# Spatial irrigation scheduling for variable rate irrigation

C.B. HEDLEY[1], S. BRADBURY[2], J. EKANAYAKE[3] , I.J. YULE[4] and S. CARRICK[3]
[1] *Landcare Research, Massey University Campus, Palmerston North*
[2] *Precision Irrigation, 581 Taonui Rd., RD5, Feilding*
[3] *Landcare Research, Gerald St., Lincoln*
[4] *NZ Centre for Precision Agriculture, Massey University, Palmerston North*
HedleyC@LandcareResearch.co.nz

## Abstract
Recent unprecedented demands on freshwater for irrigation have led to over-allocations and restrictions. Variable rate irrigation (VRI) aims to optimise scheduling according to soil differences using irrigation prescription maps coupled with software-driven variable rate irrigators and individual sprinkler control for site specific management. Irrigation scheduling is varied using soil available water holding capacity (AWC) maps, generated from soil apparent electrical conductivity maps, with real time soil moisture monitoring using wireless sensor networks (WSN). Simulated results for a Canterbury site show that water savings between 2004 and 2009 are between 4 and 7% for any one season, the years with larger savings relating to rainfall events during the irrigation period. Drainage during the irrigation period was reduced by between 16 and 33%. VRI allows irrigation to be placed where it has greatest benefit; this is particularly important when freshwater is limited during peak growth periods. It aims for improved water productivity with environmental benefits of reduced run-off and drainage.
**Keywords:** precision irrigation, EM soil mapping, available water

## Introduction
In New Zealand, irrigation energy costs are about 50% of on-farm energy costs in dairy farming systems (Barber & Pellow 2005). Therefore, farmers aim for best use of irrigation water and are investigating the potential opportunities of variable rate irrigation, which is now commercially available (Bradbury 2010). In addition, freshwater allocations for irrigation are becoming restricted, due to an unprecedented demand for irrigation to support a national drive for increased agricultural productivity. Irrigation demands about 80% of allocated freshwaters in New Zealand, which is similar to the global average (Hedley *et al.* 2009); and the area of irrigated land in New Zealand has roughly doubled every decade since the 1960s. This increase has escalated in the last decade from 460 000 ha in 2004 to 600 000 ha in 2007 (Statistics NZ) and in 2010 is estimated to be about 750 000 ha (Irrigation NZ). As water restrictions become more severe in many parts of the world, there will be increasing pressure on New Zealand soil and freshwater resources to meet the global food supply demand.

Variable rate irrigation (VRI) addresses the need to optimise irrigation scheduling, aiming for best conversion of each millimetre of irrigation water to pasture growth. A recent review of opportunities for improving irrigation efficiency (Greenwood *et al.* 2010) discusses the need for greater spatial and temporal control of irrigation, as well as opportunities provided by simulation models, new sensors and wireless telemetry. Automated control of an existing sprinkler irrigator, modified for variable rate irrigation, using a soil-based decision support tool, exemplifies these new opportunities (Hedley & Yule 2009a,b).

Existing decision support models frequently have the inherent weakness of reliance on regional weather data which does not incorporate any real-time site-specific measurements, and rainfall can vary by a large amount from the regional data being used in a water balance model. De Jonge *et al*. (2007) also stated that soil water hydraulic data must be site specific.

A soil apparent electrical conductivity ($EC_a$) map defines soil spatial variability at a resolution of a few metres, predominantly on a basis of texture and moisture differences, in non-saline soils (e.g. Sudduth *et al*. 2005; Hedley *et al.* 2004). The map can be used to target soil moisture monitoring sites and for calibration of the dataset against soil water-holding properties. An available water-holding capacity (AWC) map can then be produced (Godwin & Miller 2003), with site specific soil moisture measurements to aid spatial irrigation scheduling. The digital map is available for upload to an automated VRI system (Hedley *et al*. 2009).

A wider goal of our research is to address the need for improved freshwater-use efficiency by developing a practical, commercially affordable method to map and monitor daily soil water status for precision irrigation scheduling, using (i) EM mapping for the development of irrigation management zones, (ii) wireless sensor networks (WSNs) monitoring zone soil moisture, and (iii) resulting spatial soil moisture data available for upload to an automated variable rate irrigator (Hedley *et al.* 2010). This paper presents an analysis of the potential benefits of varying the timing and amount of irrigation according to soil differences under an irrigation system in Canterbury.

## Methods

### Site selection

A 111 ha Ashburton farm trial site was selected where variable soils exist under a linear move sprinkler irrigator. The irrigator has recently been modified with variable rate control of each individual sprinkler. The soils range from deep Wakanui silt loams (Pallic soils) at one end of the irrigator to Rakaia very stony sandy loams (previously the Waimakariri soil) (Recent soils) at the other end.

### EM mapping and identification of irrigation management zones

A Geonics electromagnetic EM38 sensor was used with on-board datalogger, RTK-DGPS and Trimble field computer on an all-terrain vehicle (ATV), for simultaneous collection of positional and topographically located apparent electrical conductivity $EC_a$ (mS/m) data. Survey data points were collected at 1 second intervals along parallel 10-m swaths, with an average ATV speed of 15 kph. This allowed a measurement to be taken approximately every 4 m along each swath. The method is termed "on-the-go EM mapping" (Adamchuk *et al.* 2004). The spatially defined $EC_a$ dataset was kriged (a geostatistical method to interpolate a prediction surface from georeferenced point data) using Geostatistical Analyst in ArcGIS (ESRI© 1999) to produce a map of soil $EC_a$, with map classes determined by 'Jenks' natural breaks classification. This classification determines the best arrangement of values into classes or "zones" by iteratively comparing sums of squares of differences between observed values within each class and class means (Hedley & Yule 2009a).

The map was then used to select nine soil sampling positions to investigate the full range of soil $EC_a$ values. At each position, intact soil cores were collected from three soil depths (0-0.2, 0.2-0.4 and 0.4-0.6 m) to assess percent stones, bulk density and AWC (volumetric soil moisture difference between field capacity and wilting point) (Hedley &Yule 2009a,b). Field capacity and wilting point were estimated in the laboratory as water retention at 10 kPa and 1 500 kPa. The sampling depth was selected to reflect the majority of the root zone from which water is extracted by plants. The results were used to define irrigation management zones, based on soil AWC differences. Soil moisture was also monitored using a WSN, with nodes installed at each of the nine soil sampling positions (results not reported here).

### Hypothetical irrigation scheduling for VRI and uniform rate irrigation (URI)

A soil water balance model (Allen *et al.* 1998) was used to simulate soil wetting and drying patterns of each management zone. The model determines root zone soil water depletion relative to field capacity (mm), on any one day, using site-specific rainfall. Irrigation events (10 mm) were scheduled on the day that zone critical soil moisture deficit (CSMD) for irrigation was reached, using a depletion factor 0.5AWC (Allen *et al.* 1998) for the mean AWC for each zone.

URI scheduled an irrigation event to the whole area when the zone with smallest AWC reached its CSMD, aiming for potential yield. If URI were scheduled according to the CSMD of an intermediate zone then yield would be lost in more droughty soils. The modelling simulates a high productivity irrigated system aiming for potential yield by eliminating water stress.

VRI varied the timing of irrigation to each zone based on its specific CSMD also avoiding water stress and maintaining potential yield.

## Results

The $EC_a$ map (Fig. 1a) reflects soil and AWC differences. Soil $EC_a$ values decrease with increasing coarseness of soil texture, and decreasing AWC (Table 1). Our results show that soil $EC_a$ is related to soil AWC (Fig. 2; $R^2$=0.83) and the regression model was used to predict the AWC datalayer (Fig. 1b). There were a wide range of measured AWC values under this irrigation system (Table 1), confirming the need for site specific management. Soil AWC varied between 34 mm in the very stony Rakaia soil at one end of the irrigator to 114 mm in the deep Wakanui silt loam at the other end (Fig. 1b). The area was divided into four zones for this analysis based on observed soil and measured AWC differences (Table 1; Fig. 1b).

The results of the soil water balance modelling which compared VRI and URI scheduling scenarios for five irrigation seasons (1 June 2004 to 31 May 2009) are presented in Table 2. The amount of water applied with URI varied between 470 and 590 mm over the 5 years. VRI enabled irrigation to be reduced to soil zones with higher AWCs, where soils have a greater ability to store and supply plant available water. Water savings for a soil with AWC 98 mm/0.6 m were between 50 and 100 mm per season. The mean reduction in irrigation depth applied by VRI compared with URI for all four zones was 26 mm per season, an overall 5 % saving. The largest water saving occurred in the 2006-07 irrigation season and was due to replenishment of the soil resource by two large rainfall events (50 mm on 30 October and 54 mm on 20 December). Site mean water saving is derived by proportioning water savings for each zone

**Figure 1** (a) Soil $EC_a$ map and (b) soil AWC map for the Ashburton site. Soil sampling sites are shown on the soil $EC_a$ map (as triangles). Irrigation management zones (A, B, C, D) are shown on the AWC map.

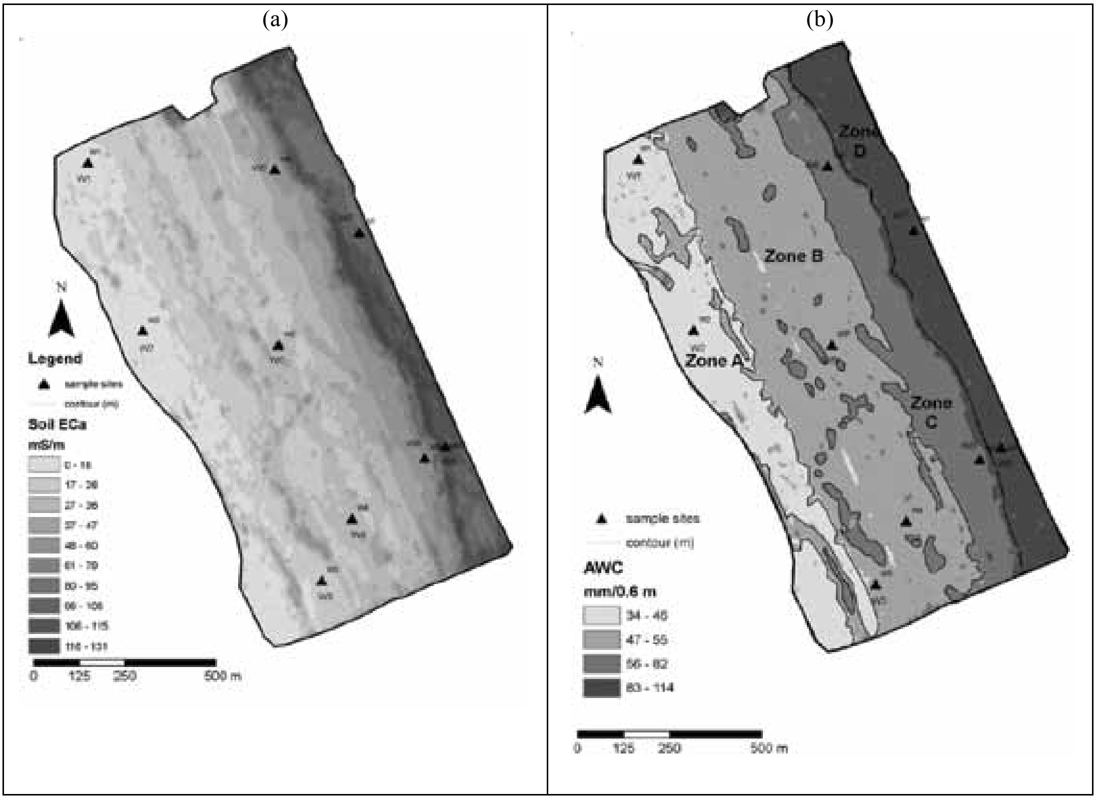



**Table 1** Soil characteristics and size of the four irrigation management zones under one irrigation system on an Ashburton farm.

| Zone | Area (ha) | $EC_a$ range (mS/m) | AWC range (mm/0.6 m) | Mean AWC (mm/0.6 m)* | Soil type and texture |
|---|---|---|---|---|---|
| A | 22.6 | 0.5-13.5 | 34-46 | 40 | Rakaia very stony sandy loam |
| B | 49.6 | 13.5-53.0 | 47-55 | 51 | Rakaia stony sandy loam |
| C | 22.0 | 53.0-79.5 | 56-82 | 69 | Mixed Rakaia sandy loam/ Wakanui silt loam |
| D | 16.6 | 79.5-132.0 | 83-114 | 98 | Wakanui silt loam |

*AWC expressed at millimetres of available water in the root zone for pastoral soils

**Table 2** Simulated irrigation savings and drainage reductions with VRI compared with URI scheduling for the period 2004-2009 at the Ashburton irrigation site.

| Season | Irrigation Saved | | Reduced drainage during irrigation | |
|---|---|---|---|---|
| | % | mm/year | % | mm/year |
| 2004-2005 | 4 | 19 | 29 | 26 |
| 2005-2006 | 4 | 22 | 16 | 22 |
| 2006-2007 | 7 | 31 | 33 | 39 |
| 2007-2008 | 4 | 23 | 19 | 22 |
| 2008-2009 | 5 | 32 | 22 | 32 |
| mean | 5 | 26 | 24 | 28 |

**Figure 2** Relationship between soil $EC_a$ and soil AWC at the study site.

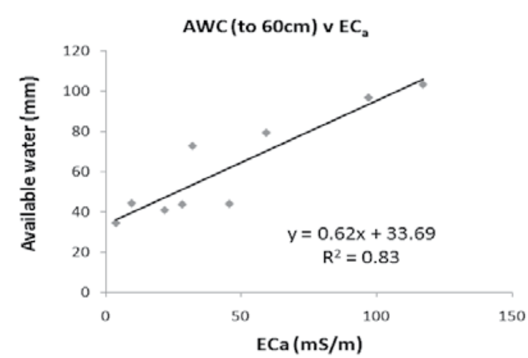
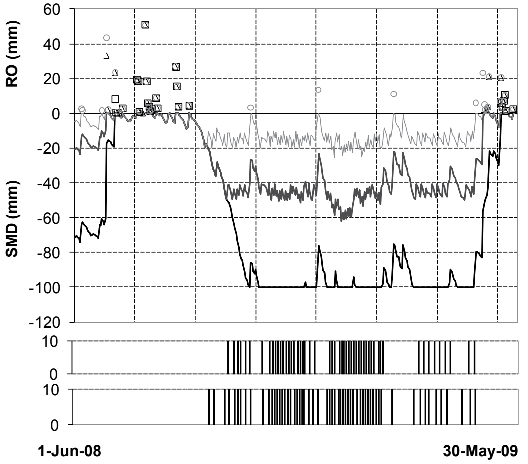


**Figure 3** Soil water balance for soil zone with largest AWC (Zone D) using URI (light grey), VRI (grey) and no irrigation (black) from June 2008 to May 2009. Also shown are scheduling frequencies of 10 mm irrigation events for VRI (top) and URI (bottom). RO = run-off and drainage; SMD = soil moisture deficit.




by the area of each zone to provide a mean value for the whole site. The soil water balance model also showed that VRI reduced drainage and run-off from this site by 28 mm per irrigation season, a mean saving of 24 %.

Fig. 3 presents the soil water balance for soil zone D, the zone with largest AWC, modelling (i) URI, (ii) VRI and (iii) no irrigation from June 2008 to May 2009. It shows that zone moisture status is maintained at a greater SMD with VRI compared with URI, making use of the ability of the soil with larger AWC to store and supply water to the plant.

## Discussion

The $EC_a$ map quantifies soil differences and has been used to develop irrigation management zones based on the varying ability of soils to store and deliver water to the pasture under one irrigation system. Soil water balance modelling shows the potential benefits of VRI are a 5 % water saving (26 mm in any one year) from 2004 to 2009. If we assume a mean cost of irrigation is \$2/mm/ha (FAR 2008), then the cost benefit is \$52/ha/yr. This financial benefit increases if saved water is re-directed elsewhere to increase yield. VRI aims to maintain larger SMDs in zones with larger AWCs and reduce drainage and run-off, minimising the risk of leaching nutrients past the root zone.

The results from this study can be compared with previous studies where the potential water savings with VRI under dairy pastures, potatoes and maize grain crops, were between 8 and 21% (Hedley *et al*. 2010). At the other sites, soils varied on a basis of AWC, depth to water table and drainage characteristics. Larger savings were obtained at the other sites partly because zones with largest AWC were proportionally larger than at the present site. This season actual VRI and URI scheduling will be compared at three farms. Crop and pasture yield will be monitored during the irrigation season to quantitatively assess water use efficiency.

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