, labour is often limited for wide-scale data collection and repeated tool runs in commercial farming conditions. In addition, there may be spatial variability in crop production and sensor data which may not be practical for wide-scale measurement and control. 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 nutrients and irrigation water use increased by spatially variable application to meet the specific needs of individual management zones (areas of crop whose properties are relatively homogenous).

Automation of data collection, processing and actuation would facilitate potentially improved efficiencies without additional labour. This can be achieved using advanced process control and multiple data streams to automatically send control signals to variable-rate irrigation and fertigation hardware. NCEA has developed tools for irrigation and fertiliser management targeted at both growers and automation systems (Table 1).

**Table 1:** NCEA's irrigation and fertiliser management systems

	<b>IPART (tool in KMSI)</b>	<b>VARIwise-Irrigation</b>	<b>NutriCalc (tool in KMSI)</b>	<b>VARIwise-Fertigation</b>	<b>VARIwise-Irrigation &amp; Fertigation</b>
<b>Optimised variable</b>	Irrigation	Irrigation	Fertiliser	Fertiliser	Irrigation and fertiliser
<b>Account for spatial variability?</b>	Sub-field scale: irrigation application	Sub-field scale: weather, soil and plant parameters; irrigation application; control outputs	Individual field scale	Sub-field scale: weather, soil and plant parameters; irrigation and fertiliser application; control outputs	Sub-field scale: weather, soil and plant parameters; irrigation and fertiliser application; control outputs
<b>Processing method</b>	Hydraulic equations	Advanced process control	Nutrient balance	Advanced process control	Advanced process control
<b>Sensors</b>	Irrigation application, pressure, irrigation uniformity (catch cans), irrigation flow rate	Weather, soil moisture, soil type, plant fruit load, cover, irrigation flow rate	Crop type, fertiliser applied	Weather, soil moisture, soil type, plant fruit load, cover, nitrogen status, irrigation flow rate	Weather, soil moisture, soil type, plant fruit load, cover, nitrogen status, irrigation flow rate
<b>Sensor data input method</b>	Manual	Manual or automatic	Manual	Manual or automatic	Manual or automatic
<b>System data output</b>	Report, recommendations	Control signals to actuators	Report, recommendations	Control signals to actuators	Control signals to actuators

## 2. Irrigation and nutrient management tools

The Knowledge Management System for Irrigation (KMSI, [kmsi.usq.edu.au](http://kmsi.usq.edu.au)) includes a suite of online irrigation, nutrient and energy calculators and database tools suitable for use by both growers and consultants. The two groups of tools are calculators which provide simple input/output interfaces, and databases which are password protect stores of information that can be used for benchmarking. These tools are targeted to growers (which require low detail) and extension/consultant tools (that requiring higher level of skill and some training). Examples include the Irrigation Performance Audit and Reporting Tool (IPART) and the Nutrient Balance and Reporting Tool.

## 2.1 IPART

IPART is designed to assist in the evaluation and collation of infield irrigation application system performance data. This includes standardisation of infield data record acquisition, calculation and presentation of infield irrigation performance evaluation (Figures 1, 2), and automated generation of grower recommendations and grower reports. Required inputs to the tools are grower's details, block information and field data (e.g. irrigation depths, flow rates). IPART was developed with funding provided by the Department of Natural Resources and Water (Queensland Government) as part of the South-East Queensland Irrigation Futures program.


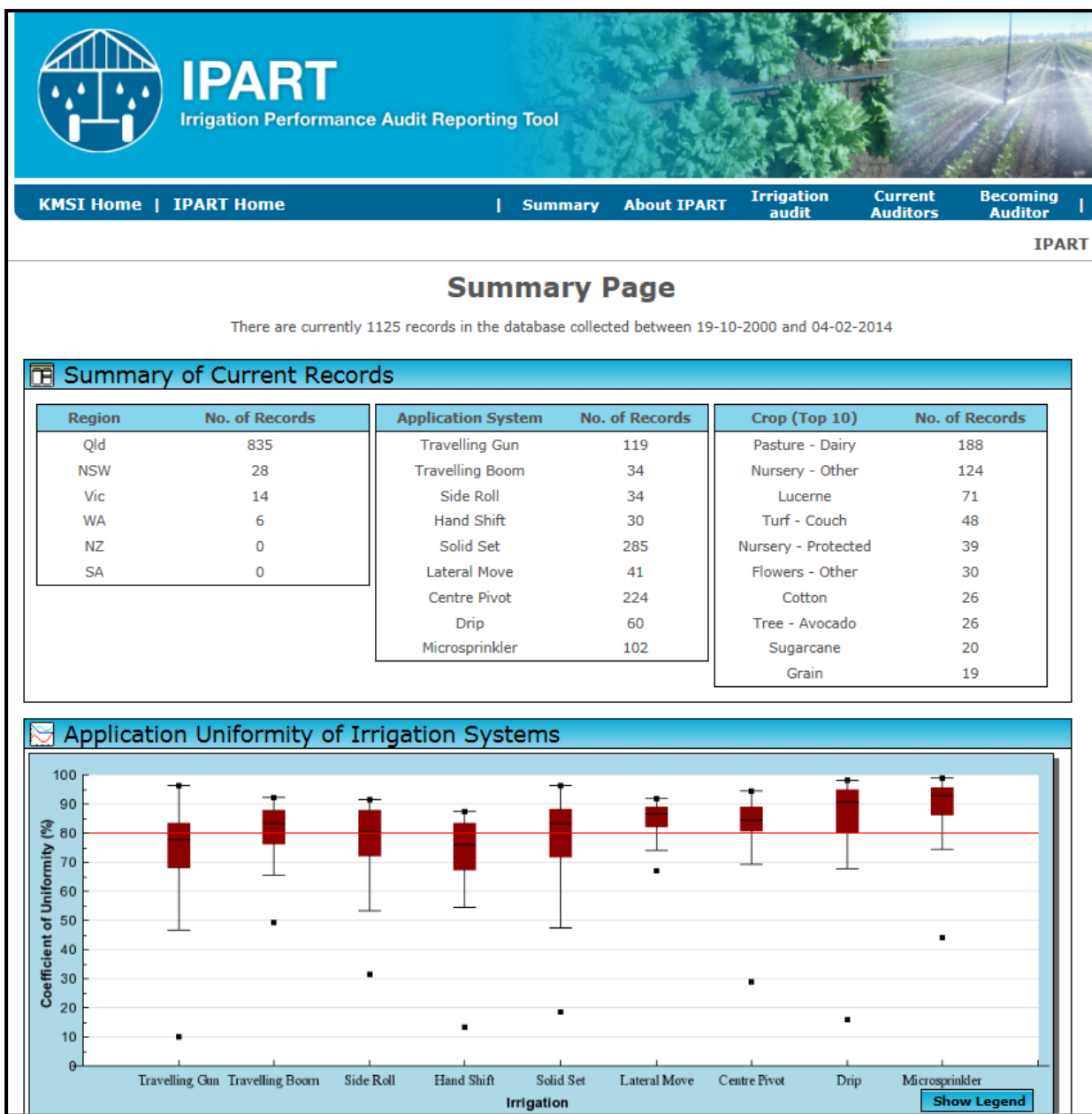
 <b>IPART</b> Irrigation Performance Audit Reporting Tool			
Centre Pivot Evaluation - Report		Generated From Evaluation #206 by Steven Raine on 16/2/2014	
<b>System Details</b>			
<b>Irrigation System</b>			
Machine Make	REINKE		
Sprinkler Height above Ground (m)	1.3		
Sprinkler Make	Nelson		
Sprinkler Model	Rotators		
Pressure Regulators Fitted?	Yes		
Pressure Regulator Value (kPa)	69.0		
Pressure at Pivot Point (kPa)	72.4		
Pressure at End - Highest Point (kPa)	28		
Speed Setting (m/hr)	27.9		
<b>Statistics</b>			
<b>Whole Pivot</b>			
Minimum Depth Applied (mm)	4.9	Measured Wetted Radius of Pivot (m)	195
Maximum Depth Applied (mm)	24.7	Total Machine Length (m)	193.1
Average Depth Applied (mm)	14.2	Effective Design Radius of Pivot (m)	193.1
Avg Depth in Lowest 1/4 (mm)	11.5	Weighted Average (CU mod HH) (mm)	12.8
Weighted Average (mm)	13.6	CU mod HH (effective area)	89.6
<b>Catch Can Row 1</b>			
Minimum Depth Applied (mm)	7.6	Weighted Average (mm)	13.9
Maximum Depth Applied (mm)	24.7	Weighted Average (CU mod HH) (mm)	13.3
Average Depth Applied (mm)	14.9	CU mod HH (effective area)	89.6
Avg Depth in Lowest 1/4 (mm)	12.1	CU mod HH (all cans)	89.9
<b>Catch Can Row 2</b>			
Minimum Depth Applied (mm)	4.9	Weighted Average (mm)	13.2
Maximum Depth Applied (mm)	20.0	Weighted Average (CU mod HH) (mm)	12.4
Average Depth Applied (mm)	13.5	CU mod HH (effective area)	89.4
Avg Depth in Lowest 1/4 (mm)	11.0	CU mod HH (all cans)	90.5

Figure 1: Example of IPART centre pivot evaluation report



**Figure 2:** Example output of application uniformity of irrigation system

## 2.2 NutriCalc

At the whole field scale the Nutrient Balance and Reporting Tool is an online nutrient management calculator designed with an interactive data record management system (Figure 3) and tiered reporting capability (Figure 4). NutriCalc can help growers develop nutrient management plans for use on-farm. NutriCalc incorporates a mapping interface and a record-keeping system for determining appropriate nutrient management strategies for particular blocks and farms.

NutriCalc enables appropriate fertilisers to be selected to meet the identified nutrient requirements and to record measured fertiliser inputs for individual blocks. The tool records yield data to enable nutrient management strategies to be re-evaluated and revised, to enable benchmarking of nutrient levels and usage against district trends.

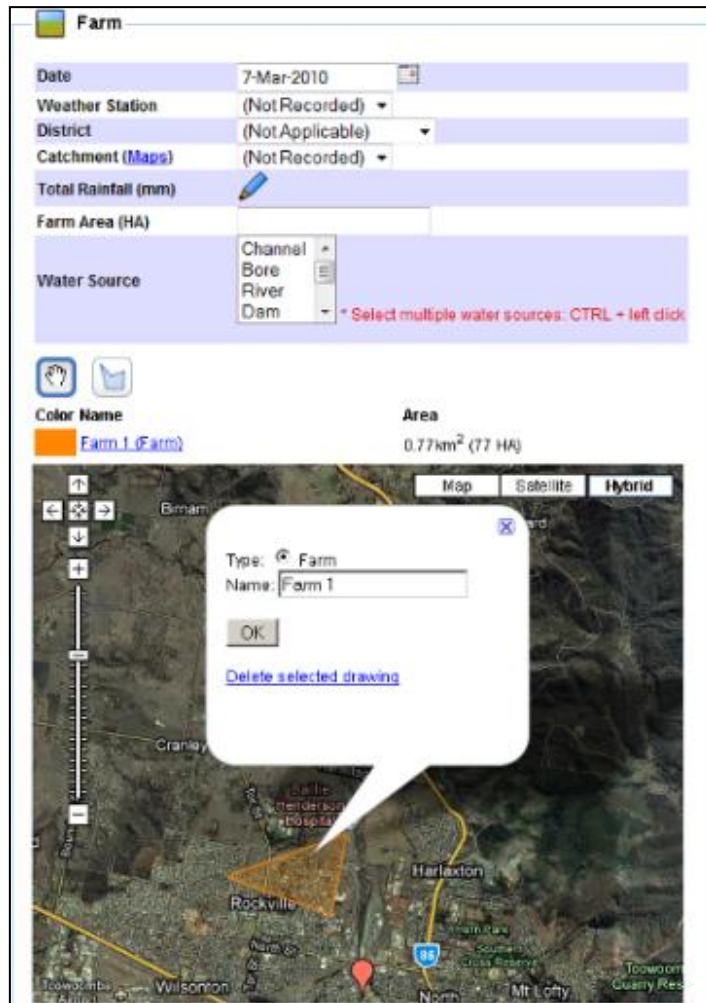


Figure 3: Example farm setup screenshot from NutriCalc



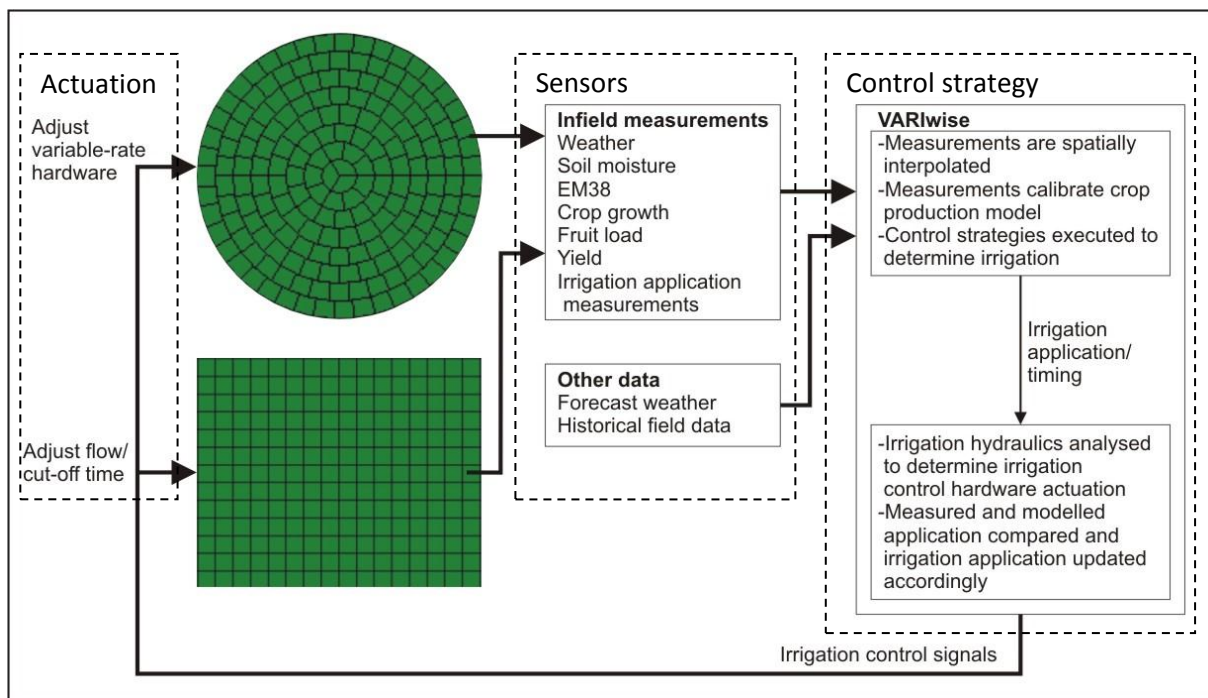
Figure 4: Example nutrient requirement report from NutriCalc

### 3. Autonomous irrigation and nutrient management

VARIwise steps toward autonomous irrigation and nutrient prescription and application by linking infield sensing, closed-loop control strategies and control actuation. ‘VARIwise’ is a software framework that implements and simulates control strategies on fields with sub-field-scale variations in all input parameters (including nutrients) (McCarthy et al. 2010). This enables:

- data input at any spatial resolution;
- incorporation of crop model output for simulated response/prediction of crop response;
- incorporation of hydraulic equations to determine irrigation and fertiliser variability according to sprinkler or surface application hydraulics; and
- implementation of control strategies that use a calibrated crop model and/or the soil/crop response to predict the application that will produce a desired agronomic response for all sub-field management zones.

The irrigation and/or fertiliser applications are adjusted according to a combination of soil and plant measurements, hydraulic modelling and calibrated crop model outputs (as required, Figure 5). Input parameters are measured using infield soil sensors and on-the-go crop monitoring cameras. The control systems can be implemented in VARIwise either in simulation through APSIM or in field implementations using irrigation and fertiliser actuators. Variants of the framework have been developed for centre pivots, lateral moves and surface irrigation systems.



**Figure 5:** Generic adaptive control system applied to surface and overhead irrigation and fertiliser systems



### **3.1 Control strategy**

Advanced process control, in an irrigation context, refers to the incorporation of multiple aspects of optimisation and control. An engineering approach generally labelled ‘advanced process control’ is now routinely applied for manufacturing and chemical process systems and combines elements from many disciplines spanning classical control engineering, signal processing, statistics, decision theory and artificial intelligence (Ikonen and Najim 2002). The application of advanced process control to irrigation presents opportunities to improve irrigation water use and crop performance.

Three advanced process control strategies have been implemented in VARIwise, as follows.

- **Iterative Learning Control [ILC]** – iteratively adjusting the irrigation and/or fertigation volume applied in each zone of the field using the incremental response, i.e. the OZCOT-determined plant growth arising from the change in particular field sensor information which has resulted from the previous water application, in each zone (McCarthy et al. 2014a).
- **Iterative Hill Climbing Control [IHCC]** – similarly adjusting the irrigation and/or fertigation volumes, but based on multiple sensor increment information, using a range of irrigation and/or fertigation volumes applied within a group of homogenous zones (McCarthy et al. 2014a)
- **Model Predictive Control [MPC]** – uses a model to predict the optimal input signal at the current time considering future events over a finite time period (McCarthy et al. 2014b)

For ILC and MPC, the irrigation events are scheduled after the crop has consumed a user-defined set volume of water.

### **3.2 Sensors**

Weather data is required for ILC and IHCC to estimate crop water use and irrigation timing, and for MPC to calibrate the crop production model. Weather data can be obtained from an infield automatic weather station and/or Bureau of Meteorology. Weather prediction is also required for MPC and is provided using SILO patched datasets in Australia.

Soil-water measurements at multiple depths are required for some control strategy implementations. For example, for ILC and IHCC the irrigation/fertigation volumes may be adjusted according to the difference in soil-water before and after the previous irrigation event. For MPC, soil-water data are used to calibrate the crop production model.

Direct measurement of soil-water using infield sensors at a high spatial resolution is not practical or feasible in a commercial cropping situation. Non-contact sensors would enable higher spatial resolution estimations of soil-water. A common non-contact soil sensor is based on electromagnetic induction (EM). EM measurements have been correlated to soil-water measurements (Hossain 2008); hence, following each survey these measurements were correlated to the soil-water measurements to estimate the spatial variability of soil-water.

For the Australian cotton production model OZCOT (Wells and Hearn 1992), plant parameters that are required to calibrate the model are plant density, leaf area index, square (flower bud) count and boll (fruit) count. However, measurement of these parameters requires labour-intensive visual assessment of individual plants. This process could

effectively be automated using cameras to automatically acquire images of the crop, and image analysis algorithms to analyse the image and extract fruit load and vegetation information.

NCEA is developing a ground-based sensing system for estimation of plant density, plant height (to estimate leaf area index), boll counts and flower counts (to estimate square counts) (Figure 6). The system uses three cameras to capture overhead views of the crop canopy and an ultrasonic distance sensor to measure crop height. The captured images are analysed to estimate plant density, flower count and boll count, whilst the height is used to estimate the leaf area index of the crop (McCarthy and Hancock 2013). Four plant sensing systems were developed and mounted on the centre pivot irrigation machine, three evenly across the controlled span and one on the span next to the trial for comparison with the field trial.



**Figure 6:** Plant sensing system

### 3.3 Actuation

Site-specific irrigation is enabled for centre pivot and lateral move irrigation machines through commercially available variable-rate hardware (e.g. Design Feats, Zimmatic, Valley). These systems adjust the irrigation application within the field by varying the speed of the machine and/or pulsing solenoid valves on each dropper. The variable-rate hardware adjustments are obtained pre-determined prescription maps, rather than real-time data input.

### ***3.4 Implementation in 2012/13 field trial***

#### *Materials and methods*

Fieldwork was conducted between October 2012 and April 2013 to evaluate the performance of the ILC and MPC strategies for irrigation application on a large mobile irrigation machine and compare these results with simulations (Figure 7, Table 2). Cotton variety Sicot 74BRF was sown under the 305 m long centre pivot irrigation machine on 9 October 2012 in Jondaryan, QLD. This evaluation also enabled the identification of the data requirements of the MPC control strategy that provided sufficient calibration of the crop model. Minimising the data requirements would provide an irrigation monitoring and control system that would be more practical for implementation in commercial cotton production.



One span of the centre pivot irrigation machine 48 m long installed with variable-rate hardware. An 8 m buffer was allowed across the span such that each plot was 32 m wide and 27 m long. The irrigation application was varied midway between the plots as the machine passes over the field. Irrigation valves and flow meters were connected to an 'irrigation controller' computer also installed on the irrigation machine tower. A GPS with an accuracy of 0.5 m was located in the centre of the span.

In field measurements were collected using: an automatic weather station; onsite; seven soil-water probes; EM surveys; and irrigation-machine plant sensing systems. A remote computer running VARIwise collated the weather station, soil-water and real-time plant sensor data to determine the required irrigation depth. This remote computer then updated a file on a remote server containing the percent of irrigation application required for each sprinkler. A mini-computer was used as the controller for the irrigation hardware (Fit-PC2, CompuLab, Israel). The computer was connected to the Internet, accessed online files on a FTP server and transmitted variable-rate irrigation control signals.

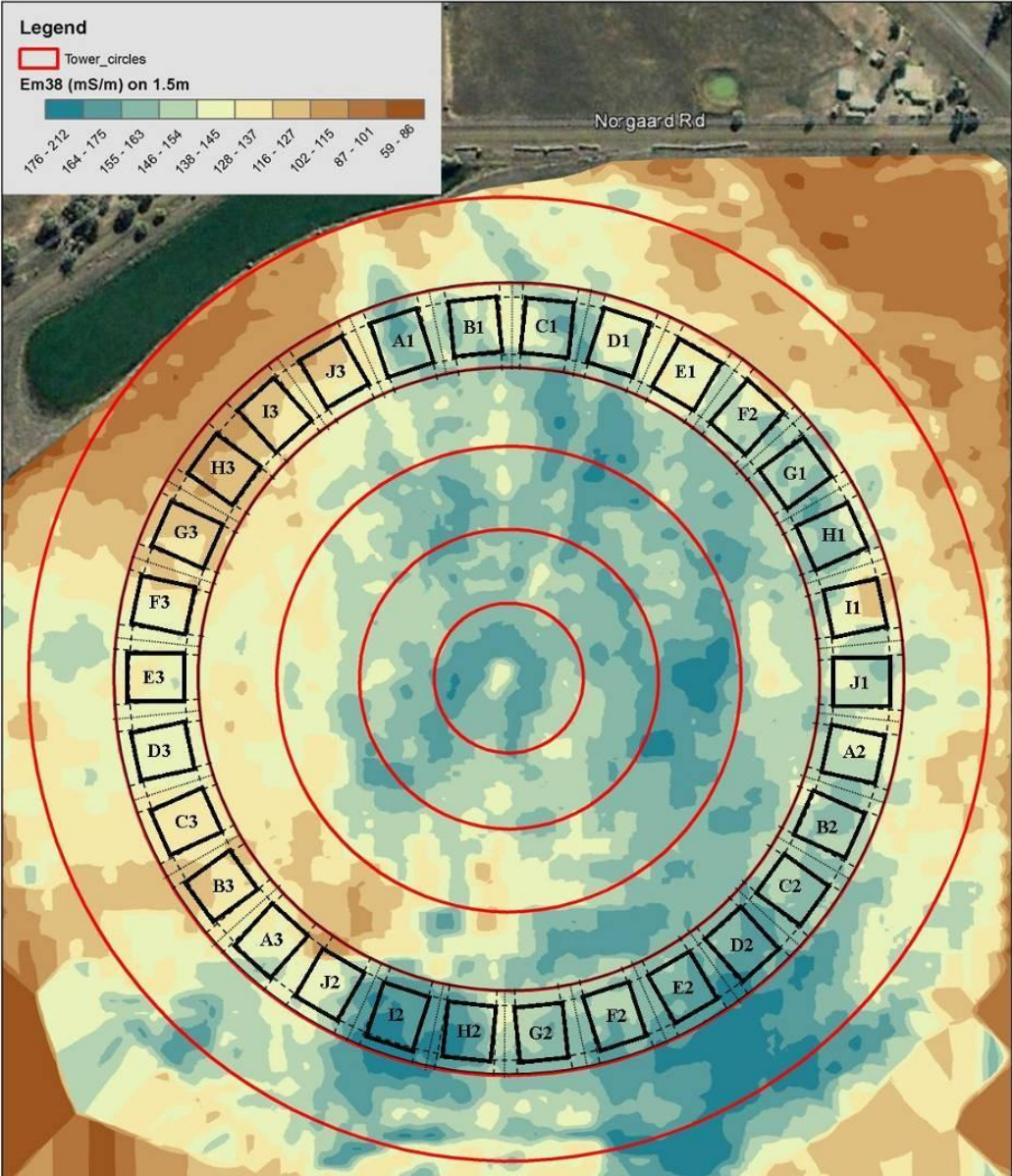


Figure 7: Horizontal EM survey conducted on Jondaryan field trial site

**Table 2:** Control strategies evaluated in 2012/13 fieldwork were W indicates weather data input, S indicates soil data input and P indicates plant data input

ID	Control strategy	Performance objective	Data input
A	MPC	Maximise yield	WSP
B	MPC	Maximise yield	WS
C	MPC	Maximise yield	WP
D	MPC	Maximise CWUI	WSP
E	MPC	Maximise CWUI	WS
F	MPC	Maximise CWUI	WP
G	ILC	Fill soil-water profile	WS
H	ILC	Achieve set soil-water deficit	WS
I	FAO-56	Fill soil-water profile	WS
J	FAO-56	Achieve set soil-water deficit	WS

### *Results and discussion*

The MPC strategies that maximised yield produced higher yields as the level of data complexity increased, and the MPC strategies that maximised CWUI produced lower yields as the level of data complexity increased. In addition the MPC strategy that maximised yield produced the highest yield with full data input and lowest yield with weather-and-soil data input. This indicates that including plant input increases the accuracy of the yield prediction. These results are consistent with the performance objective of the MPC strategies implemented: the model calibration improved with more data inputs which led to high yields for MPC maximising yield, but reduced water use (and led to yield reductions) for MPC maximising CWUI.

ILC applied more irrigation than the MPC strategies with any data input, and generally achieved lower yields. As ILC required only soil data input, the ILC strategy would be suited for achieving higher yields with low data availability. However, under limited water the MPC strategies would be preferable. Adaptive control yielded approximately 7% more cotton and applied 4% less irrigation water than FAO-56.

### **3.5 Implementation for fertigation trial**

Advanced process control can be applied to both irrigation and fertiliser management, and provides opportunities increase crop yield through multi-objective optimisation. The control strategies will be evaluated for fertigation control for cotton production in 2014/15. This will require investigation of hydraulic models for fertiliser injection to determine distribution at different flow rates. A field trial has commenced at Jondaryan on a gated pipe surface irrigation trial to verify fertiliser models.

## **4. Conclusions**

NCEA has developed grower tools and an automation framework for irrigation and fertiliser management, namely 'KMSI' and 'VARIwise', respectively. KMSI can collate data and generate recommendations for growers and consultants on irrigation and fertiliser requirements. VARIwise enables closed-loop automation of infield sensing, control strategies

and variable-rate irrigation/fertigation control. Irrigation trials have been conducted on a centre pivot irrigated cotton crop in Jondaryan, QLD to evaluate control strategies with different data input combinations. Field evaluations of fertigation control will commence in 2014/15 on a cotton crop.

### **Acknowledgements**

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