Background

In irrigated landscapes deep drainage from the bottom of the plant root zone is a key component of the water balance. Apart from wasting a precious resource, it is the potential driver for rising groundwater tables and salinity. However, there is also a requirement for a leaching fraction in irrigated agriculture to prevent the built up of salts in the root zone soil. Therefore, an important aspect of maximizing the productive use of diverted water resources and minimizing any negative environmental consequences is the management of deep drainage.

Limited information is available on the magnitude and variability of deep drainage in the plains landscape of the northern Murray Darling Basin and how it affects the salt loads in ground water and rivers. Most estimates are derived either using models or inferred from the mass balance of salts within the root zone. Because both these methods make assumptions about water and solute movement within the soil, the current estimates of deep drainage are rather uncertain. This in turn constrains landscape scale estimates of deep drainage and solute movement.

The report ‘Northern Murray Darling Basin: Better Catchment Planning & Water Resource Management R&D Program Proposal’ (Lyle and Purcell, 2002) emphasised the need to establish a subprogram to improve estimates of deep drainage in the plains landscape of the region. In the past it has been considered that deep drainage is minimal under the heavy clay soil types in the northern Murray Darling Basin (NMDB). More recent estimates on the Darling Downs and in the Namoi and Macquarie valleys have shown that this is not the case. A reliable quantification of drainage and its spatial and temporal variation are critical for the development of crop management practices that optimise drainage rates and to provide hard data for landscape scale models to estimate water and solute movement.

Objectives

The overall aim of the project was to quantify deep drainage under irrigated cotton-based production systems of the northern Murray Darling Basin using a state-of-the-art equilibrium tension drainage lysimeter by:

1. providing a reliable estimate of deep drainage under irrigated cotton production systems on a soil type characteristic of Vertosols in the northern Murray Darling Basin;
2. contributing to basic understanding of the response of deep drainage to management practices and variable climate for these systems and soil types;
3. allowing cross referencing of the results obtained from satellite sites established through a sister project and the project on drainage under rotation systems being conducted by Nilantha Hulugalle (NSW Agriculture).

The outcome of objective 2 would be the improvement of water balance models that allow crop performance and water balance components to be estimated over the long-term (40+ years) for a range of situations with different soils, climates and management practices.

The outcome of objective 3 would be the assessment of cheaper, and hence more widely deployable, methods of estimating drainage using the lysimeter as a benchmark.

The specific objectives for each year of the project were:

Year 1:

- Survey and characterise selected site for lysimeter (*completed)*
- Construct first lysimeter cell (*completed)*

- Purchase and install equipment for parallel measurement of drainage and other components of the water balance (*completed)*

Year 2:

- Monitor drainage, water balance and water quality under conventional irrigated cotton production systems *(not completed)*
- Ensure measurements allow closure of the water balance *(not completed)*
- Compare estimates of drainage made by alternative methods *(not completed)*
- Construct second lysimeter cell *(cancelled)*

Year 3:

- Initiate monitoring drainage, water balance and water quality under two management systems to provide estimate of sensitivity of drainage to management *(not completed)*

The start of the project was delayed because a technical officer with the necessary engineering, design and environmental monitoring skills was not appointed until April 2004. Hence, the project had only run for 26 months up to June 2006

The first objective of the project – to build an equilibrium tension lysimeter – has been met. Such facilities are not a standard design and there are no standard methods for construction or installation. Early in the design phase of the facility, more detailed costings led to the realisation that the budget was insufficient for two lysimeters. The decision was made to scale back the project to build only one. The design, construction and especially installation were all much more technically challenging than originally envisaged. Hence, the facility was only completed and opened in September 2006. As a result, the objective to measure drainage and subsequent objectives have not been met within this 3 year time frame. A continuation for a further three years will allow these objectives to be met.

As part of the facility, a number of alternative methods to measure components of the water balance have been in conjunction with the lysimeter. These include barrel lysimeters, soil moisture monitoring by two methods (neutron probe and capacity probes), wetting front detectors, chloride mass balance, and electrical resistivity imaging. Piezometers have been installed at 20 and 34 m depth to investigate linkages between drainage and groundwater.

Since the facility has only been recently commissioned this report will concentrate on the design of the lysimeter

Methods

Location

The lysimeter is located in paddock C1 at the Australian Cotton Research Institute (ACRI) near Narrabri in northern New South Wales (30° 11.53' South, 149° 36.31' East). The location is an experimental plot under a cotton-wheat rotation with irrigated cotton sown in October of 2004 and 2006 and wheat in June 2005. Minimum tillage is used with stubble retention and permanent beds. Alternate furrows are used for traffic and irrigation. The plot is approximately 200 m long from head to tail ditch (approximately east to west) and 24 m wide. Adjacent to the northern edge is a 4 m wide buffer strip that was part of an earthen roadway, but which is now managed the same as the plot. On the north side of the buffer is the remainder of the roadway, which is 4 m wide.

The lysimeter is under the plot at 2.1 m depth from the ridge tops. It is situated half way along the plot, and extends south 0.34 to 2.57 m from its northern edge. An access shaft is located within the buffer strip immediately adjacent to the lysimeter.

Soil Characterisation

The soil is a Haplic, Self-mulching, Grey Vertosol (Isbell, 1996), which is grey to about 1.1 m depth and brown below this.

A site characterisation was carried out in June 2004. A 2 m deep pit was dug by back-hoe about 20 m west of the lysimeter location. The profile was described and disturbed specimens were taken from one wall. Ledges were excavated at 0.31, 0.55, 1.09 and 1.77 m depth. The soil under each ledge was pre-wet with an array of drippers using 0.01M $CaCl_2$ solution to prevent dispersion. Four replicate, large cores were taken from each ledge together with four at the surface – two under a furrow and two under a hill. The cores were taken using Method 502.04 of McKenzie and Cresswell (2002) and were 220 mm diameter and 190 mm long.

Saturated hydraulic conductivity was measured on three of the replicate cores from each depth (four from the surface) using Method 510.01 of McKenzie *et al* (2002). A constant head was used for cores from the surface and from 1.09 and 1.77 m depth and a falling head for those from 0.31 and 0.55 m depth since the latter had much lower conductivity. Following this, unsaturated conductivity was measured on the same cores at supply potentials of -0.1, -0.3, -0.5 and -1.0 kPa using Method 510.04 of McKenzie *et al* (2002).

After hydraulic conductivity measurements were complete three smaller replicate cores (75 mm diameter × 75 mm length) were taken from within each large core using a hydraulic ram. These were used to determine the water retention curve using suction plates (Method 504.01, Cresswell 2002) at potentials of -1, -3, -5, -10, -33 and -66 kPa and using pressure plates (Method 504.02,Cresswell 2002) at potentials of -100, -500 and -1500 kPa. The cores were then used to measure bulk density using Method 503.01 (Cresswell and Hamilton 2002).

The disturbed specimens were used to analyse the particle size distribution and soil chemistry. For particle size distribution the specimens were pre-treated to disperse the soil and remove organic matter. The fraction less than 63 μm was analysed by sedimentation using a Sedigraph 5100 (Micromeritics Instrument Corporation) and that greater than 63 μm by dry sieving. The method is essentially a modification of Method 517.02 (Bowman and Hutka 2002). Soil chemistry analyses used the following methods (mainly from Rayment and Higginson 1992):

Electrical conductivity (1:5 extract)	Method 3A1
pH (1:5 water extract)	Method 4A1
pH (1:5 $CaCl_2$ extract)	Method 4B2
Soluble chloride	Method 5A2 - analysed in a matrix of 0.01M $(BaNO_3)_2$ to remove sulphate and phosphate interferences and flocculate suspended clay
Total carbon	LECO CNS analyser
Carbonates	Method 19A1
Exchangeable calcium	Method 15C1
Exchangeable magnesium	Method 15C1
Exchangeable sodium	Method 15C1
Exchangeable potassium	Method 15C1
Cation exchange capacity (CEC)	Method 15C1
Exchangeable sodium percent (ESP)	Method 15N1

Above 1.2 m depth the soil is 60% clay (<2 μm), 14% silt (2-20 μm) and 25% sand (20-2000 μm). Most of the clay is less than 0.5 μm (Table 1, Fig. 1). Below 1.2 m, the clay content decreases to 50% by 2 m depth with corresponding increases in silt and sand to 20% and 30% respectively.

Table 1. Particle size distribution of the soil at the lysimeter site.

Depth		**Particle size, μm**														
upper	**lower**	**2000**	**1000**	**500**	**250**	**125**	**63**	**53**	**31**	**20**	**15.6**	**7.8**	**3.9**	**2**	**1**	**0.48**
m		**Cumulative proportion (w/w) less than**														
0.00	0.04	100.0%	99.8%	99.4%	98.3%	87.9%	84.4%	83.0%	79.5%	76.7%	75.1%	73.1%	67.3%	62.9%	57.0%	50.8%
0.04	0.12	100.0%	99.6%	99.2%	98.2%	87.9%	82.3%	80.5%	77.4%	74.6%	73.0%	69.6%	64.1%	60.1%	55.6%	49.0%
0.12	0.26	100.0%	99.9%	99.8%	98.7%	89.5%	81.0%	79.5%	76.1%	73.2%	72.4%	69.4%	64.6%	60.0%	55.7%	50.9%
0.26	0.40	100.0%	99.8%	99.5%	98.4%	88.7%	81.3%	79.5%	75.6%	72.9%	72.6%	68.4%	63.4%	58.2%	54.2%	49.4%
0.40	0.54	100.0%	99.8%	99.7%	98.9%	87.8%	82.5%	81.6%	76.9%	74.5%	73.8%	69.8%	64.6%	60.1%	55.0%	51.7%
0.54	0.65	100.0%	100.0%	99.8%	99.0%	90.0%	82.3%	80.5%	77.0%	74.6%	74.1%	69.5%	64.3%	59.8%	55.7%	51.0%
0.65	0.80	100.0%	99.8%	99.6%	98.7%	90.3%	84.3%	82.9%	80.1%	78.8%	76.8%	72.8%	67.4%	62.4%	57.7%	53.8%
0.80	0.95	100.0%	100.0%	99.7%	98.7%	89.3%	81.8%	80.5%	79.0%	75.7%	74.4%	71.9%	65.7%	61.1%	57.1%	53.3%
0.95	1.10	100.0%	99.8%	99.5%	98.4%	89.7%	82.6%	80.9%	78.1%	76.6%	74.0%	71.8%	66.7%	62.7%	57.7%	53.2%
1.10	1.25	100.0%	99.1%	98.9%	98.3%	91.1%	83.4%	82.2%	77.9%	75.8%	74.0%	72.0%	67.1%	62.3%	56.7%	52.2%
1.25	1.40	100.0%	100.0%	100.0%	99.4%	91.4%	82.0%	80.6%	76.5%	74.0%	73.9%	69.8%	65.3%	59.9%	54.4%	49.3%
1.40	1.55	100.0%	100.0%	100.0%	99.6%	91.5%	81.2%	79.2%	75.3%	70.7%	69.8%	65.8%	61.0%	55.8%	51.0%	47.0%
1.55	1.70	100.0%	100.0%	100.0%	99.7%	93.9%	84.7%	82.5%	77.4%	72.1%	69.1%	62.4%	56.6%	50.9%	45.4%	41.5%
1.70	1.85	100.0%	100.0%	100.0%	99.8%	94.0%	80.6%	79.0%	75.3%	71.5%	68.2%	63.1%	56.1%	51.3%	45.9%	41.3%
1.85	2.00	100.0%	100.0%	100.0%	99.7%	91.0%	79.5%	77.8%	73.8%	69.2%	67.8%	61.6%	55.1%	49.1%	43.8%	37.2%

Table 2. Analytical data for the soil at the lysimeter site

Depth		Electrical conducivity	pH	pH	Soluble Cl	Total C	Inorganic C	Exchangeable cations					CEC	ESP
upper	lower	1:5 extract					(as $CaCO_3$)	Ca^{2+}	Mg^{2+}	Na^+	K^+	Total		
m		dS/m	H_2O	$CaCl_2$	mg/kg	%	%	mmol(+)/kg						%
0.00	0.04	0.08	7.72	7.11	6.12	0.96%	<0.2	174.5	89.1	2.6	12.9	279.0	333.6	0.77%
0.04	0.12	0.09	7.90	7.27	12.33	0.74%	<0.2	175.8	88.1	4.0	11.6	279.6	314.6	1.29%
0.12	0.26	0.07	8.02	7.32	9.61	0.67%	<0.2	177.0	85.1	4.9	7.6	274.6	314.5	1.56%
0.26	0.40	0.07	8.03	7.25	9.31	0.62%	<0.2	163.1	89.9	6.9	5.4	265.2	304.5	2.25%
0.40	0.54	0.08	8.12	7.31	22.35	0.63%	<0.2	148.7	93.1	8.1	5.8	255.6	310.7	2.60%
0.54	0.65	0.10	8.17	7.33	18.11	0.65%	<0.2	176.0	110.4	11.3	7.0	304.7	309.5	3.64%
0.65	0.80	0.11	8.24	7.51	14.80	0.64%	<0.2	151.6	103.4	11.3	6.4	272.8	286.9	3.95%
0.80	0.95	0.12	8.30	7.53	16.01	0.57%	<0.2	150.5	107.8	11.8	6.3	276.4	276.0	4.29%
0.95	1.10	0.13	8.39	7.57	13.25	0.51%	<0.2	142.2	109.2	13.2	6.1	270.6	283.8	4.64%
1.10	1.25	0.11	8.43	7.65	7.78	0.30%	<0.2	132.9	105.4	14.4	5.8	258.6	276.9	5.21%
1.25	1.40	0.11	8.49	7.56	9.05	0.24%	<0.2	134.9	102.9	14.6	5.0	257.4	263.1	5.56%
1.40	1.55	0.09	8.49	7.48	7.94	0.22%	<0.2	134.7	97.5	15.8	4.6	252.5	254.2	6.20%
1.55	1.70	0.09	8.40	7.05	8.23	0.14%	<0.2	132.0	94.7	15.7	3.7	246.2	256.1	6.14%
1.70	1.85	0.09	8.40	7.16	13.53	0.12%	<0.2	117.6	83.9	15.2	3.5	220.3	224.3	6.78%
1.85	2.00	0.09	8.38	7.15	16.03	0.11%	<0.2	122.2	84.6	15.2	3.1	225.2	245.5	6.17%

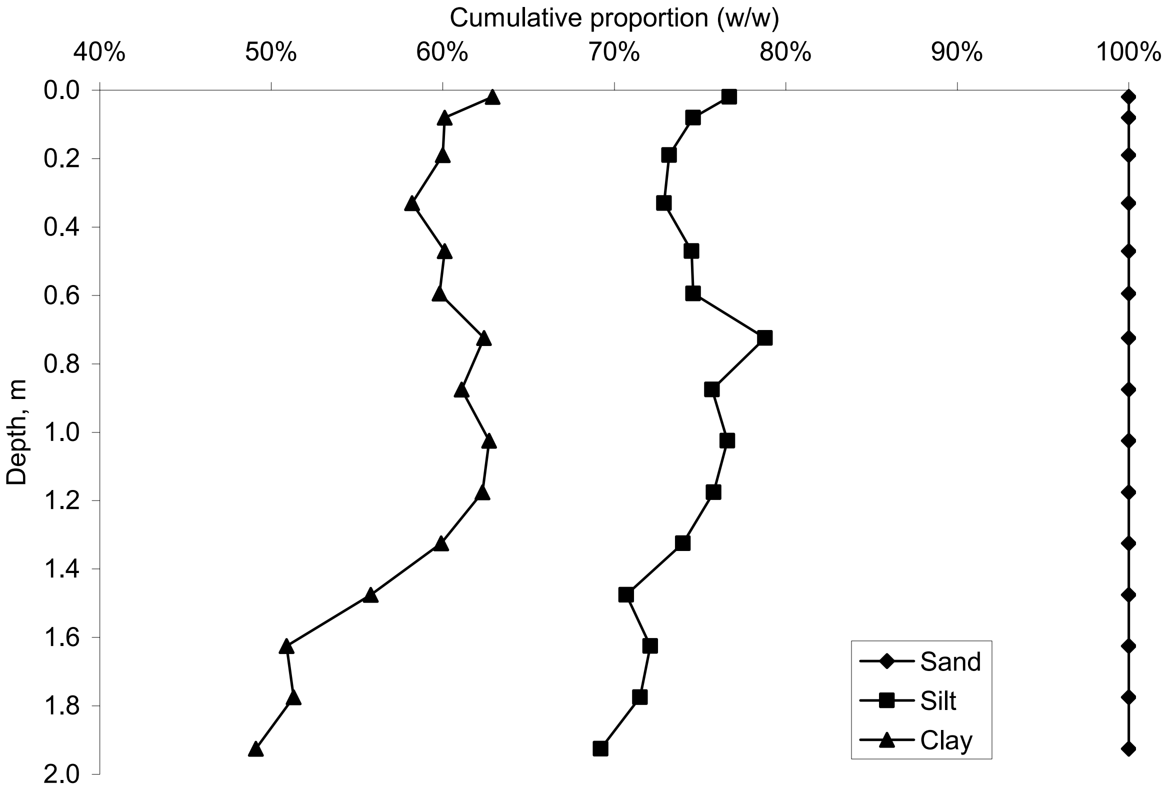


Fig 1. Particle size distribution profile at the lysimeter site showing fairly uniform particle size to 1.2 m depth. Clay is less than 2 μm; silt 2-20 μm and sand 20-2000 μm.

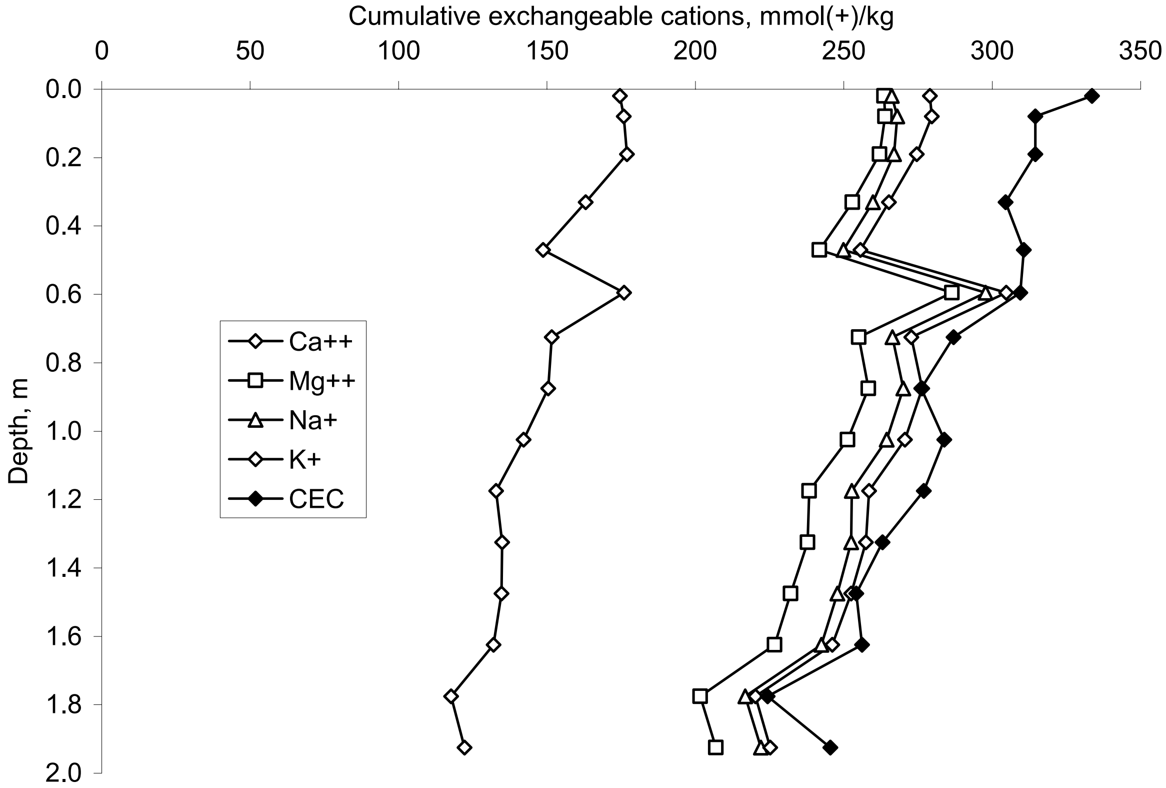
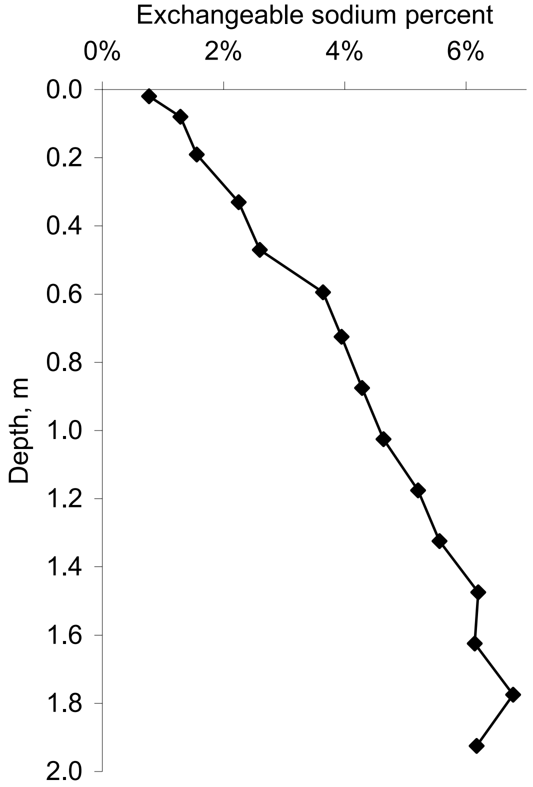


Fig. 2. Exchangeable cation profiles at the lysimeter site



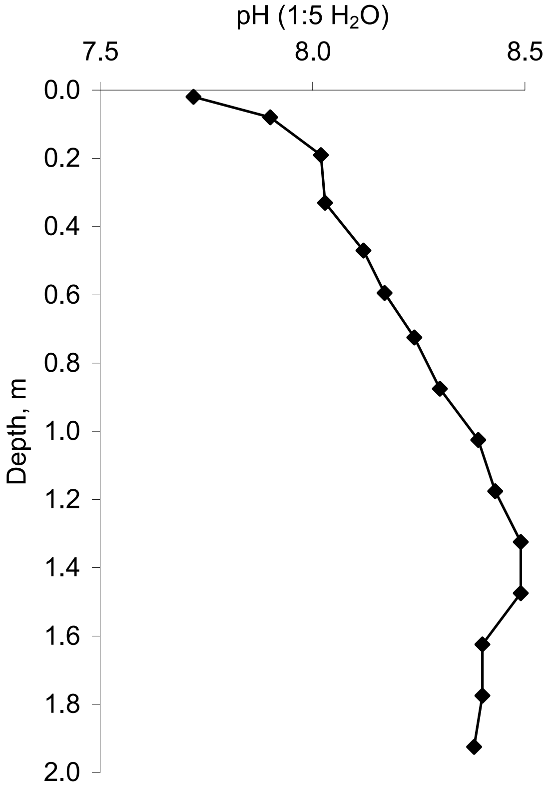


Fig. 3. Profile of exchangeable sodium percent at the lysimeter site showing a gradual increase with depth to mildly sodic values.

Fig. 4. Profile of pH of a 1:5 H_2O extract at the lysimeter site.

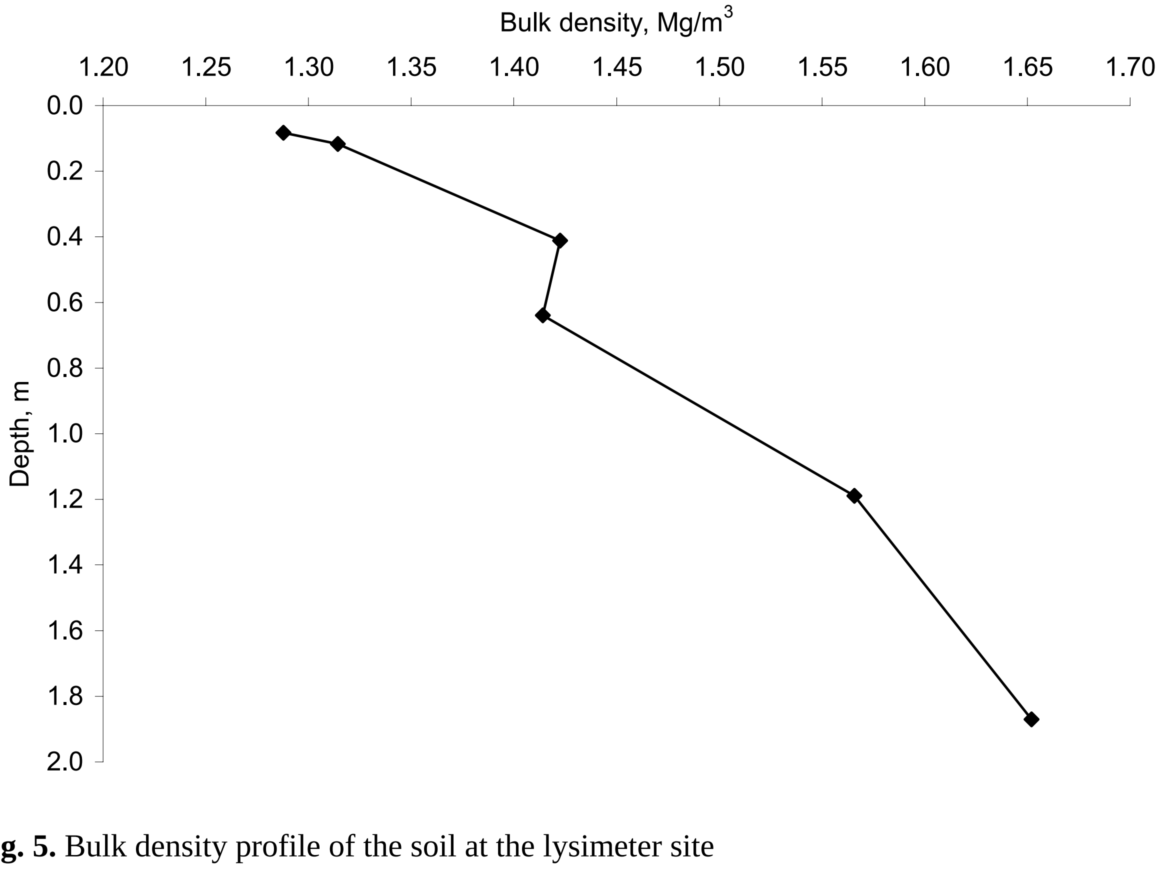


Fig. 5. Bulk density profile of the soil at the lysimeter site

The exchange complex of the soil is dominated by divalent cations, mainly calcium (Table 2, Fig. 2) with a gradual increase in ESP to mildly sodic values at 2 m depth (Fig. 3). pH increases with depth from less than 8.0 at the surface to 8.5 at 1.2 m and remains around 8.5 below this (Fig. 4).

Bulk density increases down the profile from 1.30 Mg/m^3 at the surface to 1.65 Mg/m^3 at depth (Fig. 5). There is no obvious difference at the surface between hill and furrow. The water retention curves of all layers show a gradual decline in water content with increasingly negative potentials (Fig. 6), with no obvious air-entry potential. The water held at the dry end is similar throughout the profile at about 28%, but the amount held near saturation gradually decreases down the profile. Hence there is a gradual decrease in available water (that held been the drained upper limit and permanent wilting point) with depth. Using -10 kPa as drained upper limit and -1500 kPa as permanent wilting point, the available water holding capacity is 20% at the surface and decreases to 10% at 2 m depth (Fig. 7). The available water holding capacity between the surface and 2 m is approximately 290 mm.

Hydraulic conductivity within a profile exerts a large influence on deep drainage, especially in a furrow irrigated system in which water is ponded at the surface during irrigations (*cf.* dryland situations where often it is only the heaviest rain events that cause water to pond). At the lysimeter site saturated hydraulic conductivity is greatest in the subsoil (20-75 mm/hr) (Fig. 8) despite it having the greatest bulk density and lowest available water holding capacity. This is due to the presence of cylindrical macropores, which were observed to penetrate many of the core specimens, and are probably the remains of old tree roots. However, even at slight suctions these macropores cease to function so conductivity falls by an order of magnitude. The lowest conductivities are in the subsurface (0.3 – 0.7 m depth) and are two orders of magnitude lower than the deeper subsoil (0.3-0.6 mm/hr at saturation). The small conductivity of this layer is probably the result of compaction by traffic over the years that has destroyed macroporsoity, but is too deep to be rectified by tillage as in the surface layer. The consequence of this layer is that it is likely to have a controlling influence on water movement to deeper layers. In theory at least, even if saturated conditions exist in this and shallower layers, the maximum water flow to deep layers is restricted by this layer. Deeper layers can handle this flow rate at more negative potentials without being saturated.

However, these hydraulic conductivities were measured when the soil in the cores had been completely saturated and were therefore fully swollen. It is possible that after drying cracks could penetrate the restrictive subsurface layer and result in much greater flow rates until the layer has swollen. Given the much high conductivity of the deeper layers, this could result in an initial pulse of drainage. One of the questions the lysimeter is intended to address is whether and under what circumstances such a phenomenon occurs.

Lysimeter design, construction and installation

Drainage is the most difficult component of the water balance to measure or estimate. Indirect methods to estimate drainage, for example by measuring and/or estimating the other components of the water balance and obtaining drainage by difference, often result in large uncertainty because all the uncertainties associated with measuring the other components are accumulated in the drainage calculation. Methods to infer drainage from the measurements of associated soil processes, such as using chloride mass balance, rely on certain assumptions which are more or less well established in a given situation and which add uncertainty to the estimate.

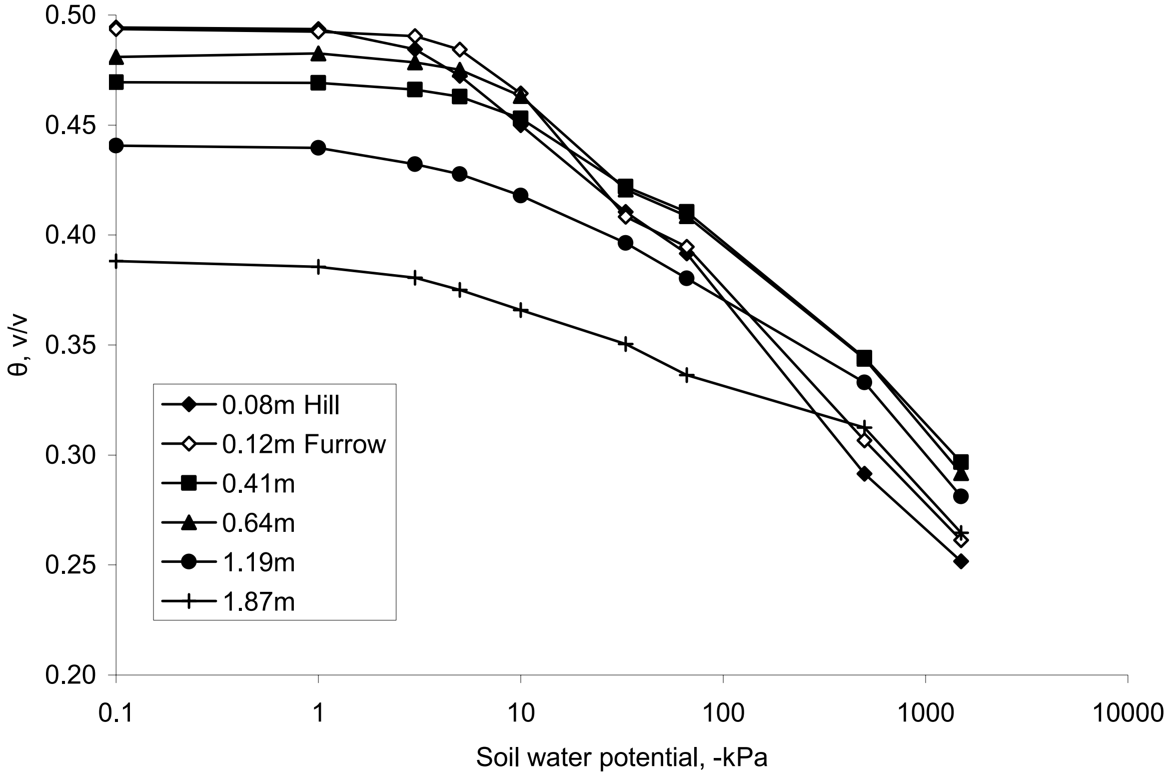


Fig. 6. Water retention of different soil layers at the lysimeter site. Depths refer to the mid-point of 190 mm long cores. The results show a) the gradual decrease in water held as potential becomes more negative and b) the decrease in water held in macropores (at potentials near to zero) down the profile.

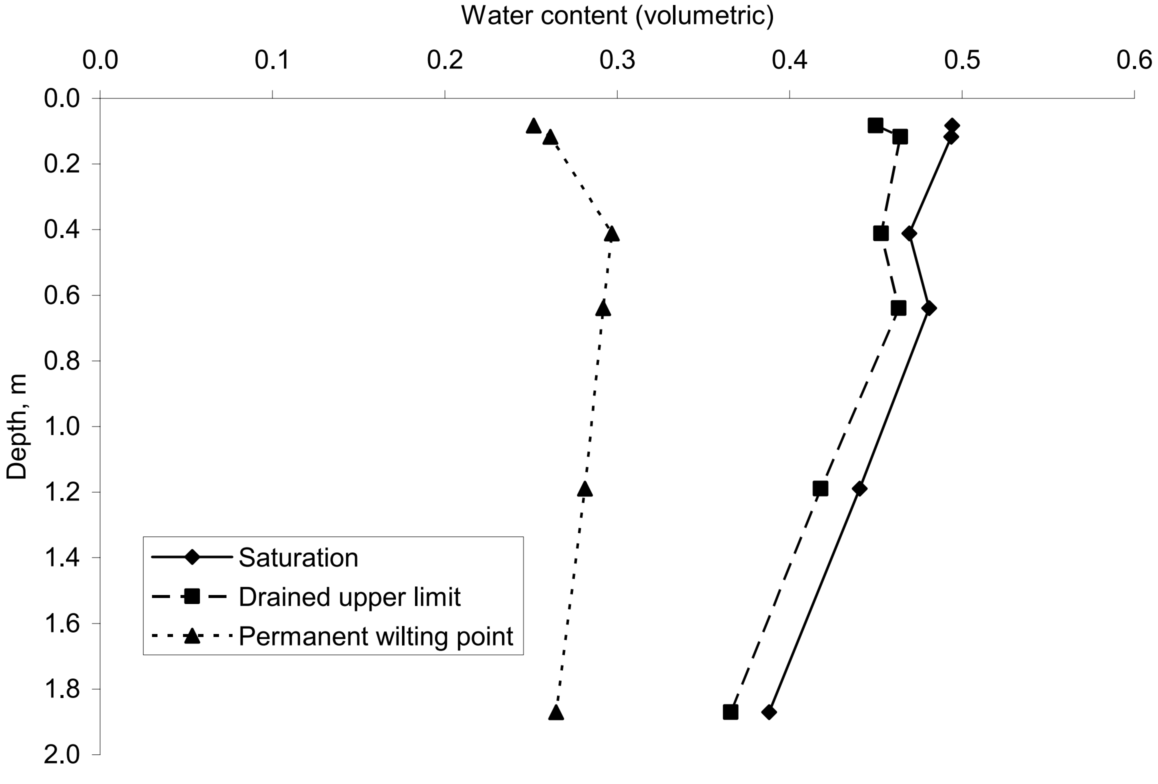


Fig. 7. Profile of available water holding capacity of the soil at the lysimeter site. Drained upper limit corresponds to a potential of -10 kPa and permanent wilting point to -1500 kPa.

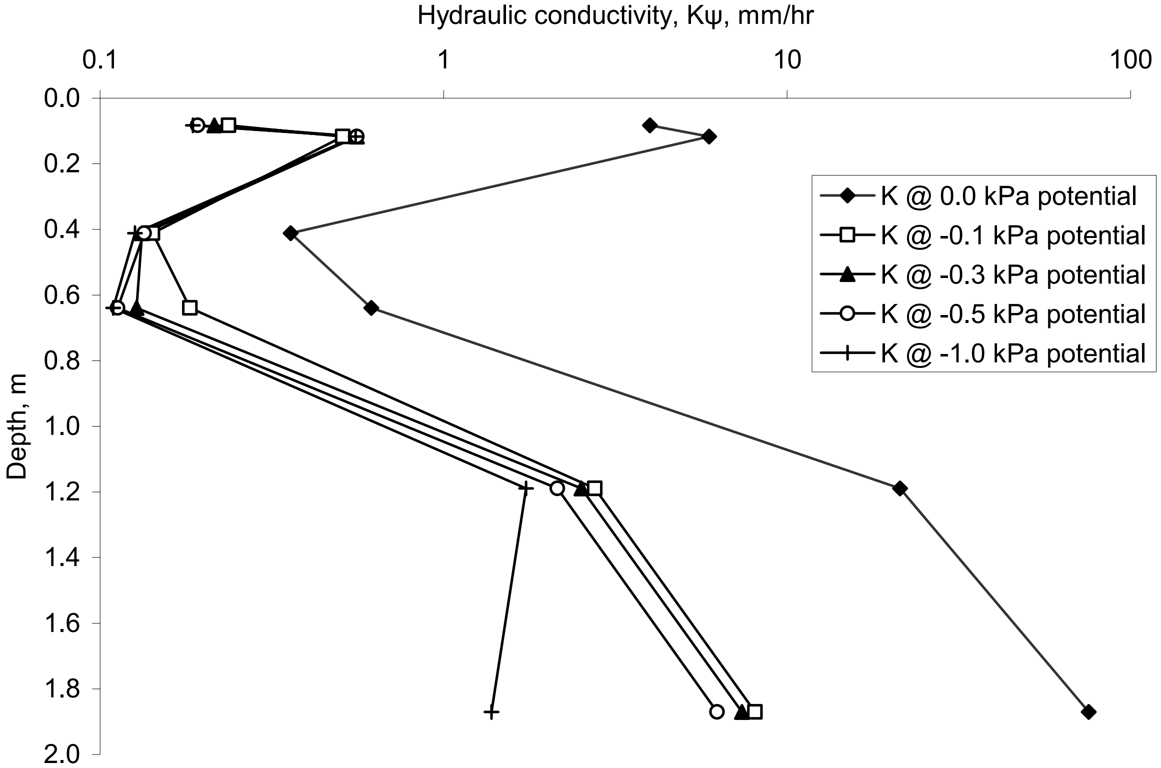


Fig. 8. Profile of near-saturated hydraulic conductivity at the lysimeter site, showing the large decrease in conductivity between saturation and -0.1 kPa potential and the restriction to flow by the subsurface layer.

Direct measurement is also difficult because most instruments interfere with drainage by altering the hydraulic gradient which is the major driver of water movement. For example, weighing lysimeters contain a large volume of soil that is isolated from the surrounding soil. They are primarily designed to measure evapotranspiration by weighing the whole device as it gains and looses water. At their lower boundary they usually have a permeable fill between the soil and the base through which drainage is directed to an outlet and measured, i.e. they are ‘free-draining’. The problem is that the potential at the outlet is zero, so the soil near the base has to accumulate water until its potential is also zero (saturated) before drainage can occur. In this situation the potential gradient at the lower boundary is only caused by gravity. However, outside the lysimeter the soil at the same depth can have a more negative potential than soil layers above (because it is drier) creating a larger downward gradient. The result is that drainage is slowed or delayed within the weighing lysimeter.

Brye *et al.* (1999) addressed the problem of disrupting the hydraulic gradient by designing an equilibrium tension drainage lysimeter (or variable tension drainage lysimeter). This consists of a collection tray that exerts a hydraulic potential equal to that in the surrounding soil. The tray is a steel box whose floor slopes towards an outlet to collect drainage. The ceiling is permeable, but has a sufficiently negative air-entry potential that it holds water against a reasonable vacuum. A vacuum is applied to the box equal to the soil water potential in the surrounding soil as measured using a tensiometer. This makes the device ‘hydraulically invisible’. The device is made possible by the use of sintered stainless steel as the ceiling. This product is made from steel particles sintered together. It has a high porosity, a carefully controlled pore size, and comes in sheets 1 mm thick. Thus it has a high hydraulic conductivity. The box is installed at the desired depth by excavating a tunnel horizontally from the wall of a soil pit. After installation the wall is sealed with plastic and the pit back filled.

An additional advantage of this deign of drainage lysimeter for swelling clay soils under furrow irrigation, is that it does not have walls as in a weighing lysimeter. These cause two problems. First, when the soil dries, the wall interferes with natural crack development and is likely to cause cracks to develop preferentially between the soil and the wall. Second, the gap between the wall and the surrounding soil is likely to make its use in a furrow irrigation situation difficult.

Pegler *et al.* (2003) improved the design by automating the vacuum adjustment using a data logger. The data logger records the tensiometer measurements at regular intervals (15 minutes) and either increases or decreases the vacuum in the lysimeter accordingly. They also used air jacks to keep the tray pushed up against the soil.

Both the above designs were installed via soil pits which limited the depth at which the lysimeters could be placed. R. Young (pers. comm.) designed a concrete access shaft to allow much deeper installation well below the root zone.

We used the basic design of Brye *et al.* (1999) and the subsequent improvements by Pegler *et al.* (2003) and R. Young for the ACRI drainage lysimeter and made additional improvements and changes for the particular situation at ACRI.

Lysimeter design

The design of the lysimeter trays is shown in Fig. 9. The trays are 910 mm long, 286 mm wide and 130 mm high. They are constructed from marine grade stainless steel with 3 mm thick walls and 4 mm thick sloping floors. In the corner where the floor is lowest is a drain tube projecting into the recess below the floor. In the opposite corner, a riser tube projects through the floor to just below the sintered metal filter and is connected to the vacuum supply. Above the floor is a steel ledge welded onto all four walls to support the sintered metal filter. The filter is also supported by 19 beams running across the short dimension of the tray between the ledges and spaced at 42.5 mm intervals. The walls project upwards above the filter for an additional 25 mm to hold contact material (see below) between the filter and the soil. Above the metal filter, which has a nominal pore size of 0.2 μm is a series of other filters to prevent fine material blocking it. Immediately above the metal filter is a fibreglass filter with a nominal pore size of 0.5 μm. Above this are 1 μm and 5 μm polypropylene filters. The filters are all held down by a steel strap bolted into the support ledge.

The tray is supported by two air jacks designed to exert an upwards force equal to the average overburden at that depth. The jacks are mounted on a bearing plate to spread the load over the floor of the tunnel in which the assembly is installed. The whole assembly weighs about 60 kg. Six trays were constructed by the CSIRO Land and Water workshop in Canberra.

The trays are installed in pairs, end-to-end. When installed the pair sits within a shoring box of 2 mm marine grade stainless steel that contains them on all sides except the top. One end of the shoring box is removable to allow the tray assemblies to be inserted. The shoring box prevents soil collapsing into the space around the air jacks. When installed the trays are connected to the access shaft by several tubes: a drain tube to collect drainage water from the floor of the tray; a vacuum tube connected to the riser through which the vacuum is applied; and two pressure tubes connected to the airbags.

The trays were tested before installation both to establish that they were airtight and to determine the properties of the metal filter. The filter is 1 mm thick and, once saturated, can

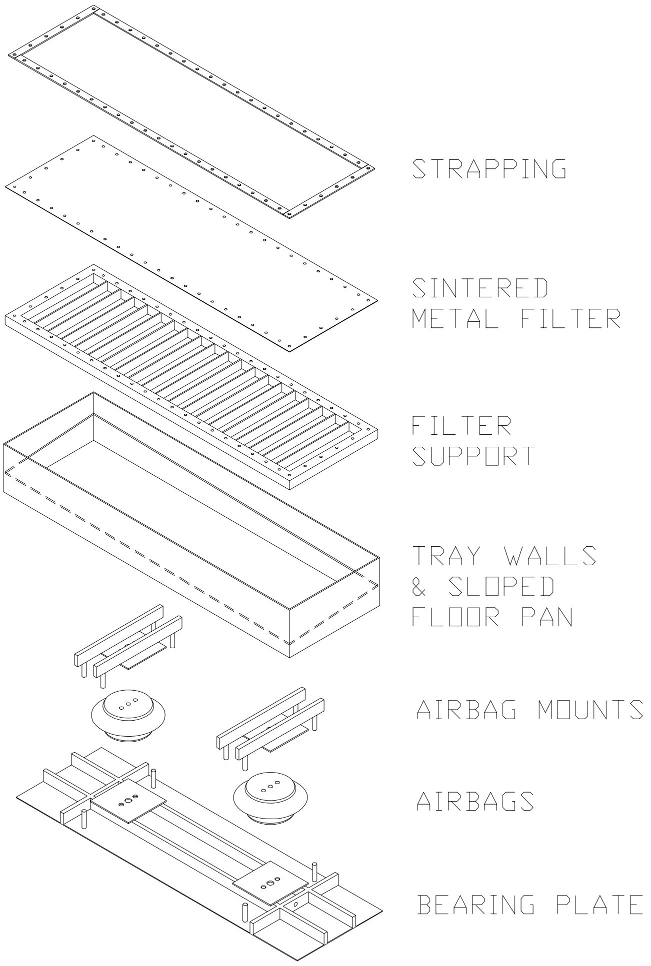


Fig. 9. Design of the lysimeter trays

hold a vacuum of -32 kPa almost indefinitely. At greater vacuums water drains from larger pores and it leaks slowly. The greater the starting vacuum, the more pores are emptied and the faster the vacuum dissipates. The decrease in vacuum after the first hour is 0.5 kPa for a starting vacuum -43.5 kPa; 1 kPa for -53.1 kPa; 8.6 kPa for -61.6 kPa; and 20.5 kPa for -72.1 kPa. The hydraulic conductivity of the filter is 0.426 mm/hr.

Contact material

It is essential that the upper surface of the lysimeter tray has good hydraulic contact with the soil above it. Previous users of this type of lysimeter used soil mixed into slurry to fill the gap between tray and soil. The soil was either native or sourced from elsewhere because it had particular properties such as very stable aggregates. In clay soil, use of native soil is unwise due to the risk of dispersion, especially if sodic. Foley *et al.* (1999) used a slurry from a Queensland Ferrosol in pristine condition and with excellent aggregate stability as a contact material for their lysimeter in a Black Vertosol. Native soil was deemed unsuitable for the ACRI lysimeter because it is both clay and slightly sodic. Moreover, it was decided not to use another soil since it could affect the chemical composition of the leachate which might be of interest during the life of the lysimeter. Therefore an inert material with suitable properties was sought.

Ideally a contact material should have a greater hydraulic conductivity than the soil at all soil water potentials. It also needs to have few particles fine enough to block the filter, or such particles need to be well aggregated. Fine sand, would have great enough conductivity near saturation, but would loose too much water at even small negative potentials to maintain

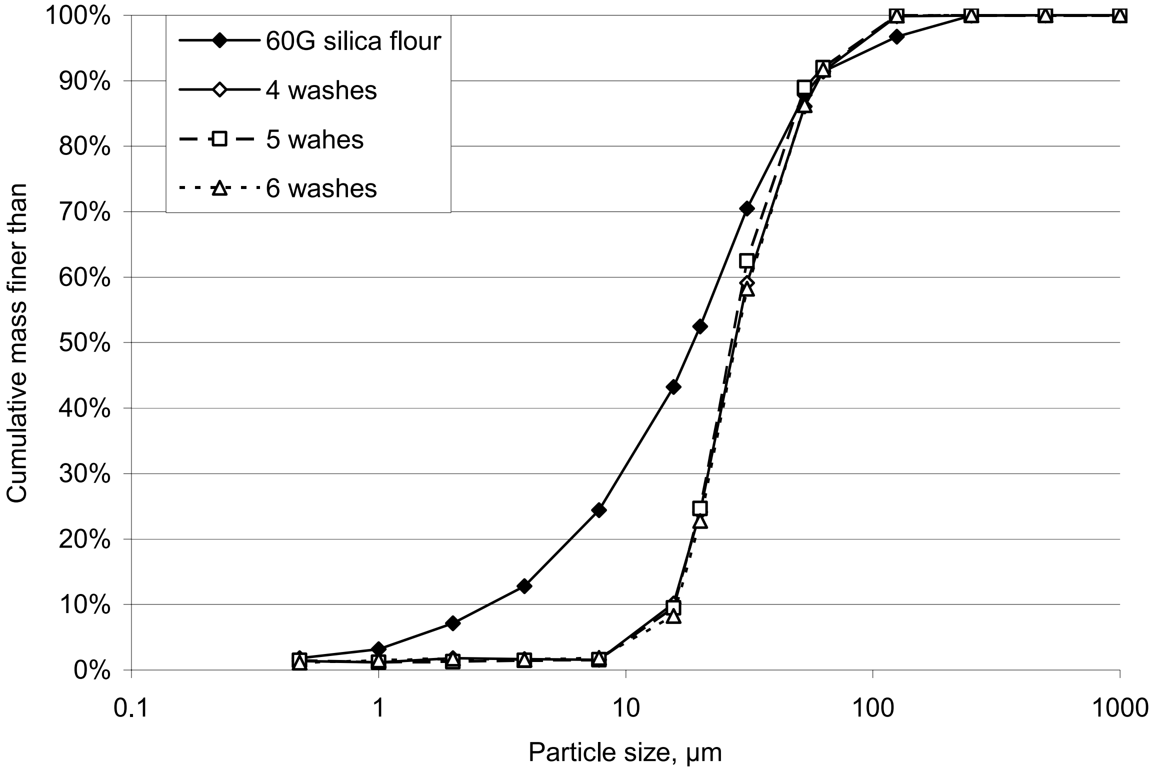


Fig. 10. Particle size distribution of ungraded 60G silica and after being washed 4 to 6 times. Washing reduces the proportions of particles less than 15 µm from 43% to 9%.

sufficient conductivity. Diatomaceous earth was considered because it maintains a high water content at quite negative potentials. However, it was discarded because it is very difficult to pack consistently. Silica flour is made by grinding sand and has many of the required properties. However, even the coarsest grade (60G) has a substantial proportion of fine particles less than 10 µm that could block the filter. We therefore developed a method of grading silica flour to remove the fraction less than 20 µm.

The silica flour was graded in a 50 L tank with an outlet positioned 464 mm from the top. The tank was filled with water and a 3 kg batch of flour introduced near the top of the tank. This was allowed to settle for a time determined by the size of particles to be removed, the temperature of the water and the distance over which the particles have to settle (464 mm). For example, a 20 µm particle will have travelled 464 mm through water at 20°C after 22.25 minutes. Coarser particles will have travelled further and finer particles less far. After the settling time had elapsed the outlet was opened to discard water with the fine material. The retained material was removed; the tank refilled and the process repeated three more times. Although the process is extremely time-consuming it produces a product in which there is almost no material less than 15 µm.

The properties of the graded silica flour were analysed. The grading process described is very successful at removing the finer particles (Fig. 10) to ensure they do not block the filter. The water retention curve of the material (Fig. 11) shows it has an air-entry potential of about -15 kPa and that at more negative potentials it rapidly looses water. The saturated hydraulic conductivity of the material is 25.6 mm/hr, which is sufficient to cope with flows from the soil unless water is flowing at the maximum rate possible for that layer (75 mm/hr). This is unlikely given the restrictive layer above. The flow rate in drier conditions is of more concern because of the rapid decrease in the water content of the silica flour. Although it was

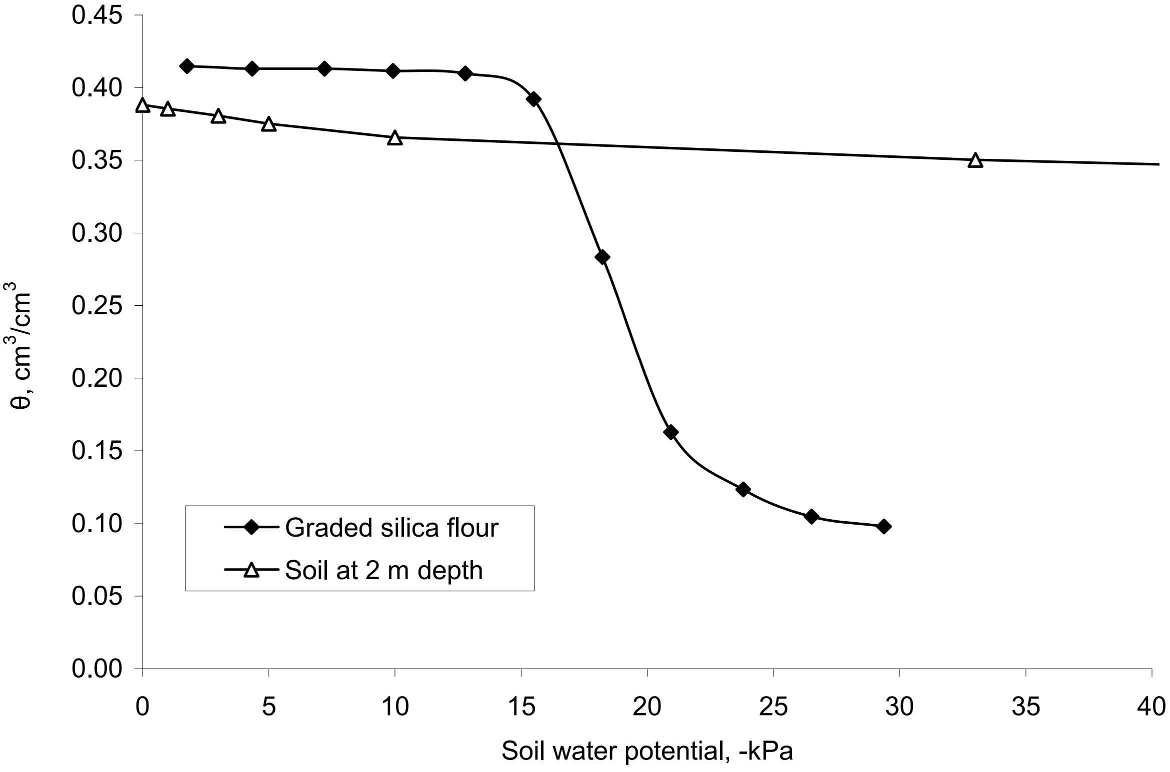


Fig. 11. Water retention by graded silica flour showing rapid decrease in water content for potentials more negative than the air-entry potential of -15 kPa. The soil at lysimeter depth is shown for comparison.

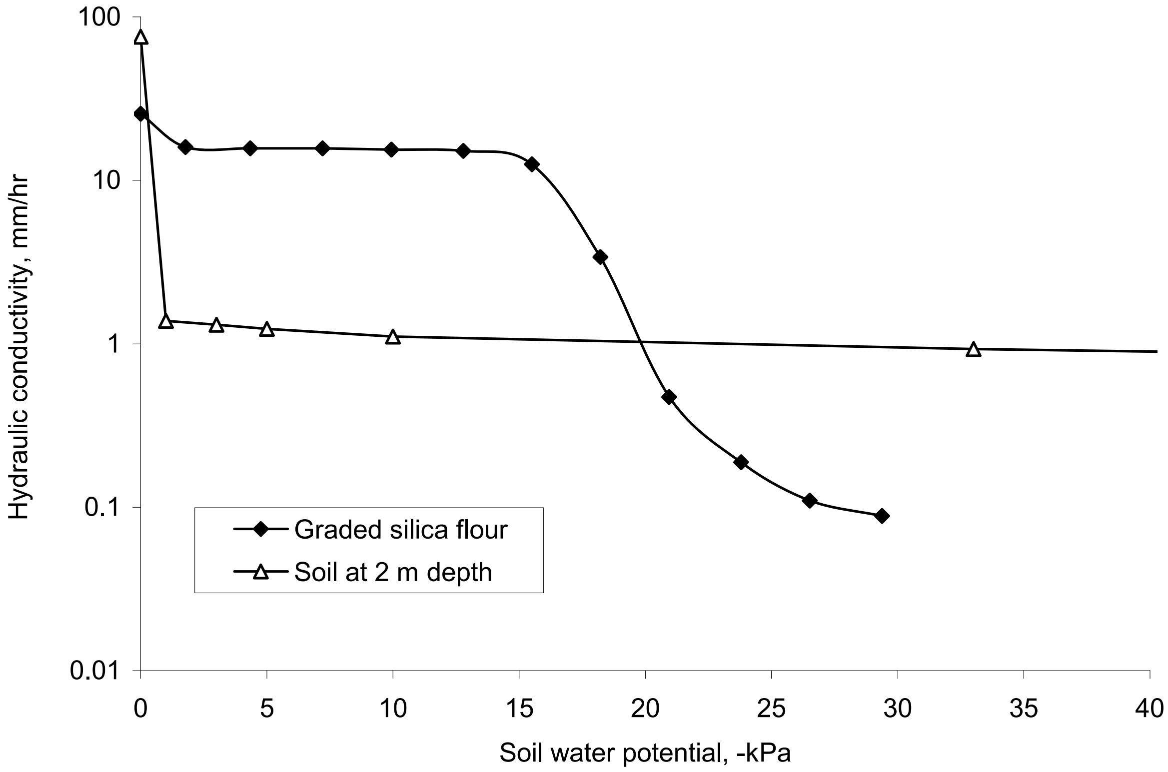


Fig. 12. Comparison of hydraulic conductivity in graded silica flour and in soil at lysimeter depth. The values at saturation are measured, other values are estimated from the water retention curve using Kozeny-Carman calculations and measured conductivities at saturation (silica flour) or -1 kPa (soil).

not possible to measure conductivities in these conditions, they were estimated using Kozeny-Carman calculations (Kozeny 1927, Carman 1937). The estimates show the conductivity at a potential of -30 kPa is in the same order of magnitude as the soil (Fig 12).

Access shaft

To allow the lysimeter to be installed at 2.1 m depth, below the root zone of cotton, a cylindrical access shaft was constructed of reinforced concrete (Figs 13, 14 and 15). The external dimensions of the shaft are 3515 mm in height and 2006 mm in diameter. The walls are 117 mm thick, the ceiling 250 mm and the floor 350 mm. The thickness of the floor is to give the whole shaft negative buoyancy. The roof is at 485 mm depth. The shaft was built in three sections which were joined at installation using concrete adhesive. There is a rectangular cut-out in the side of the shaft 400 mm high and 1000 mm wide, through which the trays could be installed. The top of this cut-out is at 2050 mm depth. The extra depth of the shaft below the cut-out is to allow sufficient work space. There are also circular cut-outs to allow installation of tensiometers.

The shaft is connected to the surface by a galvanized steel entrance hatchway 600 × 1000 mm in cross section and 600 mm high. The base is set into the concrete ceiling and the top is just clear of the surface. The hatchway is covered by a hinged lid that sits on an outwards pointing flange. When closed the lid and flange are bolted together with a gasket between them to seal the shaft. A ladder allows access down the shaft. It is attached to one short wall of the hatchway and to the concrete floor.

The sunken ceiling was designed to prevent obstruction of the irrigation furrows, which continue over the shaft. The hatchway is positioned so that its long side is parallel to the furrows. The short side is positioned relative to the hill so that a tractor wheel can pass in the furrow to the north. Although the hatch occupies more of the furrow to the south, it does not impede water flow during irrigation. The southern most side of the concrete shaft lies under the northern boundary of the plot.

To comply with safety regulations an aluminium guard rail is attached to the flange on the hatchway when the hatch is open to prevent people falling into the shaft and to provide an upwards extension of the ladder. Work in the shaft is covered by confined spaces regulations. This requires all people operating in the shaft to have training in safe operating procedure. A standby person with the same training is to be present at the surface whenever someone is in the shaft. The atmosphere in the shaft is tested before and during entry. A mast with a winch is attached to the ladder when the hatch is open. Persons working in the shaft are attached to the winch. This allows recovery from the surface in case of injury. The winch also provides fall-arrest when climbing the ladder.

The access shaft was installed by drilling a 4000 mm deep hole with a diameter of 2100 mm using a bucket drill. This first drilled a 1000 mm diameter pilot hole to 5000 mm. A reaming arm was then used to carve out the extra diameter. Before installing the shaft, the extra 1000 mm depth of pilot hole was filled with concrete to prevent its collapse causing subsidence of the shaft. The shaft was lowered in by crane one section at a time. The annulus outside the concrete was backfilled with granular soil and tamped in.

A potential problem with the sunken roof is that irrigation water or heavy rain could saturate the soil over the roof and ‘spill’ over into the surrounding soil where it might interfere with hydraulic gradients around the lysimeter. To prevent this, a drainage system was installed over the roof as follows. A trench about 3 m long was excavated from the tail ditch side of the shaft, parallel to the furrows and sloping downwards away from the shaft. A sump was excavated at the end. The hole above the roof (485 mm deep) was lined with plastic which was cut off about 100 mm above the roof. A length of plastic agricultural drainage piping was

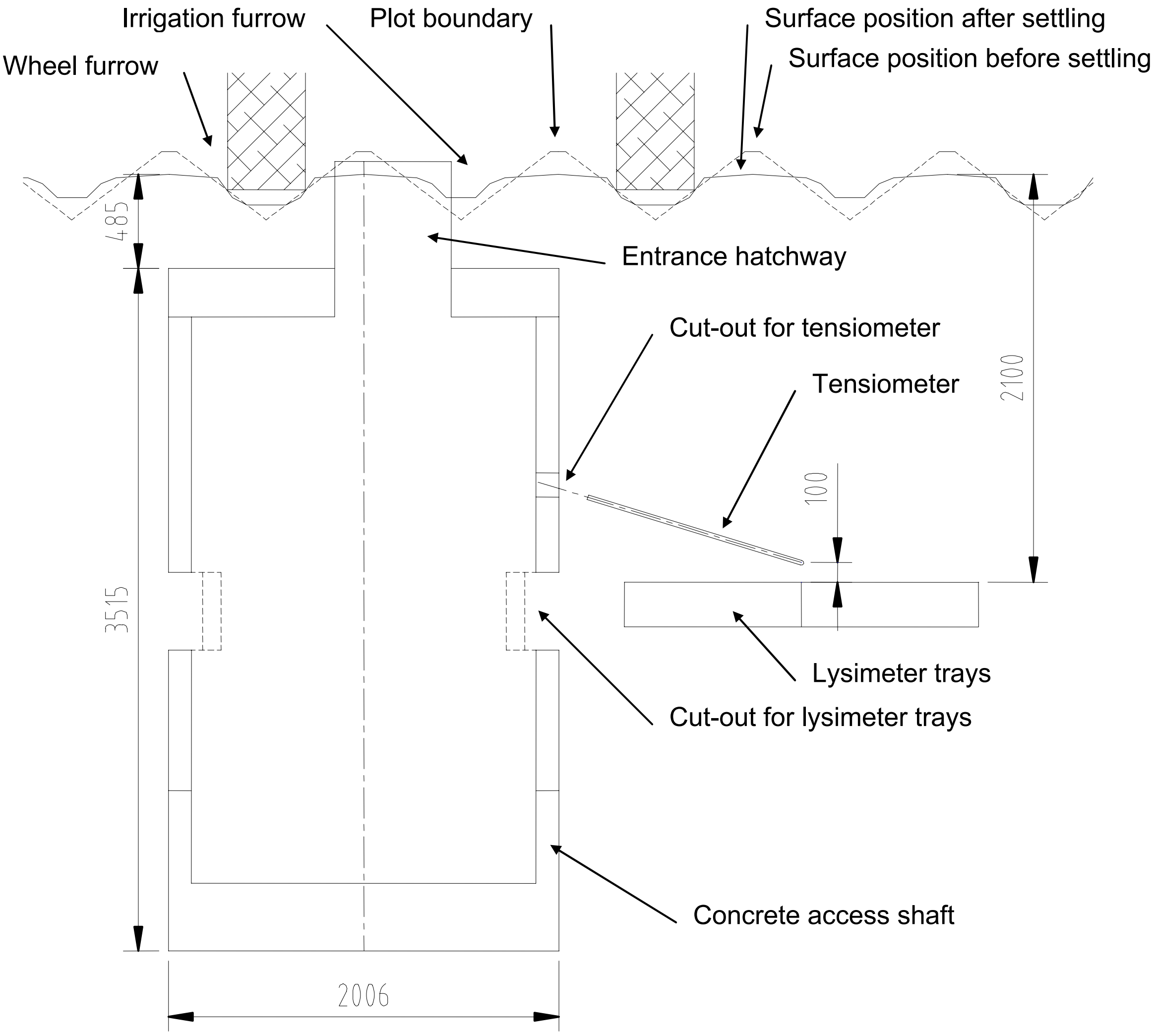


Fig. 13. Vertical cross-section through the centre of the access shaft at 90° to the furrows. Dimensions in millimetres.

placed around the circumference of the hole inside the plastic liner. The two ends were run down the trench to the sump. The hole above the roof was part-filled with gravel to cover the piping and the soil replaced above the gravel. In the trench the piping was wrapped in plastic sheet to direct drainage water to the sump. The trench was back-filled with soil. The lower part of the sump was filled with gravel, whilst the upper part was filled with soil.

Lysimeter installation

The six lysimeter trays were installed in a block 1820 mm long and 866 mm wide. Trays were installed two at a time so that the tunnel required was only 290 mm wide, minimizing the likelihood of the ceiling collapsing. To install a pair of lysimeters tunnels 2.2 m long were excavated using a steel cutting box, which cut a tunnel 290 mm wide and 232 mm high, with sharp cutting edges. This was inserted in increments of about 250 mm as follows. The bulk of the soil was removed by drilling 6 horizontal holes about 250 mm long with a soil auger through the cutting box. The soil between the holes was broken away and scraped out. The cutting box was then pushed in using a pit prop pushing against the opposite wall of the access shaft. Care was taken to ensure the direction of travel and the alignment of the box were correct. This was repeated until the full length had been excavated. The cutting box was then dismantled so it could be removed from the tunnel.

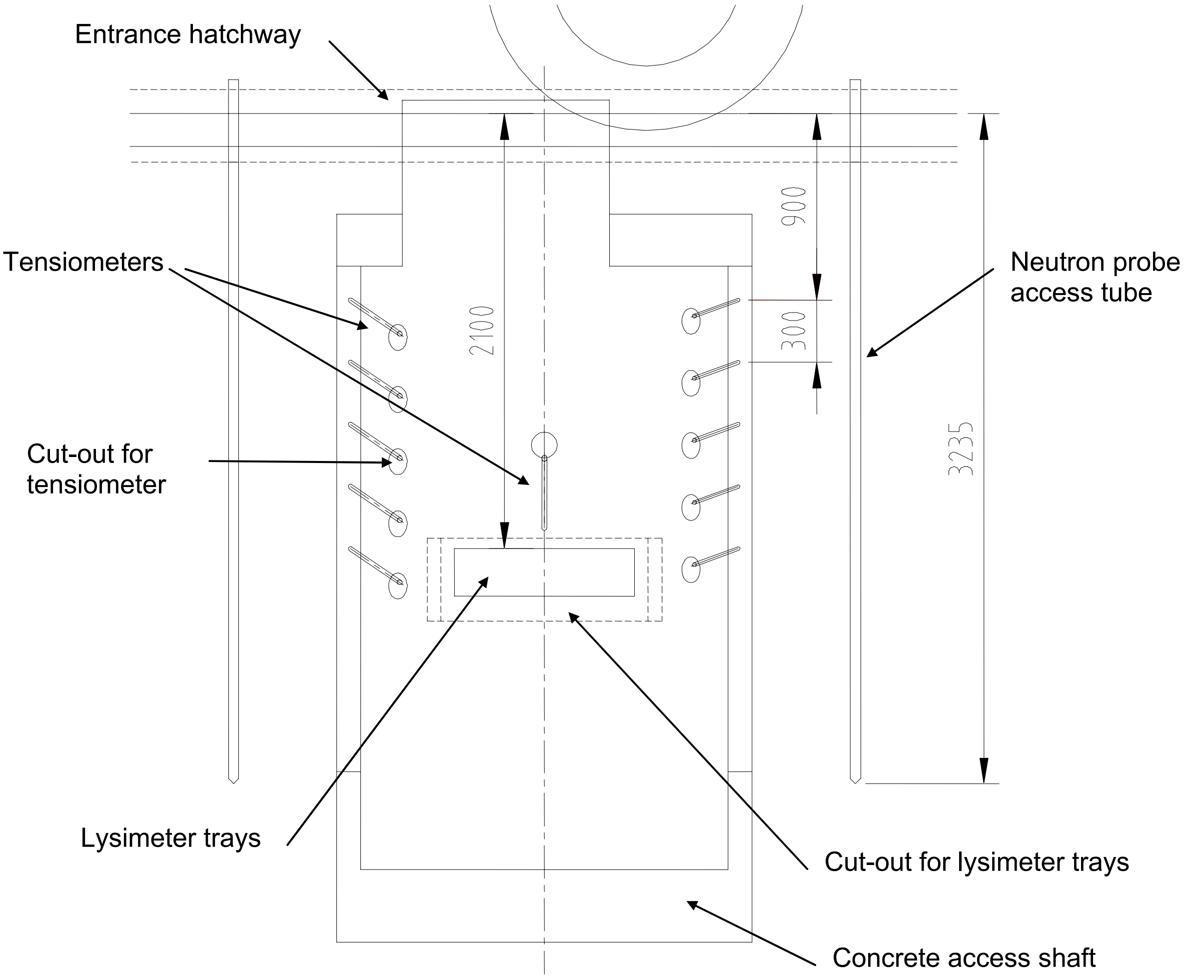


Fig. 14. Elevation view (from south) of access shaft, lysimeter trays, tensiometers arrays and neutron probe access tubes.

Unfortunately, the tunnel occasionally intercepted slickensides causing large lumps to fall from the ceiling leaving it with more relief than planned.

The sharp cutting blades of the box smeared the surfaces of the tunnel. It was important to remove the smearing because it could interfere with drainage. This was done by peeling a thin layer from the ceiling as follows. First the ceiling was dried using a heat gun. A paint roller was used to apply a generous layer of epoxy resin to the ceiling. A layer of foam rubber covered with fibreglass and placed on a wooden board was soaked in resin and jacked up against the ceiling. The resin was allowed to cure for 24 hours before the board and foam rubber were peeled away pulling a thin layer of soil with them and revealing a natural face.

The shoring boxes were installed in the tunnels first, followed by the lysimeter trays, loaded to their upper lip with 25 mm depth of graded silica flour. The graded silica flour proved extremely difficult to form to the relief of the ceiling because it did not flow. In addition, the cavities formed when bits of the ceiling fell away were up to 50 mm high and required careful packing to ensure contact. This involved leaving a gap of about 15 mm between the lip and the ceiling to allow lumps of silica flour to be pushed in and rammed towards the back of the trays. This proved very time-consuming and resulted in a much greater thickness of contact material than intended. With hindsight, the trays would have been better without the front lip (facing the access shaft).

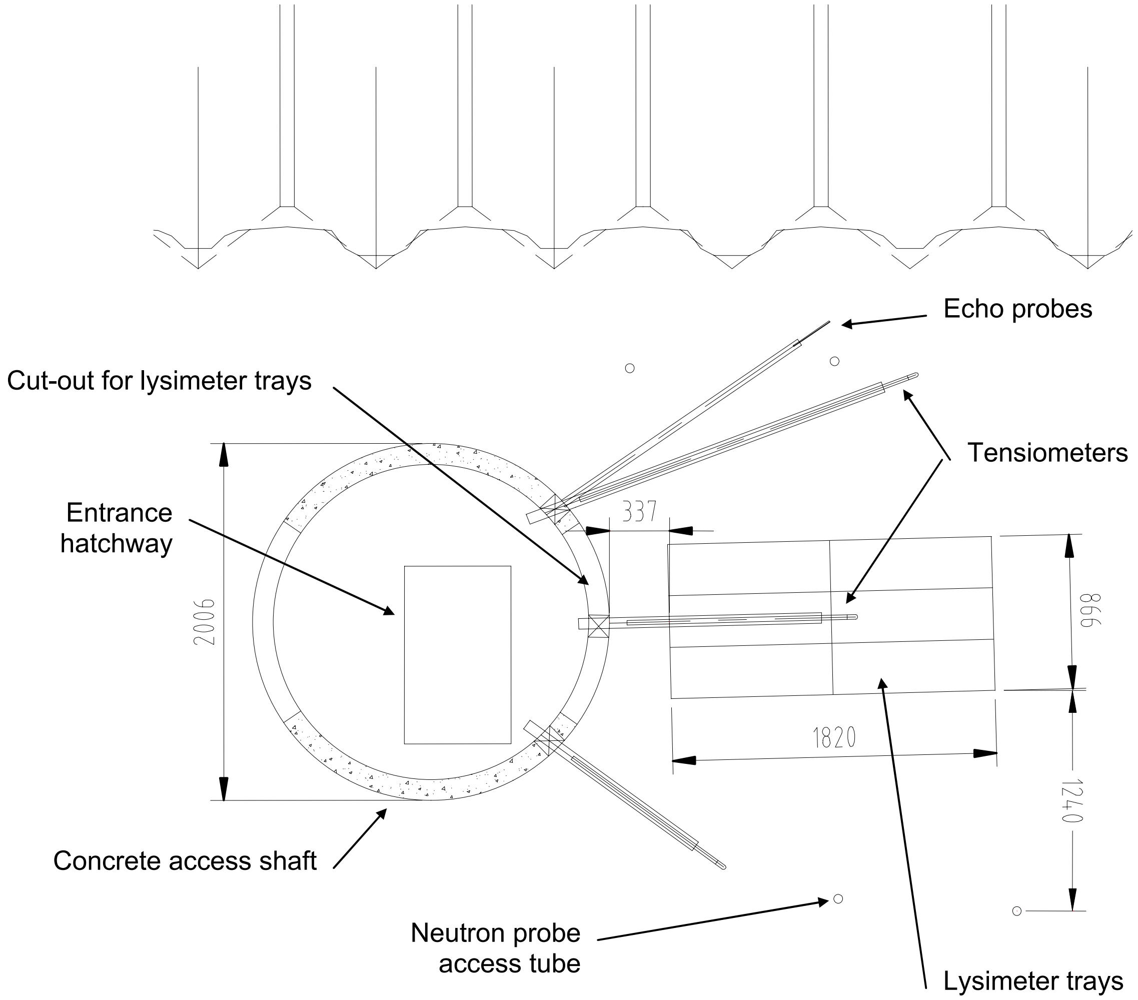


Fig. 15. Plan view of lysimeter trays, access shaft, and other instruments.

After packing the contact material, the end of the shoring box was attached. The three pairs of trays were installed sequentially. After installation the gap between the trays and the concrete was filled with native soil, air-dried and ground to less than 2 mm. A wooden barrier coated in fibreglass was used to block the hole in the concrete, and its edges were sealed with expanding foam.

Instrumentation

Two arrays of five tensiometers were installed at 300 mm intervals from 900 to 2100 mm depths (Figs, 13, 14 and 15). The lowest two tensiometers are used to control the vacuum in the trays. Another tensiometer was installed immediately above the trays with the intension of monitoring whether water is building up above the trays due to restricted conductivity.

The vacuum tubes from the trays are connected to a vacuum manifold and a pressure transducer. The manifold is also connected to a vacuum reservoir that is kept at -40 to -45 kPa by a vacuum pump and pressure switch. A data logger records the soil potential at 15 second intervals and averages them. It also measures the vacuum in the trays and determines whether it requires adjustment. If the vacuum needs increasing it opens a solenoid to connect the trays to the vacuum reservoir until the vacuum is great enough. If the vacuum is too great it opens another solenoid to connect the trays to the atmosphere.

The drain tube from each tray is connected to a cylindrical steel measuring vessel that hangs from a bracket on the wall of the access shaft. The vessels are also connected to the vacuum manifold. The vessels hang from a strain gauge that allows continuous monitoring of the amount of drainage water collected in each vessel. The vessels can be isolated from the vacuum system to allow emptying.

In addition to the tensiometer arrays, four neutron access tubes were installed around the lysimeter (Fig. 15) to allow regular monitoring of soil water content. An array of Echo capacitance probes is installed near one of the access tubes to allow continuous, but less accurate, monitoring of soil water between neutron probe measurements.

All the instruments are powered by a 12 V rechargeable battery, recharged by a solar panel, with lightening protection between the solar panel and all other equipment which is housed underground.

Alternative methods to measure drainage

One objective of the project is to test the accuracy of other methods. Various other methods have been installed near the lysimeter or will be used in its vicinity.

Barrel lysimeters have been installed at 2 m depth near the main lysimeter by D. McGarry (Queensland Department of Natural Resources and Mines). These are much less expensive to install but apply a constant potential to the base of the lysimeter barrels. In addition, their installation requires considerably more soil disturbance above the lysimeter than the main lysimeter.

Chloride mass balance determinations have been and will continue to be made in the plot to estimate drainage (N. Hulugalle and T. Weaver, NSW Department of Primary Industry).

Attempts to close the water balance using other components will also be made.

Resistivity imaging has been trialled at the site by B. Kelly (University of Technology, Sydney) and I Ackworth (University of New South Wales) and will be trialled again. This method uses a linear array of electrodes on the soil surface to provide an image of the resistivity of the soil over the whole plot length and down to several metres depth. If these images can be calibrated to estimate water content, they provide a potentially useful tool to investigate the movement of wetting fronts and their variability across whole paddocks.

Finally, wetting front detectors have been installed nearby by R. Stirzaker (CSIRO Land and Water) to investigate their potential for the tactical management of irrigation in cotton.

Results

The lysimeter was opened and commenced commissioning on 13 September 2006. Consequently there are no results to report yet. Results will be obtained during a three year replacement project from July 2006 to June 2009.

Outcomes

The absence of results means the planned outcomes in terms of improved knowledge of drainage processes, improved water balance models and testing of alternative methods have not occurred. These outcomes are now planned during the replacement project.

Several technical achievements were made during the project.

- Plans of the improved design of lysimeter trays are available. The facility is designed to have an operating life of at least 10 years.

- An access shaft was designed for use in furrow irrigated soil that does not impede the flow of irrigation water, and minimises excess water spilling into the surrounding soil by using a drainage sump. Plans of the shaft are available.

- A contact material consisting of graded silica flour was designed, together with a method of production. Analysis of the material indicates it has suitable properties.

- A tunnelling method was designed and used to install the lysimeters over distances up to 2 m.

- A method of preparing a natural surface on the ceiling of the installation tunnel was designed involving the use of an epoxy resin peel. This removes any smearing created during excavation which might interfere with drainage.

- A fully automated control and measurement system will allow the lysimeter to operate without manual intervention for several weeks at a time, for example during floods.

Conclusions

The main conclusion to date is that building a variable tension drainage lysimeter is considerably more challenging and expensive than anticipated. Projects of this type might be better preceded by a short pilot project to study the feasibility of the task and to better cost and calculate the resources required. This exercise itself requires more resources than are commonly put into a research funding proposal. The results of the pilot project could then be used to determine whether to proceed to a full scale project.

Extension opportunities

Although the lysimeter has only recently been opened, it has received many visitors including growers, students and researchers. These visits, including the official opening, have been valuable opportunities to explain that drainage can and does occur under heavy clay soils.

Future results will be disseminated indirectly through improved water balance modelling and better validated measurement techniques. In particular, better process understanding can be incorporated into more efficient irrigation methods and into computer tools such as Hydrologic.

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Part 4 – Final Report Executive Summary

Drainage from below the plant root zone is not only a waste of water resources but a potential driver of rising water tables and salinity. Better estimates of the quantity and timing of drainage are required in the clay plains of the northern Murray Darling Basin to improve understanding of drainage processes, in particular under irrigation. This will allow better assessment both of how and where improvements can be made in irrigation management and of the risk of salinity. Current drainage estimates are based on indirect measurements – such as chloride mass balance – or on calculations using measurements or estimates of other components of the water balance. Both approaches lead to large uncertainties in drainage estimates. Direct measurements of drainage are difficult because most instruments disturb the hydraulic gradient in the soil, which is the main driver for drainage, and therefore affect the amount of drainage measured.

A variable tension drainage lysimeter was built at the Australian Cotton Research Institute near Narrabri to provide accurate measurements of drainage under an irrigated cotton-wheat rotation on a Grey Vertosol typical of the region. Such lysimeters are designed not to disrupt the hydraulic gradient by being ‘hydraulically invisible’ so as not to interfere with the rate of drainage. The lysimeter consists of an array of six steel boxes whose upper surface is made of a porous, sintered steel sheet that, once saturated, allows water to flow but can hold a vacuum of up to -32 kPa. The boxes were installed at 2.1 m depth via tunnels excavated horizontally from a concrete access shaft. Thus the soil over the trays is undisturbed. The trays cover an area of 1.8 × 0.9 m. A method of preparing the soil on the ceiling of the tunnel was developed that uses a resin peel to remove any smearing. A contact material to connect the upper surface of the tray to the soil ceiling was designed and manufactured by grading silica flour.

The system mimics the hydraulic gradient in the soil by regularly measuring the soil water potential at 2.1 m depth with tensiometers and then applying a vacuum equal to this potential to the inside of the trays. A data logger continuously adjusts the vacuum to the soil water potential. Water in the soil above the trays therefore experiences the same hydraulic gradient as if the trays were not there and flows at the same velocity into the trays. The trays have sloping floors which direct the water to a drain and thence to cylindrical collection vessels that are continuously weighed allowing the rate of drainage to continuously measured. The system is designed to be fully automated.

Apart from providing accurate measurements of drainage over time, the lysimeter will be used as a benchmark against which to test other simpler – and less expensive methods – that can be deployed in a wider range of situations. Barrel lysimeters, wetting front detectors, and instruments to measure other water balance components have been installed near the lysimeter. Chloride mass balance measurements are also regularly made nearby.

In addition, the data from the lysimeter will be used to improve water balance models that provide the only way of estimating the long-term drainage of current and alternative management systems for a variety of soil and climatic conditions.

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