Rapid estimation of soil water retention functions

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Abstract
Accurate and spatially dense data on the hydraulic functions that control water movement in soils is becoming increasingly important, particularly for crop models and farmer decision support tools. The paucity of this data is the result of the time consuming laboratory techniques involved. Inverse modelling of multistep outflow experiments (MSO) has been proposed as a rapid and accurate technique to obtain the soil water retention function, $\theta(h)$. In this study MSO experiments were carried out using modified Tempe cells and undisturbed soil cores from two depths and three soil types representative of the cropping areas in NW Victoria, Australia. Each core was run through seven desorption runs that varied in the number of pressure steps and the length of time each pressure step was maintained. The inverse modelling produced $\theta(h)$ curves that, except at the very wet end, resembled closely the shape of those produced from equilibrium data. However, the inverse modelled $\theta(h)$ curves over-estimated the air entry region which had the consequence of causing the $\theta(h)$ function to over-estimate the soil water content at all matric potentials. The choice of the number of pressure steps and the length of time maintained at each step had little effect on $\theta(h)$.

Key Words
Multistep outflow, inverse modelling, retention curve, water holding, PAWC.

Introduction

The most important soil factor that controls yield in much of the Australian grain production regions is the quantity of plant available water (e.g. Rab *et al.* 2009). Prediction of the spatial distribution of soil water, and its availability to plants, will enable growers to make more informed production decisions that maximise profitability (e.g. the management of nutrients and crop canopies). For example, with accurate meteorological data and knowledge of the spatial variability in soil hydraulic properties, a dynamic soil water model can provide accurate soil water predictions. If this information is coupled with a spatial crop model it should be possible to provide a credible alternative to other techniques (such as real time NDVI prediction) for predicting the optimal spatial application of nutrients. However, the factors that control soil water retention are extremely spatially variable, both across the landscape and with depth. Despite the need for information on soil hydraulic properties there is generally a paucity of such data due to the time consuming and labour intensive techniques required for their accurate measurement. Therefore the objective of this work was to evaluate a relatively rapid and more automated methodology based on the inverse modelling of multistep outflow experiments (Hopmans *et al.* 2002).

Methods

Multistep outflow experiments were carried out using 20 individual pressure cells (Tempe cells, Soilmoisture Equipment Corp.) imported from the USA and modified for use with the metric soil cores used in Australia. They were also modified in a similar fashion to that suggested by Eching *et al.* (1994), incorporating a 6 mm diameter tensiometer inserted through the centre of the top of the Tempe cell that could then be inserted into the centre of the soil core. These micro-tensiometers were connected via a pressure transducer to a Smart Logger® (ICT International) to record the actual pressure within the soil matric. An inlet was added, off-centre, in the top of the cell and connected to a nitrogen cylinder via a pressure regulator and a pressure gauge. A pressure transducer connected to the Smart Logger® recorded the applied pressure from the nitrogen cylinder. The drainage connection at the bottom of each cell was connected to individual burettes and the water level was recorded by the Smart Logger® via a pressure transducer.

The applied pressure, water outflow, and soil matric potential were recorded while an initially saturated soil core was subjected to a series of increasing pressure steps. To obtain the soil water retention function, $\theta(h)$, a numerical hydraulic model is coupled with a parameter optimisation algorithm to minimise the deviations between the observed and simulated flow variables in the objective function (e.g. Eching and Hopmans 1993). The Shuffled Complex Evolution Metropolis algorithm was used to solve the least-squares optimisation problem (Vrugt *et al.* 2003).

The inverse multistep outflow methodology was tested using three replicate intact cores from two depths (0-10 and 20-30 cm) from three representative soils found in the main cropping areas of the Victorian Wimmera/Mallee region (i.e. Red Sodosol, Hypercalcic Calcarosol, and Grey Vertosol, classified according to the Australian Soil Classification (Isbell 2002). The cores were run through a series of seven desorption runs and were re-saturated between each run. Each desorption run varied in either the number of pressure steps or the length of time each pressure step was maintained. For the initial run each pressure was maintained until the sample reached equilibrium.

Results

The three soils varied greatly in their soil texture (Table 1). The equilibrium data showed that the three replicates at each of the three soil types were very similar for the 20-30 cm depth, confirming the uniformity of the soil structure at that depth range at each site. While for the 0-10 cm depth, the variability between the replicates increased with increasing clay content. The experimental setup generally produced good data from the sensors during the multistep experiments. To ensure the inverse modelling obtained a unique solution, the possible range of the van Genuchten parameters were constrained to values that corresponded to three broad soil texture groups (sand, loam, and clay) depending on the approximate soil texture of the sample. However, greater inverse modelling experience with Australian soils is required to obtain the optimum restrictions on the search range used.

Table 1. Particle size analysis for soils at the study sites.

Location	Soil depth (cm)	Clay (%)	Silt (%)	Fine sand (%)	Coarse sand (%)
Red Sodosol	0-10	1	2	21	76
	20-30	2	2	38	58
Hypercalcic Calcarosol	0-10	20	8	26	45
	20-30	31	10	21	39
Grey Vertosol	0-10	49	30	14	7
	20-30	49	30	15	7

The inverse modelling produced a good fit between the actual and predicted values for matric potential and outflow (e.g. Figure 1). However, the values of the van Genuchten parameters (which define the soil water retention function) obtained from the inverse modelling resulted in the soil water content being over predicted at most of the matric potentials in the retention function (e.g. Figure 2). This was progressively worse the higher the clay content. The general shape of soil water retention curves produced from the inverse modelling match those from the equilibrium data, however the inverse modelled retention curves over-estimated the air entry region that is controlled by the van Genuchten alpha parameter and is related to the inverse of the air-entry pressure. It is thought that one possible cause of this over-estimation of the soil water contents in the inverse modelled retention curve is the exclusion of water outflow data from very low tensions (<4 kPa). This data was excluded to ensure that the cores were unsaturated at the start of the experiment. The benefits of including this data are now being considered. Despite this over-estimation, the gradient of the functions are similar for both the equilibrium and inverse modelling over most of the range of matric potentials and hence the estimated values of PAWC are relatively similar in both cases.

The inverse modelling technique resulted in very similar estimations of the retention curves irrespective of the seven different desorption runs. This suggests that the inverse modelling is extremely robust, irrespective of the exact combinations of the number of pressure steps or the time that the pressure is maintained (within the range tested). It is therefore anticipated that once the cause of the over-estimation in the air entry region is eliminated this experimental procedure is likely to produce reliable results and that just a few days will be required per test to obtain sufficient data for inverse modelling.

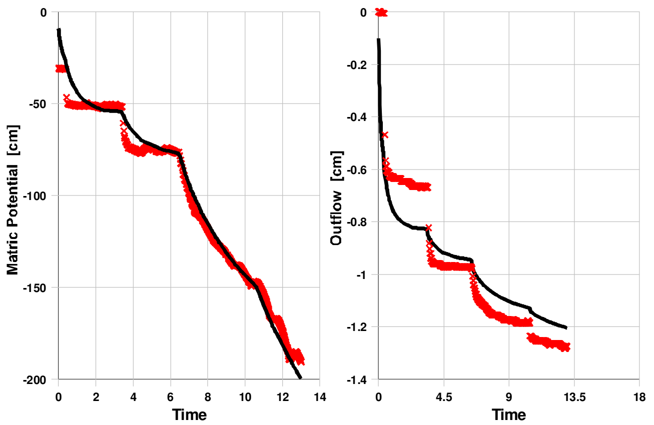

Figure 1. Measured matric potential and outflow (red markers) and the inverse modelled values (black lines) for the 0-10 cm Red Sodosol.

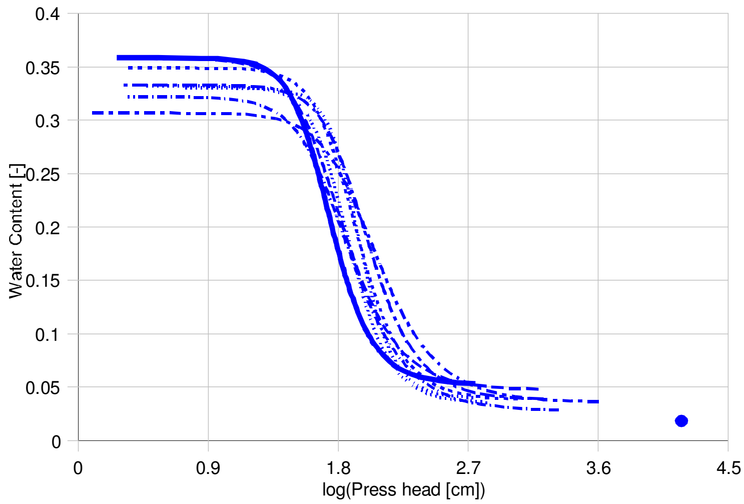

Figure 2. Best fit van Genuchten function curves for the equilibrium retention points for the 0-10 cm. Sodosol (solid line) and inverse modelling results for the 7 different desorption runs (broken lines). Dot marks the measured 1500 kPa retention point.

A further advantage of the data logging system used in this setup is that the outflow can be constantly monitored. In the soils tested, which ranged from 1 to 49% clay, the volume of outflow that occurred after pressure testing to 80 kPa in 4 days ranged between 65 and 88% of the quantity of outflow from the equilibrium test to 80 kPa (Table 2). The soil water content at each of the pressure steps in the rapid multistep outflow experiment provides pseudo retention points. Estimating the soil water retention curve using these pseudo retention points and the 15,000 kPa retention point resulted in retention curves that closely match the equilibrium retention function. This provides an alternative, or cross-checking, approach to the inverse modelling technique.

Table 2. Total outflow between the applied pressures of 4 and 80 kPa for the equilibrium desorption (Run 1) which consisted of a total of 6 pressure steps over 35 days and Run 2 which consisted of 4 pressure steps maintained for 1 day each (total of 4 days), and the fraction of outflow after 4 days compared to 35 day for each of the soil cores.

	Red Sodosol 0-10 cm			Red Sodosol 20-30 cm			Hyp. Calcarosol 0-10 cm			Hyp. Calcarosol 20-30 cm			Grey Vertosol 0-10 cm			Grey Vertosol 20-30 cm		
	Cumulative outflow (ml)																	
Run 1	53.0	54.7	48.7	60.2	31.9	46.2	...	33.8	43.2	23.7	22.2	25.2	30.0	...	26.8	26.6	28.9	29.4
Run 2	42.6	46.5	42.7	42.9	26.5	37.2	22.8	23.9	33.3	17.6	17.7	17.2	20.0	18.2	19.2	17.5	18.7	19.9
	Cumulative outflow from Run 2 as a fraction of Run 1																	
	0.8	0.85	0.88	0.71	0.83	0.8		0.71	0.77	0.74	0.79	0.68	0.67		0.71	0.66	0.65	0.68

Conclusion

This work has demonstrated that accurate estimation of the soil water retention function for intact cores can be reduced from several weeks of labour intensive work to a semi-automated test that can be completed in a few days. This test can therefore be integrated into a suite of rapid soil testing techniques (including mid-infrared and electromagnetic induction) to provide improved information about soil hydraulic properties for scientists and growers. Further research is required to validate the technique for Australian soils, especially those with high clay content and shrink-swell properties.

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