Soil Water Sensors for Managing Deep Drainage

Warren J Bond

A report to the Grains Research and Development Corporation on project CSO00004: Objective measures for managing the risk of deep drainage

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- the Barass, Ross, Todd and West families in the Condobolin district; and
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Executive Summary

The project reported here aimed to provide a means for obtaining feedback on the deep drainage of crops through the development of guidelines for installing and interpreting simple, farmer-friendly soil moisture sensors. A number of sensors were evaluated, a suitable one selected, and then deployed in 28 paddocks across four regions of NSW with different mean annual rainfall and a range of different soil types from deep sands to cracking heavy clay soils. In 20 paddocks soil water content was measured independently, and in 12 paddocks independent measurements of deep drainage were made.

The fibreglass block was found to be a suitable device for monitoring soil water status below the root zone of annual crops. It was relatively inexpensive and easy to install (at depths of 1.5 to 2 m), covered the whole range of soil water status of interest, and could be interpreted directly in terms of the soil water limits "field capacity" and "wilting point". One initial drawback was the limited availability of suitable measurement devices for it, but this can be easily overcome.

The dry conditions experienced during the three years of field testing of these sensors limited the number of instances in which deep drainage might have occurred. Rainfall conditions were really only suitable for deep drainage to occur in one year (2005), and this was not universally the case across all the regions where sensors were installed; Condobolin and Wagga Wagga were below average rainfall even in 2005.

Despite the uncertainty introduced by the below average rainfall, there was good evidence that a single measurement of soil water status below the annual crop root zone could be used to indicate when deep drainage occurred. In 11 of the 12 paddocks where independent estimates of deep drainage were available, the single sensor measurement agreed with them. This included four cases where deep drainage occurred and eight where it didn't.

A single measurement of soil water status below the annual crop root zone was also a good predictor of whether deep drainage would occur. If a measurement made in April was wetter than 200 kPa, there was a strong likelihood of deep drainage occurring in the following winter. On this basis, the measurement correctly predicted deep drainage in nine out of the 13 paddocks in which it occurred; in four paddocks deep drainage occurred but was not predicted by the measurement. Prediction of deep drainage on the basis of the measurement made below the root zone in April being wetter than 200 kPa was correct in nine out of 14 cases; ie of the 14 paddocks where the measurement predicted it should occur, deep drainage occurred in nine of them.

As expected, there was a strong positive correlation between the occurrence of deep drainage and the number of years under cropping or annual pasture, although this was also affected by the unusually dry conditions.

Few paddocks under lucerne exhibited the expected behaviour of soil water potential below the annual crop root zone. It was clear, however, that the length of time that lucerne had been established was not necessarily a good guide to how effectively it had dried the subsoil. This is attributed to factors such as poor initial establishment of lucerne and reduced plant density of lucerne after a few years, both of which are made worse by dry years. Having a measurement of soil water status is therefore likely to be a useful guide to how effective lucerne has been and when it can be removed with minimal risk of deep drainage occurring.

Simple guidelines for using and interpreting soil water monitoring devices have been prepared.
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1. Introduction

1.1. Background

Clearing of native vegetation and the introduction of farming systems based on annual plants are cited as the cause of rising water tables and soil salinisation across large areas of land in southern Australia (Peck and Williamson 1987). A number of studies have shown that there is considerably more deep drainage under annual cropping systems than under native vegetation and deep rooted perennial pastures such as lucerne (Black et al. 1981; Halvorson et al. 1988; Dunin et al. 1999). Reducing salinisation pressures will involve changing land use practices to new systems having recharge at rates no greater rate than the groundwater systems can accommodate. This will entail changing farming practices to reduce drainage beneath agricultural crops.

The impacts of salinisation are usually registered at catchment scale, occur at some distance from most farms, and take a long time to manifest themselves. Deep drainage is strongly dependent on rainfall, and therefore highly variable. Farmers require more immediate feedback of the impacts of their own practices each year if they are to manage the risk of deep drainage successfully and reduce the salinisation pressures in years to come.

The project reported here aimed to provide a means for obtaining feedback on the deep drainage of crops through the development of guidelines for installing and interpreting simple, farmer-friendly soil moisture sensors. Using the proposed sensor/guideline package, farmers will be able to determine if their crop/pasture is causing deep drainage or not, and whether deep rooted pastures such as lucerne have been effective in reducing the risk of deep drainage. This is much easier than determining the exact amount of deep drainage which is a challenging task for most researchers and is unrealistic to expect farmers to do. With this feedback farmers will be empowered to develop their own responses to the need for deep drainage reduction, by trialling new management strategies, new crops, etc, and being able to know what their immediate impact is.

A particular application of this sensor/guideline package is for the development of decision rules for phase farming with lucerne, which has been shown to be an effective strategy for reducing deep drainage in the 300-600 mm rainfall zone (Stirzaker et al. 2000; Ridley et al. 2001; Ward et al. 2002). In this system lucerne, a perennial pasture with a deep root system, is grown in alternating phases with annual crops. It is based on the concept that because lucerne can extract water from the soil below the root zone of annual crops, it has the ability to "capture" water that has not been used by those crops before it is lost to the groundwater. By doing this it also creates a buffer which refills again under a subsequent phase of annual cropping (Figure 1). Uncertainty remains, however, about when to switch from one phase to the other to maximise the impact of lucerne. This is because refilling of the buffer depends primarily on the amount and timing of rainfall (Ridley et al. 2001; Verburg et al. 2006a), both of which are highly variable (Verburg et al. 2005). The rate at which the buffer refills also depends on how much rainfall the system loses through surface runoff and evaporation from the soil surface as well as the water use of the annual crops, which determine how much water escapes past the bottom of their root zone each year.

Measurement of soil water just below the root zone of the crops might often give a timely warning of deep drainage occurring at deeper depth (below the root zone of lucerne, see Figure 1) and could therefore be used as a trigger for changing phases (Verburg et al. 2001; Verburg and Bond 2003).

Preliminary modelling (Verburg et al. 2001) confirmed the concept of using a soil water measurement below the annual crop root zone as a trigger for lucerne/cropping phase changes by showing that it reduced drainage by 35-40% compared with having phases of fixed length (3 years lucerne, 3 years crop). A more comprehensive modelling exploration of this system (Verburg et al. 2006b) was carried out in parallel to the study reported here, which concentrates on the field application and demonstration of the simple soil water measurement concept.
1.2. Concept

The concept for interpreting a deep soil water measurement is relatively simple. Several possible scenarios for changes in soil water status at depth in the soil are illustrated in Figure 2.

Figure 2a illustrates what would be expected to be shown by a soil water sensor within the root zone of a crop during a winter with sufficient rainfall for water to penetrate to the depth of measurement. The water content rises in response to winter rainfall and then falls again as the crop uses soil water. If successful crops were grown in the current and preceding years, the soil water would be expected to return to about the same level after harvest as in the preceding summer (the wilting point of the soil, the water content below which crops cannot extract water).

Figure 2. Schematic representation of some possible responses of soil water measurement in an annual crop following lucerne (a, b) and following the reintroduction of lucerne (c, d) at different depths in the soil, assuming a normal wet winter.
The response to a wet winter of a soil water sensor installed below the rooting depth of an annual crop is shown in Figure 2b. It is assumed that the soil has been dried previously to wilting point by a deep-rooted perennial such as lucerne. If there is sufficient winter rainfall to penetrate beyond the annual crop rooting depth, the soil will wet, but because there are no roots at that depth to extract the water it will remain wet after harvest and into the next cropping year. This is the scenario that indicates deep drainage and may lead to groundwater recharge if the water is not subsequently extracted, for example by lucerne.

With soil water sensors installed at different depths, their responses when compared against the expected patterns in Figure 2a,b can be used to determine the depth of rooting of the annual crop.

In the first year after lucerne is planted, soil water responses such as those shown in Figure 2c,d might be expected. At shallower depths, within the root zone of annual crops, it is likely that there will be an initial increase in water content if the rainfall exceeds the evaporative demand of lucerne in winter. This will be followed by a rapid drying to wilting point. Below the depth of rooting of annual crops, drying is likely to be observed at some stage during the first summer. The amount of drying depends on the depth of the sensor, and how well the lucerne establishes itself. In some cases (particularly just below the annual crop rooting depth) drying to wilting point might occur in the first summer, in others only partial drying, as shown in Figure 2d.

Of course these ideal scenarios will not always be observed and sensor response will often be less clear in practice. For example, the soil may not always be starting dry below the annual crop rooting depth as assumed in Figure 2b. However, as will be seen when the results from the application of soil water sensors are presented later in this report, the basic principles illustrated in Figure 2 can still be used to interpret the soil water traces.

It should be noted that the interpretation of the data does not depend on knowing the absolute value of water content. The interpretation relies only on relative states of wetness and dryness. This is important in the selection of a suitable sensor, because it is a less stringent requirement and therefore increases the options.

### 1.3. Objectives

This report describes the selection, installation and interpretation of soil water sensors that are suitable to provide a means for obtaining feedback on deep drainage. The aim was not to develop sensors as there is a large number already on the market. Instead it was to evaluate the available sensors for suitability for the current application, and to develop guidelines for their installation and how to interpret their output to provide information on the effectiveness of farming practices in managing the risk of deep drainage. Their application is demonstrated by deployment of sensors in a variety of soils, landscapes and rainfall zones.
2. Selection and Description of Soil Moisture Sensors

2.1. Selection Criteria

The following criteria were used for selecting soil moisture sensors for this study:

- Low cost (less than approximately $100 per sensor)
- Easy to use/read
- Easy to install at depths of 1.5 to 2.5 m
- Able to be permanently installed (ie not removed during sowing and harvesting)
- Long lasting (at least 5 years)
- Provide clear distinction between wet and dry conditions

These criteria were developed with a view to making it feasible for farmers to install them, minimising cost and minimising the amount of work associated with installing and using them.

2.2. General Evaluation of Water Content Sensors

Water content sensors were not considered suitable for this application because they were either too difficult to install at the required depth or too expensive. Instruments requiring access tubes, such as the neutron moisture meter (Greacen 1981) and Sentek EnviroSmart capacitance probes\(^1\) require skill in installation and are expensive. Time Domain Reflectometry (Robinson et al. 2003) is also expensive, and difficult to install at depth in a way that provides good contact with the soil and therefore reliable values. Cheaper water content sensors, based on capacitance (or frequency domain technology) similarly require good contact which is difficult to obtain with simple installation methods in most Australian subsoils. These techniques, with the exception of the neutron moisture meter, are also subject to sensitivity to temperature and in some cases soil salinity.

Another difficulty with sensing soil water content is that for many clay subsoils the difference between "field capacity" (or "drained upper limit") and "wilting point" (or "lower limit") is often quite small (of order 0.05 m\(^3\)m\(^{-3}\)), requiring a high degree of accuracy to discriminate between the two conditions.

On the other hand, instruments in this category are becoming cheaper and very easy to use and are being used in "hybrid" sensors, such as that described in section 2.4.5.

2.3. General Evaluation of Soil Water Matric Potential Sensors

Sensing soil water matric potential rather than water content has the advantage that contact with the natural soil is not required to get a reliable reading. It is therefore possible to use a "contact material" around the sensor which ensures good hydraulic connection to the soil and equilibrates with the soil.

Soil water potential sensors have the advantage of providing clear distinction between wet and dry conditions. They also provide a direct indication of how wet the soil is relative to "field capacity" and "wilting point", whereas this can only be inferred from water content measurements by making an independent characterisation of the water contents at these two critical points.

Disadvantages include their potential lack of longevity in some cases, the impact of changing soil salinity and temperature on their output, and in a few cases their expense (although most are relatively inexpensive devices).

2.4. Detailed Evaluation of Potentially Suitable Sensors

As mentioned above, water content sensors were considered generally unsuitable for this application. Detailed evaluation of sensors was therefore restricted to soil water matric potential sensors. Of those available, five that most closely met the selection criteria were selected for closer scrutiny.

2.4.1. Fibreglass block

Manufacturer/Supplier:
ELE International / Australian Calibration Services Pty Ltd

Description:
This device, sold as the ELE International Soil Moisture Temperature Cell (P/N EL23-7724/xx), consists of a piece fibreglass cloth wedged between two perforated stainless steel plates. The fibreglass absorbs or releases water to equilibrate with the matric potential of the soil in which it is placed. This changes the electrical conductivity (or resistance) of the fibreglass pad which can be read with a resistance bridge. As with all such instruments, an alternating current bridge is required to prevent polarisation of the electrodes during the measurement. It has a nominal range of measurement from saturation (0 kPa) to drier than wilting point (1500 kPa). Further information in Campbell and Gee (1986).

Advantages:
moderate cost; durable; good differentiation between wet and dry conditions

Disadvantages:
affected by salinity and temperature changes; production of a suitable hand-held read-out device was discontinued after selection, and a substitute had to be developed

2.4.2. Gypsum block

Manufacturer/Supplier:
various

Description:
This device, at its simplest, is a cylindrical block of gypsum (calcium sulphate) with two electrodes embedded in it. The block absorbs or releases water to equilibrate with the matric potential of the soil in which it is placed. This changes the electrical conductivity/resistance of the fibreglass pad which can be read with an alternating current bridge. Water in the block is maintained at the saturation concentration of gypsum as the body of the block dissolves slowly. This buffers the electrical conductivity measurement against salinity changes, but also limits the lifetime of the block as it dissolves. Its recommended range is from 25 to 500 kPa. Further information in Campbell and Gee (1986).

Advantages:
low cost; readily available in Australia; somewhat compensated for salinity changes

Disadvantages:
limited lifetime because it eventually dissolves; not as good a response to the range of soil moisture conditions as fibreglass block

2.4.3. Watermark™ Gypsum block

Manufacturer/Supplier:
Irrometer / various

Description:
The Watermark™ sensor is an improved version of the gypsum block, which measures the electrical resistance of solution in a rigid porous material. Salinity buffering is incorporated by including a source gypsum in the sensor. This design extends the life of the sensor while maintaining the salinity buffering. Its
recommended range is from 0 to 200 kPa. Further information in Eldredge et al. (1993).

Advantages:
- low cost; readily available; somewhat compensated for salinity changes; better lifetime than gypsum block

Disadvantages:
- not as good a response to the range of soil moisture conditions as gypsum block or fibreglass block

2.4.4. Campbell 229 soil water potential probe

Manufacturer/Supplier:
- Campbell Scientific

Description:
- Also called a heat dissipation matric potential sensor, this device consists of a cylinder of carefully graded rigid porous material which, like the previous sensors, absorbs or releases water as it comes into equilibrium with the soil. Unlike previous devices, the water content of the sensor, which is determined by the soil water potential, is measured by a heat dissipation method. The advantage of this method is that the temperature and salinity dependence of the output is considerably reduced compared devices using electrical conductivity. The disadvantage is that the measurement is harder to make.

Advantages:
- moderate cost; good measurement range; not affected by salinity; relatively easy to correct for temperature

Disadvantages:
- controlled current source required; no hand-held readout device available; data logging required; more difficult to use

2.4.5. Equitensiometer

Manufacturer/Supplier:
- Delta-T Devices / various

Description:
- Like the Campbell 229 probe, this device consists of a cylinder of carefully graded rigid porous material which absorbs or releases water as it comes into equilibrium with the soil. The water content within the sensor is measured in this case by the manufacturer's "theta probe" technique, a frequency domain water content device subject to temperature and salinity effects. This is an example of a hybrid sensor.

Not recommended by Australian agent, because expensive and not suitable for long deployment.

2.5. Sensors Selected for Field Trials

On the basis of the desk evaluation summarised above, it was clear that the fibreglass block best fulfilled the selection criteria, followed by the gypsum blocks. However, laboratory calibration of the fibreglass blocks was difficult as explained in section 2.6.1. Because of the need to proceed with field installations prior to sowing in autumn 2003 before the calibrations could be finalised, it was decided to install regular gypsum blocks and Watermark gypsum blocks as well as fibreglass blocks in a limited number of paddocks, to assess their performance over a year, and then decide which sensor to deploy more widely in 2004.

After the first year it was clear that the fibreglass blocks were calibrated sufficiently well, and gave the best response to wetting and drying. As will be seen in the results reported later, they covered the full range of soil water conditions from saturation to lower limit, were not difficult to install, and based on its construction was expected to have the longest life when installed.
2.6. Sensor Calibration

2.6.1. Fibreglass Blocks

Fibreglass blocks proved difficult to calibrate in the laboratory, showing an unusually high lack of reproducibility when cycled repeatedly through a range of soil water potentials. This was attributed to the difficulty of establishing and maintaining good contact between the sensors and the porous plates used to apply known soil water potentials under unconfined laboratory conditions. Given that an accurate calibration was not required for the current purpose (where only a relative scale of wetness was needed), time was not spent attempting to resolve the calibration difficulties. The following simple calibration equations adequately described the laboratory measurements and produced field results that were consistent with expectations based on other measurements and a knowledge of the soil water status at defining times; for example it yielded values wetter than 10 kPa when the soil was wet in the wettest winter, and ~ 1500 kPa when soils had been effectively dried by crops or lucerne.

For \( R \leq 3 \text{kOhm} \)
\[
\log P = (R - 1.5)^{0.5} \tag{1}
\]

For \( R > 3 \text{kOhm} \)
\[
P = 2R \tag{2}
\]

where
- \( P \) is soil water potential (kPa)
- \( R \) is measured resistance (kOhm)

2.6.2. Gypsum Blocks

The standard calibration (source unknown) used for gypsum blocks was
\[
P = 39R^{0.64} \tag{3}
\]

2.6.3. Watermark™ Sensors

The recommendations of Allen (2000) were used for the Watermark™ sensors, namely:

for \( R \leq 1 \text{kOhm} \),
\[
P = -20(R_T - 0.55) \tag{4}
\]

for \( 1 \text{kOhm} < R \leq 8 \text{kOhm} \),
\[
P = \frac{-3.213R + 4.093}{(1 - 0.009733R - 0.01205T)} \tag{5}
\]

for \( R > 8 \text{kOhm} \),
\[
P = -2.246 - 5.239R_T - 0.06756R_T^2 \tag{6}
\]

where
- \( R_T = R[1+0.018(T - 24)] \tag{7} \)
- \( T \) is the soil temperature at the sensor (°C)

Equation [7] adjusts for the temperature effect on the measurement if the temperature at the sensor is known. As soil temperature measurements were not made, it was assumed that the temperature was always 24 °C, i.e. no temperature correction was made.

Equation [5], from equation (8) of Shock et al. (1998), compensates for temperature without using equation [7], and a temperature of 24 °C was also used there.
3. Field Deployment of Soil Moisture Sensors

3.1. Deployment Locations

Sensors were deployed in two stages. In autumn 2003, fibreglass blocks, regular gypsum blocks and Watermark™ gypsum blocks were installed side by side (and in triplicate) in five paddocks. In autumn 2004, fibreglass blocks were installed in a further 23 paddocks, 8 with duplicate installations and 15 with single installations.

The locations of farms where sensors were installed are shown in Figure 3, and details of the installations are summarised in Table 1.
Table 1  Locations and details of soil moisture sensor installations

<table>
<thead>
<tr>
<th>Region</th>
<th>Farm</th>
<th>Date</th>
<th>Paddocks</th>
<th>Sensor Type</th>
<th>Reps</th>
<th>Depths (m)</th>
<th>Other soil water measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condobolin</td>
<td>Baleveolan</td>
<td>Mar 04</td>
<td>N, S</td>
<td>F</td>
<td>1</td>
<td>0.9, 1.2, 1.5</td>
<td>Neutron probe</td>
</tr>
<tr>
<td></td>
<td>Derriwong</td>
<td>Mar 04</td>
<td>E, W</td>
<td>F</td>
<td>1</td>
<td>0.9, 1.2, 1.5</td>
<td>Neutron probe</td>
</tr>
<tr>
<td></td>
<td>South Gipps</td>
<td>Mar 04</td>
<td>E, W</td>
<td>F</td>
<td>1</td>
<td>0.9, 1.2, 1.5</td>
<td>Neutron probe</td>
</tr>
<tr>
<td></td>
<td>Vermont Hill</td>
<td>Mar 04</td>
<td>E</td>
<td>F</td>
<td>1</td>
<td>0.9, 1.2, 1.5</td>
<td>Neutron probe</td>
</tr>
<tr>
<td>Harden</td>
<td>Cusacks</td>
<td>May 03</td>
<td>W</td>
<td>F, G, W</td>
<td>3</td>
<td>1.2, 1.6, 2.0</td>
<td>Envirosmart</td>
</tr>
<tr>
<td></td>
<td>Cusacks</td>
<td>Mar 04</td>
<td>E, S</td>
<td>F</td>
<td>1</td>
<td>1.2, 1.6, 2.0</td>
<td>Envirosmart</td>
</tr>
<tr>
<td></td>
<td>Garanguila</td>
<td>Apr 04</td>
<td>E, W</td>
<td>F</td>
<td>1</td>
<td>0.8, 1.2, 1.6</td>
<td>Envirosmart Drainage Meter in paddock W</td>
</tr>
<tr>
<td></td>
<td>Lowlynn</td>
<td>Mar 04</td>
<td>E, W</td>
<td>F</td>
<td>1</td>
<td>0.8, 1.2, 1.6</td>
<td>Envirosmart</td>
</tr>
<tr>
<td></td>
<td>Traralgon</td>
<td>Mar 04</td>
<td>N</td>
<td>F</td>
<td>1</td>
<td>0.8, 1.2, 1.6</td>
<td>Envirosmart</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S</td>
<td>F</td>
<td>1</td>
<td>0.8, 1.2, 1.6, 2.0</td>
<td>Envirosmart</td>
</tr>
<tr>
<td>Temora</td>
<td>Blandfield</td>
<td>Apr 04</td>
<td>B2, B6</td>
<td>F</td>
<td>2</td>
<td>0.7, 1.1, 1.5</td>
<td>Neutron probe</td>
</tr>
<tr>
<td></td>
<td>Carumbi</td>
<td>May 03</td>
<td>A08</td>
<td>F, G, W</td>
<td>3</td>
<td>1.1, 1.5</td>
<td>Neutron probe</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>A10</td>
<td>F, G, W</td>
<td>3</td>
<td>0.7, 1.1, 1.5</td>
<td>Neutron probe</td>
</tr>
<tr>
<td></td>
<td>Derricks</td>
<td>May 04</td>
<td>E1, B13</td>
<td>F</td>
<td>2</td>
<td>0.8, 1.2, 1.6</td>
<td>Neutron probe</td>
</tr>
<tr>
<td></td>
<td>Glenlee</td>
<td>Apr 04</td>
<td>P9, P33</td>
<td>F</td>
<td>2</td>
<td>1.2, 1.6, 2.0</td>
<td>Neutron probe</td>
</tr>
<tr>
<td></td>
<td>Sinclairs</td>
<td>Apr 04</td>
<td>E10, K4</td>
<td>F</td>
<td>2</td>
<td>0.8, 1.2, 1.6</td>
<td>Neutron probe</td>
</tr>
<tr>
<td>Wagga</td>
<td>Charles Sturt University (CSU)</td>
<td>May 03</td>
<td>2</td>
<td>F, G, W</td>
<td>3</td>
<td>1.3, 1.7</td>
<td>Neutron probe</td>
</tr>
</tbody>
</table>

a With Condobolin and District Landcare Management Committee at sites that were part of their project entitled “The impact of land management practices on deep drainage and dryland salinity”
b With Harden-Murrumburrah Landcare Group at sites that were part of their project “The impact of land management practices on deep drainage and dryland salinity”
d Measures soil water content non-destructively; measurements made at ~ monthly intervals
e Measures soil water content non-destructively; measurements made continuously (hourly)

Sensors were installed at at least two depths in each paddock, usually at 3 depths and in one case at 4 depths. The aim was to have at least one sensor above the maximum rooting depth of annual crops (to show behaviour like that identified in Fig. 2a,c) and at least one below the maximum rooting depth of annual crops (to show behaviour like that identified in Fig. 2b,d). At the time of installation there was little information about the rooting depth of annual crops in most paddocks, the exception being those at Wagga Wagga where measurements of the depth of soil water extraction had been made for 5 years previously. An estimate of maximum rooting depth of annual crops was therefore made in each paddock based on soil type and local experience and sensors were installed to bracket that depth.

A range of soil types were included across the regions and farms where sensors were installed. In general, soils were typical of the dominant soil types in each area. The exceptions were at Temora, where paddocks with two distinctly different soils were included. At Blandfield and Carumbi, the soils were heavy clay swelling/cracking soils, with prominent gilgai features at Carumbi. At Glenlee, paddocks were chosen with deep sands, remnants of prior streams in the area.
<table>
<thead>
<tr>
<th>Region</th>
<th>Farm</th>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condobolin</td>
<td>Baleveolan</td>
<td>North</td>
<td>≥ 1 yr lucerne</td>
<td>lucerne</td>
<td>fallowed</td>
<td>barley</td>
</tr>
<tr>
<td></td>
<td></td>
<td>South</td>
<td>unknown</td>
<td>oats</td>
<td>not sown</td>
<td>not sown</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Crops → 1 yr lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
</tr>
<tr>
<td>Derriwong</td>
<td>East</td>
<td>≥ 2 yr fallow</td>
<td>fallow</td>
<td>oats</td>
<td>not sown</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>Crops</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
</tr>
<tr>
<td>South Gipps</td>
<td>East</td>
<td>≥ 3 yr lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>wheat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>≥ 3 yr crops</td>
<td>oats</td>
<td>wheat</td>
<td>barley</td>
<td></td>
</tr>
<tr>
<td>Vermont Hill</td>
<td>East</td>
<td>≥ 3 yr lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>wheat</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harden</td>
<td>Cusacks</td>
<td>East</td>
<td>≥ 5 yr lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
</tr>
<tr>
<td></td>
<td></td>
<td>West</td>
<td>≥ 5 yr crops</td>
<td>wheat</td>
<td>triticale</td>
<td>wheat u/s c</td>
</tr>
<tr>
<td></td>
<td></td>
<td>South</td>
<td>≥ 5 yr phalaris/clover pasture</td>
<td>wheat</td>
<td>oats</td>
<td>wheat</td>
</tr>
<tr>
<td>Garangula</td>
<td>East</td>
<td>≥ 5 yr pasture</td>
<td>pasture</td>
<td>pasture</td>
<td>pasture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>≥ 3 yr pasture</td>
<td>canola</td>
<td>wheat</td>
<td>wheat u/s c</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>→ 2 yr crops</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lowlynn</td>
<td>East</td>
<td>≥ 2 yr crops</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>→ 3 yr lucerne</td>
<td>wheat</td>
<td>canola</td>
<td>wheat</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>→ 2 yr crops</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traralgon</td>
<td>North</td>
<td>≥ 5 yr pasture</td>
<td>pasture</td>
<td>wheat</td>
<td>canola</td>
<td></td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>≥ 2 yr pasture</td>
<td>canola</td>
<td>wheat</td>
<td>canola u/s c</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>→ 3 yr crops</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temora</td>
<td>Blandfield</td>
<td>B2</td>
<td>≥ 4 yr crops</td>
<td>wheat</td>
<td>wheat u/s c</td>
<td>lucerne</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B6</td>
<td>crops → 4 yr lucerne</td>
<td>lucerne</td>
<td>wheat</td>
<td>wheat</td>
</tr>
<tr>
<td>Carumbi</td>
<td>A08</td>
<td>crops → 3 yr lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>wheat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A10</td>
<td>lucerne → 4 yr crops</td>
<td>wheat</td>
<td>barley u/s c</td>
<td>lucerne</td>
<td></td>
</tr>
<tr>
<td>Derricks</td>
<td>B13</td>
<td>≥ 3 yr crops</td>
<td>lucerne b</td>
<td>wheat</td>
<td>wheat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>≥ 5 yr crops</td>
<td>wheat</td>
<td>lucerne</td>
<td>lucerne</td>
<td></td>
</tr>
<tr>
<td>Glenlee</td>
<td>P9</td>
<td>≥ 2 yr lucerne</td>
<td>lucerne b</td>
<td>wheat</td>
<td>wheat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P33</td>
<td>≥ 5 yr crops</td>
<td>wheat</td>
<td>wheat u/s c</td>
<td>lucerne</td>
<td></td>
</tr>
<tr>
<td>Sinclairs</td>
<td>E10</td>
<td>≥ 3 yr lucerne</td>
<td>lucerneb</td>
<td>wheat</td>
<td>wheat</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K4</td>
<td>≥ 4 yr crops</td>
<td>barley u/s c</td>
<td>fallow</td>
<td>wheat u/s c</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wagga</td>
<td>Charles Sturt University</td>
<td>P12</td>
<td>crop → 3 yr lucerne</td>
<td>canola</td>
<td>wheat</td>
<td>triticale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P14</td>
<td>5 yr crops</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
</tr>
</tbody>
</table>

---

* a crops means annual crops
* b sprayed out in winter or spring, fallowed
* c u/s = undersown with lucerne
The four general areas where sensors were installed cover a range of average rainfalls from 451 mm at Condobolin to 609 mm at Harden. The likelihood of deep drainage and the performance of the sensors are obviously dependent on rainfall, so this spread is useful for testing purposes. Unfortunately, rainfall was below average in most cases for the three years of the field deployment, as can be seen in Table 3. In 2004 rainfall was below average at all locations by between 12% (at Condobolin) and 29% (at Temora and Wagga Wagga). While 2005 was a better year, being 5% above average at Harden and 10% above average at Temora, rainfall was still 12% below average at Wagga Wagga and 19% below average at Condobolin.

Deep drainage is unlikely to occur in this rainfall zone in years with below average rainfall, unless much of that rainfall occurs over a relatively short period. It is even less likely to occur when the previous year’s rainfall was also below average. Hence the climatic conditions during the field testing of the sensors were not at all suitable for seeing their response to deep drainage conditions. The exception was at Harden and Temora in 2005, where the rainfall was (a) sufficiently high, (b) >60% of the year’s rain fell between June and October.

Within each region, rainfall was quite variable. For example the on-farm rainfall measured at the four farms instrumented at Harden ranged from 554 to 636 mm in 2005. Where possible, therefore, on-farm rainfall is presented when the soil water sensor results are discussed.

### Table 3 Annual rainfall for the four regions where field deployments were made

<table>
<thead>
<tr>
<th>Location</th>
<th>Condobolin 050052</th>
<th>Temora 073038</th>
<th>Wagga Wagga 073127</th>
<th>Harden 073016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>451</td>
<td>531</td>
<td>552</td>
<td>609</td>
</tr>
<tr>
<td>2003</td>
<td>347</td>
<td>443</td>
<td>439</td>
<td>594</td>
</tr>
<tr>
<td>2004</td>
<td>398</td>
<td>379</td>
<td>391</td>
<td>456</td>
</tr>
<tr>
<td>2005</td>
<td>364</td>
<td>582</td>
<td>486</td>
<td>641</td>
</tr>
</tbody>
</table>

b Mean from 1957 to 2005 for all sites

### 3.2. Installation of Sensors

In each paddock, installation sites were chosen to avoid any anomalous conditions, such as depressions, trees (and old stumps) and tracks. They were also located far enough from fences and paddock corners to avoid headlands. In paddocks where 3 replicates were installed, they were located between 20 and 200 m apart. In paddocks where 2 replicates were installed, they were located 3.5 m apart, a convenient distance so that their cables could be brought back underground to a single, central measurement point, as described below.

The sensors were installed in a 55 mm diameter hole drilled at each site to a depth 10 to 20 mm deeper than the deepest installation depth. The sensors were placed against the side of the borehole and packed firmly in moist diatomaceous earth to ensure good contact with the soil. Diatomaceous earth was packed 10 to 20 mm above the top of each sensor, followed by a layer of bentonite to ensure that the sensors were hydraulically separated from each other.

The shallower sensors were placed in the borehole such that they were not directly above any of the deeper ones, thus avoiding any interference of the measurement cables of the deeper sensors on the contact with the side of the borehole of the shallower ones. Bentonite was packed above the shallowest sensor to within 0.4 m of the soil surface.

2 Diatomaceous earth is a highly porous, highly conductive material used for ensuring good hydraulic contact between the sensor and the soil. It is commonly sold as swimming pool filter powder, eg. Dicalite. It was wet to approximately 1500 kPa (0.15 kg/kg).

3 Granular grouting bentonite (eg. Benseal™) was used.
At sites where the three different types of sensors were installed, the fibreglass blocks were installed in one borehole, and the regular gypsum blocks and Watermark TM gypsum blocks were installed together in another borehole 0.3 m away.

Two different methods were used to enable the sensor cables to be terminated in such a way that they could be avoided during sowing and harvesting. For the sensors installed in 2003, a 0.2 m long piece of 55 mm diameter PVC pipe was pushed into the top of the borehole so that its top finished 0.2 m below the soil surface and its bottom sat on the bentonite (0.4 m below the soil surface). A second piece of 55 mm diameter PVC pipe, 0.4 m long, was then joined to it with a detachable coupling, terminating 0.2 m above the soil surface with a cap. Prior to sowing and harvest the top section of PVC pipe was excavated (with minimal disturbance to the surrounding soil) and removed. The cables were pushed down into the lower section of pipe which was then capped, and the hole refilled. After sowing and harvest, the upper section of pipe was reinstalled, once again bringing the cables to the surface.

The disadvantages of this method are that effort is required to bury and expose the cables twice a year (in a cropped paddock), and that soil disturbance occurs directly above the sensors on a regular basis. A method that avoided both of these was therefore developed.

In 2004, a trench 0.4 m deep was dug from the borehole in which the sensors were installed to a second (larger diameter) borehole 1.5 m away. A casing made from 70 mm diameter PVC pipe was installed in this second borehole and terminated 50 to 100 mm below the soil surface with a cap. The cables from the sensors were run along the trench and into this casing. In paddocks where 2 replicates of sensors were installed, both sets of cables were run back to the same, central PVC casing.

Being entirely below the soil surface, the casing was not a problem during harvest. In addition, being narrow relative to the tine spacing used for sowing and at least 50 mm deep, the chances of the top of the casing being hit during sowing were also small. Only half a dozen instances of this occurred during the project, and in all cases the damage was slight and easily repaired with a new cap, or at worst by sliding the casing out of the ground and replacing it with a new one. Finishing the casings slightly deeper below the soil surface would probably have eliminated these instances. Finally any maintenance to the casing and the measurements themselves occurred 1.5 m away from where the sensors were buried so caused no disturbance whatsoever.

3.3. Measurement of Sensors

3.3.1. Manual measurement

The sensors at Harden, Temora and Wagga Wagga were measured manually with a hand-held alternating current resistance bridge. Although handheld bridges are commercially available to measure resistance in the range suitable for gypsum blocks (0 – 50 kOhm), the wider range of the fibreglass blocks (0 – 1000 kOhm) could not be measured by those. An Australian manufacturer of handheld bridges for use with gypsum blocks (Tain Electronics Pty Ltd) was commissioned to make a version with the extended range so that it could be used to measure all three sensors being used.

Measurements were made at intervals of approximately 1 month from soon after their installation (allowing for time for equilibration with the soil) until May 2006.

3.3.2. Data logging

The sensors at Condobolin were measured with data loggers because of the relative remoteness of the sites. A micrologger custom built by CSIRO Land and Water and designed to slip into the PVC casings described in the second type of installation was used. Their size was such that the top of the logger was 0.25 m below the soil surface, thereby avoiding damage even if the top of the casing was hit during cultivation. The microloggers used little power (battery life of several years) and had storage capacity for more than a year's data from 4 sensors. The loggers were downloaded twice – once in April 2005 and once in March 2006.
3.3.3. Note on presentation and interpretation

In all graphs in this report, the soil water matric potential values are presented on a logarithmic scale. This is done to reflect the fact that soil water content is logarithmically related to soil water potential. Thus, on a logarithmic scale soil water potential changes reflect more closely actual water content changes in the soil. In other words there is approximately as much change in water content when the soil water potential changes from 10 to 100 kPa as when it changes from 100 to 1000 kPa.

Although soil water potential values are strictly negative, the negative signs have been omitted to enable the logarithmic scale to be used.

As a guide to interpretation:

- a value of zero indicates that the soil is saturated - ie. water will ooze from the soil;
- a value of ~10 to 20 kPa indicates that the soil is at field capacity or drained upper limit - this is the practical upper limit of wetness; a well-drained soil, would rarely be wetter than this for more than a day or two;
- a value of 1500 kPa indicates that the soil is at wilting point - ie. so dry that plants cannot extract more water from it.

Apart from in section 4.1 where replication is examined in detail, individual results from replicate sensors are not presented, only the average value for each paddock. Where marked deviation between replicates occurred this is noted in the comments on the data.

Data collected during the initial equilibration period after installation is not presented.

3.4. Complementary Measurements

Neutron moisture meter measurements were made at the sites indicated in Table 1 following standard procedures as outlined by Greacen (1981) using a Campbell Pacific Nuclear model 503DR neutron probe. Calibration curves had been obtained as part of previous studies (unpublished data). Measurements were made to at least 3 m, and the accumulation of water beneath the root zone of annual crops was used to calculate deep drainage.

At the Harden sites water content was measured with Sentek EnviroSmart soil water monitoring probes, details of which may be found at the Sentek website (http://www.sentek.com.au/products/envirosmart.asp). A field-derived calibration adjustment factor of 0.64 was applied to the measurements obtained using the manufacturer-supplied calibration curves. Measurements were made to a depth of 1.6 m.

The drainage meter installed in the West paddock at Garangula (Harden) provides a qualitative indication of when drainage occurs, for how long and its relative magnitude compared with other drainage events. More information can be found in Bond and Hutchinson (2006).
4. Results and Interpretation

Complete data sets and a detailed description and interpretation of the soil water potential data (and complementary measurements where made) for each paddock are presented in the Appendices. In this section, the key results are analysed in the light of the project objectives outlined in section 1.3 and their implications are discussed.

Section 4.1 deals with the comparison of replicate measurements from the same types of sensors to determine the necessity of replication for these measurements. It also presents the evaluation of the different types of sensors and the reasons for selecting the fibreglass blocks for the majority of installations.

The usefulness of soil water potential measurements just below the root zone of annual crops as indicators of deep drainage is discussed section 4.2, while section 4.3 deals with the use of the measurements as indicators for changing phase in lucerne/crop phase farming systems.

4.1. Initial Sensor Testing Results

4.1.1. Spatial variability of measurements

Data from one of the paddocks (14) at Charles Sturt University is presented in Figure 4 to illustrate the variability between replicate installations of sensors. In this case the three replicates were spaced between 60 and 180 m apart. It is evident that while there is some scatter between the replicates they all show the same patterns of behaviour.

![Figure 4: Comparison of replicate sensor measurements (symbols) and the mean (solid lines) for the three types of sensors tested, namely fibreglass blocks (F), Watermark™ sensors (W) and gypsum blocks (G). The results are for the two measurement depths in paddock 14 of the Charles Sturt University site.](image)

Comparison of replicate measurements in four other paddocks are presented in Appendix A. In most cases they are comparable with those in Figure 4, but in a few instances there is more divergence between the replicates. Three fibreglass blocks and five Watermark™
sensors failed by either developing an electrical short circuit or an open circuit somewhere in the cabling or the sensor itself. Given that nearly 200 sensors were installed, this seems an acceptable failure rate (4%).

4.1.2. Comparison of sensor types

Figure 4 also shows the comparison between the three different types of sensors in Charles Sturt University paddock 14. This paddock was sown with lucerne in August 2003 after 5 years of cropping. The expected behaviour is therefore for the soil to start off relatively wet at both depths, then be dried to wilting point (~1500 kPa) at 1.3 m in the first summer, partially dried at 1.7 m in the first summer and dried to wilting point in the second summer (compare with Figure 2c,d).

The expected behaviour was shown clearly by the fibreglass block data, particularly the two stages of drying in summer 2003 and summer 2004 resulting in values of ~1500 kPa. The values in winter 2003 were not as wet as might be expected or as wet as the other types of sensors indicate. Values of soil water potential at 1.5 m depth measured independently (with the filter paper technique; Greacen et al. 1989) in this paddock in April 2001 averaged 100 kPa (range 80 to 140 kPa). Although measured 2 years prior to the start of the measurements in Figure 4, neutron moisture meter measurements showed that the soil at 2.5 m dried only slightly over that period. Thus the gypsum blocks and Watermark™ sensors seem to provide a better description of the wetter conditions in winter 2003 than the fibreglass blocks.

The gypsum block data also showed the expected behaviour clearly. Although not reaching 1500 kPa as soon as the fibreglass blocks, they were wetter initially, more in keeping with expectation. It is interesting that although gypsum blocks are only recommended to 500 kPa, they were able to attain 1500 kPa.

The Watermark™ sensor data showed the same patterns, but did not reach anywhere near 1500 kPa. This is not surprising because the range of Watermark™ sensors is limited to 200 kPa, after which their output changes very little in response to changes in soil water status.

Comparison of results from the different types of sensors in the four other paddocks where all three were installed are presented in Appendix A. The comparisons are similar to those observed in Figure 4. The fibreglass blocks were initially drier than the gypsum blocks soon after installation in all other paddocks as well. This suggests that a longer equilibration time is needed for fibreglass blocks than for other sensors. This is possibly because it is more difficult to get them into direct contact with the soil, and when installed into dry soils (as all of these sensors were) it takes a long time for equilibration to occur through the diatomaceous earth contact material.

It was concluded that despite the initial concerns about calibration under laboratory conditions (see section 2.6.1) the fibreglass blocks performed well under field conditions. They were stable, covered the full soil water range of interest and showed a clearer response to wet conditions following rainfall as can be seen in Figures A.3, A.4 and A.5 in Appendix A. The main drawback of these sensors was that they took longer to equilibrate initially in dry soils. Fibreglass blocks were therefore chosen for the more widespread installations carried out in 2004.

4.2. Evaluation of Soil Water Measurements as Indicators of Deep Drainage

Wetting did not occur at the bottom of the annual crop root zone in any paddock in 2004, and only in one of the five paddocks monitored in 2003. In 2005, however, the fibreglass blocks indicated that 15 of the 28 paddocks monitored were wet to at least the bottom of the root zone, and 12 of those were wet deeper, indicating that deep drainage had occurred. These
paddocks are listed in Table 5. Eight of these 12 paddocks were in the Harden region, which received the most rainfall in 2005. In three of the eight paddocks, independent estimates of deep drainage were available (Table 4) and in each case there was agreement between the methods. Of the nine other paddocks where there were independent estimates, deep drainage was observed in only one, which is also listed in Table 5 (Carumbi paddock A10). In that case, water content measurements showed that the lucerne in that paddock quickly used the water that had drained in the following spring/summer.

It was concluded, therefore, that the fibreglass blocks installed below the rooting depth of the annual crops were a good indicator of whether > 5 mm of deep drainage occurred.

Table 5 Paddocks in which deep drainage was indicated winter 2005 either by the soil water potential below the annual crop root zone became wetter or by independent estimates.

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Deep drainage indicated by sensor after winter 2005</th>
<th>Independent estimate of 2005 deep drainage (mm)</th>
<th>Cropping history</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blandfield B6</td>
<td>Yes</td>
<td>na</td>
<td>2 years cropping preceded by 5 years lucerne</td>
</tr>
<tr>
<td>Carumbi A08</td>
<td>Yes</td>
<td>34</td>
<td>1 year cropping preceded by 5 years lucerne</td>
</tr>
<tr>
<td>Carumbi A10</td>
<td>No</td>
<td>8</td>
<td>1 year lucerne preceded by 6 years cropping</td>
</tr>
<tr>
<td>Cusacks East</td>
<td>Yes</td>
<td>na</td>
<td>≥ 8 years lucerne</td>
</tr>
<tr>
<td>Cusacks South</td>
<td>Yes</td>
<td>na</td>
<td>3 years cropping preceded by 5 years phalaris/clover pasture</td>
</tr>
<tr>
<td>Cusacks West</td>
<td>Yes</td>
<td>na</td>
<td>undersown lucerne preceded by ≥ 8 years cropping</td>
</tr>
<tr>
<td>Garangula East</td>
<td>Yes</td>
<td>na</td>
<td>≥ 8 years annual pasture</td>
</tr>
<tr>
<td>Garangula West</td>
<td>Yes</td>
<td>Yes(^a)</td>
<td>undersown lucerne preceded by 4 years cropping</td>
</tr>
<tr>
<td>Lowlynn East</td>
<td>Yes</td>
<td>na</td>
<td>6 years lucerne preceded by ≥ 2 years cropping</td>
</tr>
<tr>
<td>Lowlynn West</td>
<td>Yes</td>
<td>na</td>
<td>5 years cropping preceded by 3 years pasture</td>
</tr>
<tr>
<td>Sinclairs K4</td>
<td>Yes</td>
<td>na</td>
<td>undersown lucerne preceded by fallow and ≥ 5 years cropping</td>
</tr>
<tr>
<td>South Gipps East</td>
<td>Yes</td>
<td>18</td>
<td>1 year cropping preceded by ≥ 5 years lucerne</td>
</tr>
<tr>
<td>Traralgon South</td>
<td>Yes</td>
<td>na</td>
<td>undersown lucerne preceded by 5 years cropping</td>
</tr>
</tbody>
</table>

\(^a\) Independent estimates of drainage (where available) obtained from neutron moisture meter measurements except at Garangula West where a drainage meter was installed. (na indicates not available)

\(^b\) The drainage meter does not permit a quantitative estimate at this stage

Of the 13 paddocks where water movement past the annual crop root zone was indicated (either by the fibreglass block measurements or independently), nine were under crop (or crop undersown with lucerne) in 2005, three under lucerne and one under annual pasture, as shown in Table 5. It would not be expected that the water that moved to depth in the lucerne paddocks would actually become deep drainage as the vigorous growth of lucerne over summer should have removed that water. This was observed in Carumbi A10 and Cusacks...
East, but not in Lowlynn East. In the latter the lucerne was in poor condition and had a very low plant density in the vicinity of the sensors, and was obviously not growing well enough to reverse the deep wetting over winter.

Four of the paddocks in Table 5 had crops undersown with lucerne. It would normally be expected that the growth of lucerne following the harvest of the annual crop would quickly extract that water and prevent it from becoming deep drainage. This was not the case, however. Only in one of the four paddocks did drying occur deeper than the annual crop rooting depth (Garangula West, see Appendix B.2.2, page 41); in the others only partial drying of the annual crop root zone occurred. This is attributed to the very poor establishment of undersown lucerne observed in all paddocks in 2005/06, which in turn is attributed to the very dry conditions that have been experienced since harvest in 2005. It suggests that in years with low summer rainfall, establishment of lucerne is difficult and cannot be relied on to immediately reverse any deep drainage. In the event of another wet winter in the year after undersowing, it is very likely that irreversible deep drainage could occur, although because of the dry year in 2006 we were unable to test this hypothesis.

Finally, of the 13 paddocks where deep drainage was indicated, seven had been under annual crops or pasture for at least 5 years, one for 2 years and two for only 1 year (the other three were under lucerne as discussed previously). This shows that there is a greater likelihood of deep drainage occurring when paddocks have been under crop for extended periods of time, but that under certain conditions deep drainage may occur after shorter periods of cropping. It should also be noted that there were four paddocks that had been under annual pasture or crops for 5 years or more in which deep drainage was not indicated in 2005. Three of these paddocks were at Condobolin where rainfall has been considerably below average in the last 3 years, and the other at Harden in a paddock that had a particularly vigorous canola crop in 2005.

Of the three cases that had had only one or two years of cropping two were quite wet going into winter 2005 despite having had several years of lucerne. In April 2005 the soil water potential just below the root zone of annual crops in the South Gipps East paddock, despite having been under lucerne for at least five years before the switch to cropping, and 165 kPa in paddock B6 at Blandfield which had had only one previous crop in the dry year 2004 following 4 years of lucerne. As will be seen in section 4.3, these are values of soil water potential within the range where deep drainage is predicted to occur in the following winter. Clearly in these cases the lucerne did not succeed in adequately drying the subsoil, possibly because of poor performance during the preceding dry years. In the third case where there was drainage in the first year of cropping (paddock A08 at Carumbi) it is suspected that water was conveyed to depth by deep cracks. In addition, it had a rather poor stand of lucerne in the year or two prior to 2005.

4.3. Evaluation of Soil Water Measurements as Indicators for Lucerne Phase Changes

4.3.1. Changing phase from cropping to lucerne

As reported in the preceding section, either fibreglass blocks or independent measurements suggested that deep drainage past the bottom of the annual cropping root zone had occurred in 13 of the 28 paddocks monitored in winter 2005. However, did the measurements from the fibreglass blocks just below the root zone of annual crops before sowing predict that this was likely to happen?

The soil water potential just below the root zone of annual crops in April 2005 is summarised for all monitored paddocks in Figure 5. There is a clear cut-off around 200 to 300 kPa. Of the 13 paddocks in which deep drainage occurred, nine had soil water potentials of < 200 kPa below the root zone in April 2005. From another perspective, there were 12 paddocks that had soil water potentials below the root zone of < 200 kPa in April 2005, and of these deep drainage occurred in nine and the whole root zone was wet in another. Of the 16 paddocks in
which soil water potential below the root zone was > 200 kPa in April 2005, deep drainage occurred in only 4 (25%) of them. It can be concluded that if the soil water potential below the root zone was < 200 kPa in April, there was a high likelihood of deep drainage occurring in the following winter. This agrees with the findings of the modelling study (Verburg et al 2006b) run in parallel to this field evaluation, for which the comparable figures to those above were 55% and 10%, respectively.

This rule is not perfect, however, with four paddocks that had deep drainage not being predicted. Of these, three were almost as wet (at between 340 and 415 kPa). The other, which was very dry (1260 kPa), was paddock A08 at Carumbi, which was wet to depth quicker than would be expected through the deep cracks created during the lucerne phase in that soil. This suggests that the soil water potential measurement is not likely to be a good guide in swelling/shrinking soils. There could also be a difficulty in maintaining good contact between the sensor and the soil in those soils.

Figure 5: Soil water potential in April 2005 just below the root zone of annual crops in all monitored paddocks, classified according to their wetting behaviour in winter 2005.

If the soil water potential below the root zone was analysed in November 2005 the predictive cut-off was 300 kPa. Nine of the 13 paddocks with deep drainage in 2005 had values less than 300 kPa, while of the 14 paddocks with values less than 300 kPa deep drainage occurred in nine and wetting occurred to the bottom of the annual crop root zone in another one. Clearly, however, the predictive power of the November 2004 measurements was not quite as good as for those in April 2005.

4.3.2. Changing phase from lucerne to cropping

The expected behaviour for a sensor installed just below the root zone of annual crops after lucerne is sown is for an initial drying in the first summer (as shown in Figure 2d), followed by complete drying to wilting point (~1500 kPa) either late in the first summer or in the second summer. This behaviour was observed in only two (Charles Sturt University paddock 14 and Glenlee paddock 33) of the 20 paddocks in which lucerne was present immediately before or during the monitoring period (Figure 6). Another paddock (Garangula West) was heading in the right direction but had not achieved wilting point by the end of the second summer. A further three paddocks (Carumbi A08, Cusacks East and Sinclairs E10) were close to or below wilting point after four to six summers under lucerne. Although Cusacks East paddock became wet at that depth in 2004, despite that being a relatively dry year, it was dried again in 2005. This is attributed to the observation that the lucerne had become rather sparse in that paddock as a result of its age and the dry conditions in 2004 and was unable to respond to the rain that did fall in 2004. It recovered in 2005 when conditions were more suitable. Two paddocks were drier than 600 kPa after lucerne was removed after three summers (Derricks B13 and Glenlee P9).

Two paddocks showed a steady wetting trend and became quite wet after two to four summers of lucerne (Derriwong West) and three to five summers of lucerne (Lowlynn East). In both cases the lucerne had become sparse and was not performing well under low rainfall
conditions. At Lowlynn, the monitoring location was on a ridge with a shallow soil, and this may also have contributed to the findings.

A number of paddocks in which lucerne had been established since 2004 either remained wet or became wetter during their first one or two summers (Carumbi A10, Cusacks West, Blandfield B2, Traralgon South, Sinclairs K4). In each case the lucerne was sown under an annual crop (usually wheat) and in most cases the lucerne did not establish well because of the dry conditions in 2004/05 and (after harvest) in 2005/06. Although the lucerne in Carumbi paddock A10 did establish well, it has a heavy clay, sodic soil that is difficult to dry out, similar to Blandfield.

![Figure 6: Soil water potential at the end of summer just below the root zone of annual crops in all monitored paddocks that had lucerne at some time just prior to or during the monitoring period. Paddocks in which lucerne was established in or after 2003 are shown in orange symbols and lines, while those in which lucerne was established earlier are shown in green. The dashed lines represent 600 and 1500 kPa, respectively.](image)

Lucerne was removed from eight paddocks in either 2004 or 2005. Deep drainage occurred in three of these in 2005. Of these, one (South Gipps East) had a soil water potential below the crop root zone in April 2005 (200 kPa) within the range that suggested deep drainage would occur (see section 4.3.1). Therefore, although it had been under lucerne for 5 years, it had not been dried sufficiently as indicated by the soil water potential measurement, was at risk of deep drainage occurring and this did indeed happen, despite it not being a particularly wet year. Another (Blandfield B6) had a soil water potential in April 2005 (500 kPa) that was borderline, ie it had not been dried suggesting that it should remain under lucerne until further drying had occurred in order to avoid deep drainage. The third (Carumbi A08) had a soil water potential in April 2005 (1260 kPa) that showed that lucerne had effectively dried the paddock, yet deep drainage still occurred. This is because of the deep cracks developed in the soil in that paddock, transmitting water to depth very quickly, as discussed elsewhere in this report (eg. Section 4.3.1 and Appendix B.3.2).

Of the five paddocks in which there was not deep drainage after lucerne was removed in 2004 or 2005, only one (Sinclairs E10) had soil water potential below the crop root zone in April 2005 that indicated that lucerne had dried the soil effectively and that a return to cropping was without risk of deep drainage. Another (Derricks E10) was almost dried completely (900 kPa below the crop root zone). The other three paddocks were between 340 and 600 kPa. One of these (Glenlee P9) showed some wetting to depth, while the other two were in the Condobolin district where rainfall was comparatively low in 2005.
These results are difficult to interpret conclusively because paddock conditions have been affected by the series of years with below average rainfall. It is clear, however, that the length of time that lucerne has been established is not necessarily a good guide to how effectively it has dried the subsoil. This is attributed to factors such as poor initial establishment of lucerne and reduced plant density of lucerne after a few years, both of which are made worse by dry years. Having a measurement of soil water status is therefore likely to be a useful guide to how effective lucerne has been and when it can be removed with minimal risk of deep drainage occurring.
5. Guidelines for using and interpreting simple soil water monitoring devices

On the basis of the findings presented in this report, which are consistent with those in the parallel modelling study by Verburg et al. (2006b), the following guidelines have been developed.

Soil water sensor

The guidelines assume the deployment of a soil water matric potential sensor, such as the gypsum block or fibreglass block, with a commercially available measurement device.

Installation depth

Sensors need to be installed 0.3 to 0.5 m below the maximum rooting depth of annual crops. This is somewhat soil specific, but in most soils is 1.1 to 1.5 m. If the rooting depth is unknown, it is recommended that two sensors be installed – one at ~1.5 m and one at ~1.9 m. The shallowest sensor that behaves as if it is below the root zone (see Figure 2b) should then be used for interpreting the soil wetting behaviour.

Installation procedure

After selection of a typical location in the paddock, a hole should be drilled to a depth a few mm deeper than the installation depth. The sensor should then be packed in moist swimming pool filter material, as described in section 3.2, and the cables brought to the surface and terminated in a way that allows cultivation over the top of the sensor location.

Measurement

Measurements should be made at approximately monthly intervals, recorded and graphed against time.

Interpretation

1. Deep drainage has occurred when measurement below the rootzone gets sharply wetter after winter or other periods of greater than average rainfall.

2. If the subsoil is wetter than 200 kPa, it is recommended that the paddock be sown to lucerne to minimise the risk of deep drainage occurring in the following or subsequent years.

3. Under lucerne, the subsoil needs to dry to around 1500 kPa before there can be a return to cropping with minimal risk of deep drainage occurring.
6. Summary and Conclusions

The fibreglass block was found to be a suitable device for monitoring soil water status below the root zone of annual crops. It met the criteria of being low cost and easy to install (at depths of 1.5 to 2 m), covered the whole range of soil water status of interest, and could be interpreted directly in terms of the soil water limits “field capacity” and “wilting point”. One initial drawback was the limited availability of suitable measurement devices for it, but this was relatively easily overcome.

The dry conditions experienced during the three years of field testing of the use of these sensors for determining deep drainage and phase changes limited the number of instances in which deep drainage might have occurred. Rainfall conditions were really only suitable for deep drainage to occur in one year (2005), and this was not universally the case across all the regions where sensors were installed; Condobolin and Wagga Wagga remained below average rainfall in 2005.

Despite the uncertainty introduced by the below average rainfall, there was good evidence that a single measurement of soil water status below the annual crop root zone could be used to indicate when deep drainage occurred. In 11 of the 12 paddocks where independent estimates of deep drainage were available, the single sensor measurement agreed. This included four cases where deep drainage occurred and eight where it did not.

A single measurement of soil water status below the annual crop root zone was also a good predictor of whether deep drainage would occur. If a measurement made in April was wetter than 200 kPa, there was a strong likelihood of deep drainage occurring in the following winter. On this basis, the measurement correctly predicted deep drainage in nine out of the 13 paddocks in which it occurred; in four paddocks deep drainage occurred but was not predicted by the measurement. Measurable deep drainage (> 5 mm/year) occurred in nine (75%) of the 12 paddocks where the soil water potential below the root zone in April was wetter than 200 kPa, and in only four (25%) of the remaining 16 paddocks.

As expected, there was a strong correlation between the occurrence of deep drainage and the number of years under cropping or annual pasture, although this was also affected by the record dry conditions.

Few paddocks under lucerne exhibited the expected behaviour of soil water potential below the annual crop root zone. It was clear, however, that the length of time that lucerne had been established was not necessarily a good guide to how effectively it had dried the subsoil. This is attributed to factors such as poor initial establishment of lucerne and reduced plant density of lucerne after a few years, both of which are made worse by dry years. Having a measurement of soil water status is therefore likely to be a useful guide to how effective lucerne has been and when it can be removed with minimal risk of deep drainage occurring.

Simple guidelines for using and interpreting soil water monitoring devices have been prepared.
Appendix A. Comparison of Replicates and Sensors

Figure A.1 Comparison of replicates and sensors in Charles Sturt University paddock 12 (replicates between 60 and 120 m apart).

Figure A.2 Comparison of replicates and sensors in Charles Sturt University paddock 14 (replicates between 100 and 220 m apart).
Figure A.3 Comparison of replicates and sensors in Carumbi paddock A08 (replicates between 20 and 40 m apart).
Figure A.4 Comparison of replicates and sensors in Carumbi paddock A10 (replicates between 20 and 40 m apart).
Figure A.5 Comparison of replicates and sensors in Cusacks West paddock (replicates between 15 and 20 m apart).
Appendix B. Data Summary for All Sites

B.1 Condobolin

B.1.1 Baleveolan

Cropping history

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>≥ 1 yr lucerne</td>
<td>lucerne</td>
<td>fallowed</td>
<td>barley</td>
</tr>
<tr>
<td>South</td>
<td>unknown</td>
<td>oats</td>
<td>not sown</td>
<td>not sown</td>
</tr>
</tbody>
</table>

Rainfall (Condobolin ARS)

![Rainfall Graph]

Data from the SILO Patched Point Dataset (http://www.bom.gov.au/silo/)

Comments

The neutron probe measurements showed an increase in water content at all depths in the North paddock in response to the winter rainfall in 2005, and a subsequent drawdown by the barley crop. This was not reflected in the soil water potential data, however, which were measured 200 m away. The soil water potential data were effectively flat, with a slight oscillation reflecting temperature effects (rising in summer, falling in winter).

There was a smaller increase in water content at 0.9 and 1.1 m in the South paddock. The soil water potential showed more change than in the North paddock, but the timing of the changes were more in keeping with temperature effects than soil wetting (appearing wetter in summer rather than winter). The smaller effect of the winter rainfall on water content in this paddock could be related to the uncropped surface of the South paddock shedding more of the rainfall as runoff.

The South paddock was slightly wetter (soil water potential closer to zero) than the North, which is consistent with the cropping history and rainfall. The North paddock had been under lucerne until 2003, which should have dried the soil to a depth of > 1.5 m, and there has not been sufficient rainfall since then to rewet the soil. With only one crop in the last 3 years, the South paddock would be expected to be drier; if not for the low rainfall in this period it would likely have been wetter.

Indicators for changing phase

The limited duration of the data in this very dry period makes it difficult to interpret in terms of guidance for phase changes. However it suggests that the soil is not wet enough in either paddock to warrant a lucerne phase.
Soil water potential

Soil water content

North

South
B.1.2 Derriwong

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>≥ 2 yr fallow</td>
<td>fallow</td>
<td>oats</td>
<td>not sown</td>
</tr>
<tr>
<td>West</td>
<td>Crops → 1 yr lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
</tr>
</tbody>
</table>

**Rainfall** *Condobolin ARS*

![Rainfall Graph](http://www.bom.gov.au/silo/)


**Comments**

There was a steady decline in water content measured by the neutron probe in the East paddock, mostly occurring in the first half of 2005. The winter rains in 2005 rewet the soil at 0.9 m, which was subsequently dried again, and possibly reached 1.1 m as well. The drying in early 2005 was also reflected by the soil water potential measurements at 0.9 m, but they did not show any rewetting in winter. At the deeper depths soil water potential was effectively constant.

There was also a decline in water content measured by the neutron probe in the West paddock but it was smaller and continuous. The winter rain in 2005 caused an increase in water content at 0.9 m but not at the deeper depths. In contrast, the soil water potential measurements showed a steady wetting trend throughout the 2 year period. This cannot be reconciled with the water content data.

Both paddocks were reasonably dry when measurements commenced. Given their cropping history the West paddock (under lucerne) would be expected to have been drier and not to get wetter. However, by 2005 it was quite a poor stand of lucerne with low plant density, which may explain the behaviour.

**Indicators for changing phase**

The limited duration of the data in this very dry period makes it difficult to interpret in terms of guidance for phase changes. However it suggests that the soil is not yet wet enough in the East paddock to warrant a lucerne phase, and that the lucerne in the West paddock has not dried the soil sufficiently to permit a return to cropping without the risk of deep drainage.
Soil water potential

Soil water content
**B.1.3 South Gipps**

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>≥ 3 yr lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>wheat</td>
</tr>
<tr>
<td>West</td>
<td>≥ 3 yr crop</td>
<td>oats</td>
<td>wheat</td>
<td>barley</td>
</tr>
</tbody>
</table>

**Rainfall (on-farm)**

![Rainfall Graph]

Data from Ben West

**Comments**

After a steady, small decline through 2004 and early 2005, the water content in the East paddock increased at all depths (but by the greatest amount at 0.9 m) in response to the winter rain in 2005. Although there was some drawdown in summer the water content at all depths remained above the early 2005 levels. The soil water potential measurements reflect these changes as well, with strong wetting (to near saturation) in winter 2005, and only partial drying. All depths were still around field capacity in March 2006, suggesting that the roots of the wheat crop did not reach 0.9 m. Data from the 3 individual neutron tubes showed considerable variability, with the depth of crop water extraction varying between 0.9 and 1.3 m. From the water content data it was calculated that there was 18 mm deep drainage past 1.2 m in 2005.

Water content in the West paddock showed a similar pattern except that wetting in winter 2005 was only observed down to 1.3 m and the increases were smaller than in the East paddock. Deep drainage was negligible. The soil water potential measurements reflected this; only the 0.9 and 1.2 m sensors wet in 2005, and not as much as those in the East paddock.

Both the water content and soil water potential measurements showed that the soil was drier in 2004 in the East paddock than in the west paddock, which is consistent with the former being under lucerne for 5 years while the latter was under crop for that time. In May 2006 both paddocks were equally wet.

The greater rewetting at depth of the East paddock (after only 1 year of crop) compared to the West paddock is somewhat unexpected. It may reflect the different surface preparation of the two paddocks in 2005, with the East paddock being cultivated more than the West to overcome the compaction after 5 years of grazing. This may have allowed more water to enter. The old lucerne root channels may also have assisted water to move to depth in this soil. The two paddocks are also further apart than at other farms (2 km), and it is possible that the East paddock received rainfall that the West did not during isolated storm activity. It is also noted that this farm received quite high rainfall in the months from June to November (398 mm) which would have maximised any potential for wetting.
Indicators of deep drainage

There was a good correlation between deep drainage estimated from the water content measurements and whether or not the soil water potential sensor at 1.5 m wet in winter 2005. It did wet in the East paddock where there was 18 mm drainage, and it did not wet in the West paddock where there was negligible drainage.

Indicators for changing phase

The measurements do not allow a good estimation of the annual crop rooting depth to be made, but it appears that the fibreglass block at 1.5 m is suitable to be used as an indicator for phase changes. In the paddock that has been cropped for at least 6 years (West) the soil at 1.5 m is at field capacity suggesting that a change of phase back to lucerne is warranted to avoid the risk of deep drainage. Indeed this was already indicated in 2004, but deep drainage did not occur because of the low rainfall.

In the paddock moved to cropping last year (East), there was considerable rewetting at 1.5 m in the first year, and a change of phase back to lucerne is indicated. This is an extremely short time under cropping especially given the low rainfall. In fact the soil was already quite wet (200 kPa) in April 2005, suggesting that lucerne should not have been removed. Despite it having been in place for at least 5 years, the lucerne had not dried the subsoil effectively. The lucerne was in very poor condition in March 2004, with a very low plant density, and would certainly not have been effective at that stage. It was not much better in September 2003.
Soil water potential

Soil water content

Soil Water Sensors for Managing Deep Drainage
B.1.4 Vermont Hill

Cropping history

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>≥ 3 yr lucerne</td>
<td>lucerne</td>
<td>Lucerne (sprayed out in spring)</td>
<td>wheat</td>
</tr>
</tbody>
</table>

Rainfall (on-farm)

![Rainfall Graph]

Data from Roger Todd

Comments

Water contents showed little change below 1 m during the whole measurement period, but did increase temporarily at 0.9 m in winter 2005 and again before May 2006. The soil water potential measurements similarly showed no change below 1 m (apart from temperature-induced oscillations). At 0.9 m, however, there was a steady rise between June 2004 and March 2005 and another rise between December 2005 and March 2006. The latter is attributed to a combination of the temperature effect and a slow response to the high rainfall in November (which is also reflected in the water contents). The earlier behaviour is difficult to explain, although it is possible that the initial rise is a temperature effect, and the failure to see the winter rainfall is because it was counterbalanced by the winter temperature-induced decline.

Indicators for changing phase

The limited duration of the data in this very dry period makes it difficult to interpret in terms of guidance for phase changes. However it suggests that the soil is not wet enough to warrant a change back to a lucerne phase at this stage. Like the East paddock at South Gipps, however, this paddock was still relatively wet when the lucerne was removed (300 kPa at 1.5 m in August 2003), and like South Gipps the lucerne was performing very poorly in March 2004. This paddock would therefore be expected to have a limited time under cropping before there is deep drainage once average rainfalls return.
B.2 Harden

B.2.1 Cusacks

Cropping history

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>≥ 5 yr lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
</tr>
<tr>
<td>West</td>
<td>≥ 5 yr crop</td>
<td>wheat</td>
<td>triticale</td>
<td>wheat undersown with lucerne</td>
</tr>
<tr>
<td>South</td>
<td>≥ 5 yr phalaris/clover pasture</td>
<td>wheat</td>
<td>oats</td>
<td>wheat</td>
</tr>
</tbody>
</table>

Rainfall (on-farm)

Comments

Rainfall was sufficient in winter 2003 to cause wetting to at least 1.2 m in all paddocks, and to 1.6 m in the West and South paddocks as indicated by the water content measurements. Only the West paddock had soil water potential sensors installed in 2003, but these responded in the same way as the water content measurements. Drying followed, but in all cases where wetting occurred the soil was wetter at the end of 2003 than at the beginning.

In the dry year of 2004, water content was not observed to increase below 1 m in any paddock, nor did it show any water use during spring or summer. The gentle oscillation in water content at these depths is caused by the soil water sensors’ response to soil temperature, causing an apparent rise in water content in summer (peaking in February/March) and a decline in winter (reaching a low in July/August). Soil water potential did indicate wetting at 1.2 m in the West paddock, and subsequent drying to below pre-wetting levels.

The very wet month of June in 2005 (133 mm) caused wetting at all depths in all paddocks as indicated by both the water content and soil water potential measurements (to field capacity). In the West paddock, soil water potential at 1.2 m rapidly dried to its pre-June condition and when measurements finished was nearly down to wilting point. The water content also showed drying at 1.2 m, but had not dried as much as suggested by the soil water potential before the water content sensors failed in January 2006. The soil water potential sensor at 1.6 m also dried steadily from December 2005 until measurements ceased in May 2006, while that at 2 m was still at field capacity (although starting to dry) when measurements ceased. This is consistent with the paddock being sown with lucerne under wheat in 2005, the lucerne slowly getting established after the wheat harvest and continuing to dry the soil to depth in summer and autumn. It did not dry the soil as quickly as the established lucerne in the East paddock, which by May 2006 had dried the soil to wilting...
point at all measurement depths. In contrast to the East and West paddocks, the wheat in the South paddock showed strong drying only at 1.2 m, with some drying at 1.6 m, and the soil at 2 m remaining above field capacity in May 2006.

It is concluded that the rooting depth of annual crops at this site is between 1.2 and 1.6 m, and that the heavy rains in winter 2006 caused water to move past this depth potentially resulting in deep drainage. In the East paddock, this potential deep drainage was prevented by the established lucerne crop. In the West paddock it is expected that the developing lucerne crop, struggling to establish in the dry conditions since December 2005, will eventually remove that water and prevent any further deep drainage. In the South paddock, lucerne will need to be re-established at some time in the next few years to capture this water and prevent deep drainage.

**Indicators for changing phase**

The measurements suggest that the fibreglass block to be used as an indicator of phase changes is at 2 m in this soil, which seems to encourage deep rooting by annual crops. In the paddock planted to lucerne in 2005 (West), the soil at 2 m had hardly started drying by May 2006 after the wetting in 2005, so obviously more years of lucerne are required before this paddock can be returned to crops. In the paddock that has been under lucerne for > 8 years (East), the soil water potential at all depths, including 2 m, was approaching wilting point in May 2006, so that continued cropping is possible without a greatly increased risk of deep drainage. The paddock moved to cropping 3 years ago (South) wet to field capacity at 2 m in 2005 and stayed there, suggesting that it should planted to lucerne to minimise the risk of deep drainage.

It is noted, however, that in this highly permeable soil, with a relatively high average annual rainfall, there is a high risk of deep drainage no matter what crop is planted when above average rainfall is received in the winter months.
Soil water content

Cusacks West

Cusacks East

Cusacks South
B.2.2 Garangula

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>≥ 5 yr pasture</td>
<td>pasture</td>
<td>pasture</td>
<td>pasture</td>
</tr>
<tr>
<td>West</td>
<td>≥ 3 yr pasture</td>
<td>canola</td>
<td>wheat</td>
<td>wheat undersown with lucerne</td>
</tr>
</tbody>
</table>

**Rainfall (on-farm)**

Water content in the East paddock increased in response to winter rainfall in all three years at 0.8 m, in 2004 and 2005 at 1.2 m, but only in 2005 at 1.6 m. The soil water potential measurements showed a similar pattern except that the wetting at 1.2 m in 2004 was not detected. By May 2006 the soil water potential values were below the pre-winter 2004 values, as were the water contents at 0.8 and 1.2 m, and the water content at 1.6 m was approaching it. Although the pasture in the East paddock was largely an annual pasture, it seems to have been effective at drying the soil to 1.6 m.

Similar patterns were observed in the West paddock, except that in this case the soil water potential sensor at 1.2 m also showed wetting in 2004. Drying was continuing at all depths in May 2006 as the lucerne sown under wheat in 2005 established itself.

A drainage meter installed in the West paddock in March 2004 also confirmed the above results. It showed no drainage at 1.6 m in 2004, but a significant amount in 2005, starting in August and continuing until November (see [http://www.clw.csiro.au/fenceline/projects/garangula/Paddock1-Drainage.html](http://www.clw.csiro.au/fenceline/projects/garangula/Paddock1-Drainage.html))

**Indicators for changing phase**

The measurements suggest that the fibreglass block at 1.6 m is probably sufficiently below the annual crop rooting depth to be used as an indicator of phase changes. In the paddock recently planted to lucerne in 2005 (West), the soil has not yet dried sufficiently at 1.6 m to return to cropping. In the paddock that has been under annual pasture for 8 years (East) the response of the 1.6 m sensor is ambiguous. However, the paddock could probably benefit from a change of phase to lucerne to dry the profile out.
Soil water potential

-soil water potential (kPa)


Garangula East

-soil water potential (kPa)


Garangula West

-soil water content (vol/vol)


Garangula East

-soil water content (vol/vol)


Garangula West

Soil Water Sensors for Managing Deep Drainage Page 41
B.2.3 Lowlynn

Cropping history

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>≥ 2 yr crop</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
</tr>
<tr>
<td></td>
<td>→ 3 yr lucerne</td>
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<td></td>
</tr>
<tr>
<td>West</td>
<td>≥ 3 yr pasture</td>
<td>wheat</td>
<td>canola</td>
<td>wheat</td>
</tr>
<tr>
<td></td>
<td>→ 2 yr crop</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rainfall (on-farm)

Comments

In 2004, wetting occurred only at 0.8 m but was indicated by both the soil water potential and water content measurements in both paddocks. The soil was re-dried more effectively in the West (cropped) paddock than in the East (lucerne) paddock.

In 2005, wetting to field capacity occurred at all depths. Again, drying was more effective at all depths in the West paddock than in the East. At 1.6 m both paddocks remained close to field capacity ( < 30 kPa) in May 2006.

Although it is expected that lucerne would be more effective at drying the soil than the crops in the West paddock, and indeed would have dried the soil at all depths to close to wilting point each summer, the lucerne in the vicinity of the sensors (on a rocky ridge) was sparse and not performing well.

Indicators for changing phase

The measurements suggest that the fibreglass block at 1.6 m is sufficiently below the annual crop rooting depth to be used as an indicator of phase changes. In the paddock that has been in lucerne for 6 years (East), the soil has not been dried sufficiently at 1.5 m to return to cropping. As mentioned above, however, this could be because the lucerne is not performing well where the sensors are placed. In the paddock under cropping for the past 5 years (West), the soil remained wetter than 100 kPa after the 2005 season, suggesting that it is time to change phase to lucerne to minimise the risk of deep drainage in subsequent years.
Soil water potential

Soil water content
B.2.4 Traralgon

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
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</thead>
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<tr>
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</tr>
<tr>
<td>South</td>
<td>≥ 2 yr pasture</td>
<td>→ 3 yr crop</td>
<td>canola</td>
<td>wheat</td>
</tr>
</tbody>
</table>

**Rainfall (on-farm)**

![Rainfall Graph]

**Comments**

In 2004, only the 0.8 m depth in the South paddock showed any signs of wetting in winter and subsequent drying, and that was indicated by both the soil water potential and water content sensors. There was some indication of wetting at 0.8 and 1.2 m by the soil water potential sensors in the North paddock, but these seemed to be associated with an equilibration trend (and temperature) rather than wetting.

In 2005 all sensors at all depths indicated wetting to field capacity and subsequent drying. Drying was faster in the North paddock than in the South, but it continued for longer and was eventually more effective in the South. This is consistent with the South paddock being undersown with lucerne in 2005, possibly reducing the water use effectiveness of canola in 2005 and taking some time to establish after the canola harvest. By winter 2006 a visual assessment showed that the lucerne was still performing poorly, as reflected by it not having dried down the soil more effectively.

**Indicators for changing phase**

The measurements suggest that the fibreglass block at 2 m is probably necessary in this paddock to be sufficiently below the annual crop rooting depth to be used as an indicator of phase changes. This only existed in the South paddock, and suggests that the soil at the beginning of winter 2006 was sufficiently wet to require a lucerne phase, which it is currently in. Without a 2 m sensor in the North paddock, no recommendation can be made.
Soil water potential

Soil water content
B.3 Temora
B.3.1 Blandfield

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
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</thead>
<tbody>
<tr>
<td>B2</td>
<td>≥ 4 yr crop</td>
<td>wheat</td>
<td>wheat undersown with lucerne</td>
<td>lucerne</td>
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<tr>
<td>B6</td>
<td>crop → 4 yr lucerne</td>
<td>lucerne</td>
<td>wheat</td>
<td>wheat</td>
</tr>
</tbody>
</table>

**Rainfall (Quandialla)**

![Rainfall Graph]

**Comments**

Paddock B6 (almost at wilting point) was drier than B2 at the beginning of the measurements, which is expected because it had been under lucerne for 5 years whereas paddock B2 had been continuously cropped for at least 5 years.

There was insufficient rainfall in 2004 to cause wetting at 0.7 m in either paddock. In 2005 both paddocks wet at 0.7 m, while paddock B6 also wet clearly at 1.1 m and possibly to a small extent at 1.5 m.

The shallower wetting in B2 in winter 2005 is attributed to the lucerne drying the soil above 0.7 m more effectively than the crop and summer fallow in B6 in the preceding summer/autumn period, creating a larger storage for the rainfall. This effect is expected to be particularly large in the heavy swelling clay soil in these paddocks.

As expected, in spring/summer 2005 lucerne in paddock B2 dried the soil more effectively at 0.7 m than the wheat crop in B6. The wheat did not appear to dry the soil at 1.1 m much at all, and at 1.5 m a wetting trend continued to May 2006. This suggests that 1.1 m is the limit of rooting depth for crops in this soil, which agrees with the observations at Carumbi which has the same soil type. It also suggests that there was deep drainage in paddock B6 in 2005.

**Indicators for changing phase**

The measurements suggest that the fibreglass block at 1.5 m is sufficiently below the annual crop rooting depth to be used as an indicator of phase changes. In the paddock planted to lucerne in 2004 (B2), the soil has not yet dried sufficiently at 1.5 m to return to cropping. In the paddock moved to cropping in 2004 (B6), the soil was wetter than 100 kPa after the 2005 season suggesting that it should be returned to lucerne to minimise the risk of deep drainage.
Soil water potential

Soil water potential (kPa)

- 0.7 m
- 1.1 m
- 1.5 m

Blandfield B6

Blandfield B2
B.3.2 Carumbi

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
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</thead>
<tbody>
<tr>
<td>A08</td>
<td>crop → 3 yr lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
<td>wheat</td>
</tr>
<tr>
<td>A10</td>
<td>lucerne → 4 yr crop</td>
<td>wheat</td>
<td>barley undersown with lucerne</td>
<td>lucerne</td>
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**Rainfall (Quandialla)**

<table>
<thead>
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<th>2006</th>
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<td>0</td>
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<tr>
<td>MA</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

**Comments**

In paddock A08, the soil water potential was at wilting point at both depths when measurements started which is consistent with the paddock having been under lucerne for 4 years. Comparison of the water content profiles in paddocks A08 and A10 suggested that the lucerne had actively removed water down to a depth of at least 3 m. By 2003, however, after a series of dry years the lucerne was getting sparse, and the swelling soil had developed large, deep cracks. The wetting at 1.1 m between December 2003 and February 2004 was only observed in two of the three fibreglass block replicates and not observed in the water content measurements. It is attributed to water from summer storms (100 mm in January and February) penetrating to depth in this paddock through cracks which, being unevenly distributed, did not affect the sensors uniformly.

The soil water potential measurements showed a steady rise between the time of installation in 2003 and May 2004 in paddock A10. There was no support for these changes in the water content measurements and they may be a result of slow equilibration in this heavy clay soil. By early 2005 both the soil water potential and water content data showed a distinct difference between the two paddocks, the cropped paddock (A10) being much wetter that that under lucerne.

Water content at 0.7 m appears somewhat erratic before June 2005, particularly in paddock A10, but the rises and falls are largely associated with rainfall events and drying by the crop. As expected, there was little evidence of wetting or drying at any depth in 2004, except for 0.7 m in paddock A10.

In winter 2005 wetting was evident in the soil water potential data at 1.1 m and to a lesser extent at 1.5 m in paddock A08 and at 0.7 m in paddock A10. The water content measurements showed similar patterns. The shallower wetting in paddock A10 compared with A08 is attributed, as at Blandfield, to the lucerne in 2004/05 drying the soil above 1 m more effectively that the crop/fallow in A08 and creating a larger buffer for storing rainfall so that it did not penetrate as deep.

Drying in paddock A08 only occurred to 1.1 m, as shown by both data sources, and the soil remained wetter at this depth than prior to winter. This suggests that, like Blandfield, 1.1 m is
about the limit of extraction by annual crops in this soil. In paddock A10, drying was evident at all depths by the 2nd year lucerne’s deeper rooting system. The drying at 1.1 and 1.5 m was clear in the water content measurements but only barely discernible in the soil water potential measurements.

The wetter subsoil under the previously cropped paddock (A10) in 2003/04, and the rapid and irreversible wetting at 1.5 m when crops returned to the lucerne paddock (A08) suggest that there is the potential for deep drainage past the annual crop rooting depth in this soil even during this run of relatively dry years. The water content measurements showed that 34 mm of water passed the bottom of the annual crop root zone (1.1 m) depth in paddock A08 in this first year of cropping after lucerne. The use of lucerne phases is therefore necessary to prevent this water becoming groundwater recharge.

There was also 8 mm of drainage past 1.1 m in paddock A10 under lucerne in 2005. However, this was quickly removed again by the lucerne in summer 2005/06. After two summers of lucerne a total of 35 mm of water had been extracted from the soil below 1.1 m in paddock A10, nearly all of it in the second summer because the dry conditions in the first year slowed the establishment of the lucerne.

**Indicators for changing phase**

The measurements suggest that the fibreglass block at 1.5 m is sufficiently below the annual crop rooting depth to be used as an indicator of phase changes. In the paddock recently planted to lucerne (A10), the soil has not yet dried sufficiently at 1.5 m to return to cropping. In the paddock recently moved to cropping (A08), although the soil had wet to 600 kPa by May 2006, it is not yet time to change phase. The water content measurements showed that the soil has a potential storage buffer of 80 mm below 1.1 m, and that only 34 mm had been filled, so that further wetting at 1.5 m is possible before a change back to lucerne is required.
Soil water potential

Soil water content
B.3.3 Derricks

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>B13</td>
<td>≥ 3 yr crop</td>
<td>lucerne (sprayed out in spring)</td>
<td>wheat</td>
<td>wheat</td>
</tr>
<tr>
<td></td>
<td>→ 2 yr lucerne</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>≥ 5 yr crop</td>
<td>wheat</td>
<td>lucerne</td>
<td>lucerne</td>
</tr>
</tbody>
</table>

**Rainfall (Sebastopol)**

![Rainfall graph](image)

**Comments**

In paddock B13 (cropped) a small amount of wetting and subsequent drying was evident at 0.8 and 1.2 m in 2004, and somewhat more in 2005, although the soil did not get anywhere near as wet as at sites further east, presumably because the rainfall was quite a deal less. There was little change at 1.6 m.

In paddock E1 (lucerne) wetting and drying was observed at 0.8 m in both years but not at 1.2 or 1.6 m. This is consistent with lucerne keeping the soil above 1 m dry so that the winter rainfall was all retained above that depth.

The soil water potential at 1.2 and 1.6 m was about the same in both paddocks in May 2006 as at the beginning of measurements and, apart from 1.2 m in paddock B13, changed little during the two years of measurements. This is attributed partly to the lower rainfall than at other sites. It may also be because the soil is quite shallow on this site and the deeper sensors are located in weathered bedrock, into which both water and plant roots may have trouble penetrating.

**Indicators for changing phase**

There are no clear indicators of phase changes here, possibly because of the low rainfall, and possibly because the shallow bedrock means that water penetration to depth is less likely than subsurface lateral flow across the top of the bedrock at this site.
Soil water potential

![Graph showing soil water potential over time for Derricks B13 and E1 sensors. The graph plots soil water potential (kPa) against time from June 2003 to June 2006, with data points for depths of 0.8 m, 1.2 m, and 1.6 m. The graphs illustrate fluctuations in soil water potential throughout the period.](image-url)
B.3.4 Glenlee

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>P9</td>
<td>≥ 2 yr lucerne</td>
<td>Lucerne (sprayed out in spring)</td>
<td>wheat</td>
<td>wheat</td>
</tr>
<tr>
<td>P33</td>
<td>≥ 5 yr crop</td>
<td>wheat</td>
<td>wheat u/s c</td>
<td>lucerne</td>
</tr>
</tbody>
</table>

**Rainfall (Temora ARS)**

![Rainfall Graph]

**Comments**

Paddock P9 was relatively dry (close to wilting point) at all depths when measurements started in 2004, while paddock P33 was much wetter. This is consistent with their cropping histories; P9, after several years of lucerne, would be expected to be drier than P33 after several years of crops.

Paddock P9 showed only gradual changes at all depths during the two years of measurements. At 1.2 and 1.6 m there was some wetting in both winters, but little evidence of drying. At 2 m the soil water potential was largely unchanged. Although the latter showed some inexplicable drying, this was only seen in one of the two replicates (not shown). The results seem to suggest a gradual wetting under cropping, and that the annual crops had a rooting depth of less than 1.2 m.

In paddock P33 there was little change until 2005, when the winter wetting could be clearly seen at 1.2 m. It is uncertain whether the oscillations at 1.6 and 2 m reflect wetting and drying or temperature changes. It is somewhat surprising that the 2005 winter rains penetrated deeper in the lucerne paddock (P33) than the cropped paddock (P9), but it could be because the lucerne struggled in the summer of 2004/05 and did not dry the surface soil very well. The water use by the lucerne in summer 2005/06 is clearly evident at all depths, with the 2 m depth reaching wilting point (surprisingly) before the shallower depths.

**Indicators for changing phase**

The measurements suggest that the fibreglass block at 1.6 m is sufficiently below the annual crop rooting depth to be used as an indicator of phase changes. In the paddock recently planted to lucerne (P33), the soil has not yet dried sufficiently at 1.6 m to return to cropping after two summers of lucerne, but is expected that after the coming third summer it will be ready to change phase. In the paddock recently moved to cropping (P9), there has been a little rewetting at 1.6 m after two years, but not enough to warrant changing phase back to lucerne.
Soil water potential

GlenLee P9

GlenLee P33
B.3.5 Sinclairs

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
<th>Prior to 2003</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>E10</td>
<td>≥ 3 yr lucerne</td>
<td>lucerne (sprayed out in spring)</td>
<td>wheat</td>
<td>wheat</td>
</tr>
<tr>
<td>K4</td>
<td>≥ 4 yr crop</td>
<td>barley undersown (with lucerne (failed))</td>
<td>fallow</td>
<td>wheat undersown</td>
</tr>
</tbody>
</table>

**Rainfall (Temora ARS)**

![Rainfall Chart]

**Comments**

Paddock E10, coming out of lucerne, was close to wilting point at 1.2 and 1.6 m as expected. It was a little wetter at 0.8 m when the first measurements were made in July, the only depth which appeared to receive any winter rainfall. In 2005 both 0.8 and 1.2 m were wet to field capacity by the winter rainfall and subsequently dried by the wheat crop, although they were wetter in May 2006 than in May 2005 before winter. The soil at 1.6 m remained at about wilting point throughout the measurement period. The rooting depth of annual crops on this soil therefore seems to be between 1.2 and 1.6 m.

Paddock K4 had had a mixed history. It had come out of several years of cropping, but had had one year of lucerne which had failed prior to the first measurements. Hence the soil was quite wet at 1.6 m, and driest (wilting point) at 0.8 m showing that the lucerne had dried the soil at the shallower depth before it failed. All depths showed wetting in 2004, which is consistent with the paddock being left without a crop. The slight downturn in June 2005 is likely to be a temperature effect. Wetting to field capacity occurred at all depths after June 2005. Wetting to 1.6 m occurred in this paddock and not paddock E10 probably because it was wetter throughout the shallower depths prior to the winter rains and therefore had less storage capacity so that the rainfall penetrated deeper. By December when the cover crop of wheat was harvested, only the 0.8 m depth had dried to any extent. The 1.2 m depth did not start drying below field capacity until March 2006, and at 1.6 m the soil was still wetter than field capacity in May.

Given the wetting to field capacity at 1.6 m in paddock K4, and the observation that the rooting depth is not likely to be much deeper than 1.2 m, it is clear that there was deep drainage in paddock K4 in 2005. Had the lucerne sown in 2003 not failed, it is very likely that this would have been prevented.

**Indicators for changing phase**

The measurements suggest that the fibreglass block at 1.6 m is sufficiently below the annual crop rooting depth to be used as an indicator of phase changes. In the paddock planted to lucerne last year (K4), the soil has clearly not yet dried sufficiently at 1.6 m to return to
cropping. In the paddock recently moved to cropping (P9), there has been no measurable rewetting at 1.6 m after two years, and a change of phase back to lucerne is not yet warranted.

It is interesting to note that the soil water potential at 1.6 m in 2003 did indicate that a change from cropping to lucerne was needed to avoid deep drainage. Although this was done, because the lucerne failed and the paddock effectively continued with shallow rooted crops for another 2 years deep drainage did occur as predicted by the sensor measurement.

Soil water potential
B.4 Charles Sturt University

**Cropping history**

<table>
<thead>
<tr>
<th>Paddock</th>
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<tr>
<td>P14</td>
<td>5 yr crop</td>
<td>lucerne</td>
<td>lucerne</td>
<td>lucerne</td>
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</table>

**Rainfall (on-farm)**

The soil water potential measurements at both depths in paddock P12 started at about wilting point in June 2003, consistent with the paddock having been in lucerne until 2002 which was a relatively dry year. They drifted up slightly in 2003, most likely a process of equilibrating with the very dry soil, and then remained unchanged for the rest of the measurement period apart from showing the distinctive oscillations in response to soil temperature. The water content data also show no change during the measurement period, and also correspond to the known wilting point values in this paddock. This is consistent with the relatively low rainfall (between 190 and 300 mm/yr below average) in the four years since the removal of lucerne.

The soil was wetter at both depths in paddock P14 than in paddock P12, particularly at 1.7 m, consistent with the fact that P14 had been cropped for five years. The soil water potential data showed an increase through to January 2004, particularly at the shallower depth, but this was not seen in the water content data, so may have been equilibration of the sensors. The water content at 1.3 m decreased sharply between December 2003 and February 2004, as did the soil water potential at 1.3 m between January and March 2004. This is attributed to the lucerne roots reaching this depth early in 2004. Both levelled out by May, the soil water potential at wilting point. A similar decline in both water content and soil water potential was seen about a month later at 1.7 m. This is consistent with the expected growth rate of lucerne roots of about 1 mm per day (0.3 m/month). The decline at 1.7 m continued slowly over winter but showed a slightly faster change in summer 2004/05 as the lucerne became more active again and dried the soil to wilting point at this depth. The water content was higher at 1.7 m in P14 than P12, but this is consistent with variability in wilting point values between the two paddocks.

**Indicators for changing phase**

From previous experience in this paddock it is known that the fibreglass block at 1.7 m is sufficiently below the annual crop rooting depth (1.2 m) to be used as an indicator of phase changes. In the paddock planted to lucerne in 2003 (P14), the measurements indicated that the soil had dried to wilting point by the beginning of 2005 (after two summers of lucerne).
and that it could be returned to cropping without an immediate risk of deep drainage. In the cropped paddock, no significant wetting was observed by the 1.7 m sensor after four relatively dry years of cropping, so that a return back to lucerne is not yet warranted.
Soil water potential

Soil water content
References


