Department of Primary Industries

Irrigation Research South

Optimising sub-surface drip irrigation design for the Australian processing tomato industry: moisture characteristics of two Riverine plains soils.

www.dpi.nsw.gov.au

Published by the NSW Department of Primary Industries

Optimising sub-surface drip irrigation design for the Australian processing tomato industry: moisture characteristics of two Riverine plains soils.

First published August 2021

ISBN number

More information

Sam North & Don Griffin, Water Research South, Deniliquin, 2710

www.dpi.nsw.gov.au

Acknowledgments

This project was made possible with funding from the Australian Processing Research Council (APTRC). Thankyou to Kagome staff and the Weeks family for access to the soil sites and to Alex Schultz, NSW DPI, for the loan and assistance with the loggers.

Reference number INT21/117667

Contents

Executive summary 4
Introduction 5
Methods 5
Results 8
Prediction of K_{sat} for the A horizon of the duplex RBE 8
Soil water characteristic curves 10
Duplex RBE – Bunnaloo loam 10
Uniform clay – Rochester clay 11
Soil hydraulic properties 13
Discussion 14
Conclusions 16
References 16

Executive summary

Moisture characteristic curves were fitted to volumetric water content and matric potential data obtained from two contrasting soils: a duplex red brown earth (Bunnaloo loam; chromosol); and a uniform clay (Rochester clay; vertosol). The data was obtained from calibrated frequency-domain, capacitance water sensors and granular-matrix, matric potential sensors connected to loggers. The logger data gave narrower 95% confidence limits and covered a wider range of soil water content/potential readings than was possible to collect using manual gravimetric sampling.

The hydraulic parameters obtained from this logger data (table below) are recommended for use in modelling water flows from sub-surface drip irrigation in these two soils for the purposes of aiding better irrigation design.

Hydraulic parameters for use in modelling flows in the duplex RBE and uniform clay obtained from paired, calibrated standardised EnviroPro readings and Watermark matric potential readings.

Parameter	Units	Duplex RBE		Uniform clay
		10 cm	20-50 cm	0-50 cm
θ_s	*(m/m)*	0.38	0.35	0.38
θ_r	*(m/m)*	0	0	0.09
α	(cm^{-1})	0.0105	0.0060	0.0086
n		2.354	2.204	1.121
K_{sat}	*(cm/day)*	76*	12	46
R^2		0.86	0.93	0.56

Introduction

The Australian processing tomato industry has set a target to lift yields from the current average of 90 t/ha (ABS, 2018) to 200 t/ha. Soil constraints are considered a key area for improvement to meet this target. Low pH, high salinity, migration of clays away from drip emitters, and coalescence of continually wet soil have been identified as issues affecting soil structure and thus water and oxygen supply to plants (Barber *et al.*, 2001; Lanyon and Kelly, 2010). However, efforts to improve soil structure with liquid gypsum (Yong *et al.*, 2015) and mitigate waterlogging with oxygenation in drip lines have had no significant effect on yields (Brown, 2016).

A field study in the summer of 2019-20 (North, 2020) identified poor matching of sub-surface drip irrigation application rates to soil type as a potential yield limiting factor in the duplex red brown earth (RBE) soils (chromosols; Isbell & NCST, 2016) used by the industry. All nine crops in the study were irrigated using drip-tape placed at a depth of 20-25 cm with drippers spaced every 50 cm. Four crops had tape with 1.05 L/hr emitters, while the other five crops had tape with 1.6 L/hr emitters. A lack of replication within soil type, together with the influence of irrigation management, meant significant differences in the wetting patterns from these two emitter rates were not able to be detected. Consequently, further investigation was warranted to determine the influence of tape design on wetting patterns and deep drainage losses. A field trial to determine optimum tape designs for a range of soil types was considered too costly, given the number of different combinations of emitter rate, spacing, depth, and soil type that would need to be evaluated. Instead, a modelling approach was chosen because of the ease with which a large number of design permutations could be tested to determine a small number of theoretically optimum designs to assess in a field trial.

The HYDRUS model (https://www.pc-progress.com/en/Default.aspx?support-hydrus) is a Microsoft Windows based modelling environment for the analysis of water flow and solute transport in variably saturated porous media. The software for HYDRUS is readily available and well supported and it has been used to evaluate sub-surface drip irrigation systems internationally (e.g. Simunek *et al.*, 2012) and nationally (e.g. Cote *et al.*, 2003). The objective of the work reported here was to collect field soil moisture characteristic data from the two major soil types used by the industry (i.e. duplex RBEs and uniform clays) to use as input to the model.

Methods

Two sites were selected out of the nine previously used in the 2019-20 study: a uniform clay (vertosol, Isbell & NCTS, 2016; Rochester clay; Skene & Harford, 1964) at Strathallan, Victoria; and a duplex RBE (chromosol, Isbell & NCTS, 2016; Bunnaloo loam, Johnston, 1952) at Bunnaloo in NSW. Soil sampled in December 2019 was used to determine the particle size distribution and dry bulk density of the surface soil (0-5 cm) and the sub-soil at the level of the drip tape (20-25 cm). Saturated hydraulic conductivity at the depth of the drip tape was determined in May 2020 using constant head well permeameters (Amoozegar, 1989). The values obtained are shown in Table 1.

Table 1. Particle size distribution of the duplex RBE and the uniform clay from samples taken in December 2019 and saturated hydraulic conductivity (K_{sat} cm/day) from well permeameter measurements made in May 2020.

Soil type	Horizon	Clay %	Silt %	Sand %	Texture	Bulk density	K_{sat}
Duplex RBE (*Chromosol*)	0-5 cm	25	26	49	silty loam	1.05 g/cm^3	--
	15-25 cm	34	26	41	clay loam		12
Uniform clay (*Vertosol*)	0-5 cm	46	15	40	medium clay	0.99 g/cm^3	--
	15-25 cm	45	13	43	medium clay	1.31 g/cm^3	46

The water content-matric potential relationships in the wet range (0 to -1800 cm water) for these two soils were determined from paired measurements of volumetric water content (θv) and matric potential (ψ) at 10, 20, 30, 40 and 50 cm depths. Measurements of water content were made using EnviroPro® capacitance sensors (https://enviroprosoilprobes.com) calibrated for soil type. Measurements of ψ were made using Irrometer® Watermark™ sensors (https://www.irrometer.com). Loggers attached to the sensors recorded and stored readings made on the hour every hour.

Seven replicate pairs of θv and ψ sensors were installed 3-5 m apart in a uniform area of soil roughly 20 m by 10 m that was considered representative of the paddock. Each set of paired sensors was installed inside a 60 cm diameter steel infiltration ring which was driven 10 cm into the soil surface. Each ring was centred over the top of the drip tape and off previous traffic lanes/furrows (see Figure 1 and Figure 2). The EnviroPro capacitance sensor string was installed in the centre of the ring, with the five matric potential sensors installed 20 cm from it and equidistant from each other (Figure 3 left).

Water was ponded in the rings to a constant head (5 cm) after sensor installation (Figure 3 right) and 220 L of water was allowed to infiltrate the soil under each ring. Once all water had infiltrated, the soil in each ring was covered with straw for insulation and then plastic sheeting to prevent evaporation.

Soil samples were collected across a range of water contents to calibrate the capacitance water sensors using a thin wall soil corer to extract cores (4.4 cm diameter, 10 cm high) from within the rings at depths of 5-15, 15-25, 25-35, 35-45 and 45-55 cm depths.

The collected soil water data was used as input to the program RETC (van Genuchten *et al.*, 1998) to determine the best-fit model for the soil water retention curve and, from that, the theoretical pore-size distribution for predicting the unsaturated hydraulic conductivity functions of the two soils. The best fit model was determined according to the following criteria (van Genuchten *et al.*, 1991):

- maximum R^2;
- maximum T-value (T = mean / se mean);
- minimum standard error;
- minimum range in the 95% confidence interval.

Figure 1. Infiltration rings and logger set-up at the duplex RBE (Bunnaloo loam) site.

Figure 2. Infiltration rings and logger set-up at the uniform clay (Rochester clay) site.

Figure 3. Photo showing (left) the arrangement of sensors within each infiltration ring, with the green EnviroPro probe in the centre and the five Watermark sensors arranged equidistant around it; and (right) water ponded on the soil surface within a ring during soil profile wetting (right).

The specific mathematical form of the soil water retention function has no influence on the conductivity prediction as long as it describes the data accurately (Kosugi *et al.*, 2002). However, the range in measured water contents was limited to the range of the matric potential sensors (i.e. 0 to 200 kPa) so, to avoid high correlation between predicted parameters with such a narrow water range, the number of parameters to estimate was limited in RETC to find the best fit model. This included:

- determining θs from core samples taken in saturated soils.
- fixing θr at either 0, if $\theta r < 0.001$ on the first estimation, or at 0.09 for a clay soil; (Rawls and Brakensiek, 1982);
- restricting *m* and *n* to either m=1-1/n or m=1-2/n;
- fixing α if the correlation between *n* and α was greater than 0.98.

Saturated hydraulic conductivity was only measured at the depth of the drip tape, approximately 25 cm from the surface. Therefore, there was no measure of K_{sat} for the surface soil horizon in the duplex RBE. RETC contains a module called Rosetta™ that allows estimation of K_{sat}, from soil texture and bulk density. As Rosetta™ uses US/FAO particle size limits for the sand and silt fractions, particle size fractions for our samples were first converted to US/FAO fractions (Minasny and McBratney, 2001).

Results

Prediction of K_{sat} for the A horizon of the duplex RBE

K_{sat} values predicted from texture and bulk density using Rosetta™ for the B horizons of seven of the 2019-20 monitoring sites are shown alongside measured values in Table 2. There was good correspondence between measured and predicted K_{sat} at three of the seven sites: two duplex RBEs (Bunnaloo loam and Koyuga clay-loam) and one uniform clay (Rochester clay). At the other four sites, however, predicted Ksat was appreciably less (20-50%) than measured K_{sat}. This is attributed to structure in the clay sub-soils at these sites which allows higher flows through macropores under conditions of a small positive head, as was used for measuring K_{sat}.

Flows predicted by Rosetta™ will be based on an idealised, uniformly distributed range of pores sizes and thus the effects of structure, ped aggregation and macropores in allowing greater conductivity in saturated soils are not reflected in the predicted values of K_{sat}. This is supported by Figure 4, which shows that K_{sat} increases with cation exchange capacity across the seven soils examined. This is the opposite trend to that expected if texture determined K_{sat}, indicating the importance of clay surface charge on aggregation and structure, and hence water flows in these soils.

Greacen (1981) cites a K_{sat} value of 90 cm/day for the A horizon of sodic RBE soils, while Mehta and Wang (2005) found the average K_{sat} of the A horizon of Group 2 soils across the Shepparton, Rochester and Murray irrigation areas of northern Victoria was 65 cm/day (n= 112). The predicted K_{sat} value from Rosetta™ for the Bunnaloo loam was 76 cm/day. This is within the range reported in the literature, so was adopted for this study.

Table 2. Australian and US/FAO particle size fractions, bulk density and measured K_{sat} (cm/day) from the surface and the depth of the drip tape at seven of the 2019-20 tomato crop monitoring sites, together with the values of K_{sat} predicted by the Rosetta™ module in RETC.

	Depth *(cm)*	**Sand** *(%)*		**Silt** *(%)*		**Clay** *(%)*	**Bulk density** *(g/cm³)*	**K_{sat}** *(cm/day)*	
		Aus	US	Aus	US			**Meas.**	**Pred.**
Bunnaloo loam (MB)	20-25	41	21	25	45	34	1.3	**12**	**17**
Koyuga clay loam (BA Blk-6)	20-25	42	22	26	46	32	1.38	**13**	**11**
Rochester clay (WE)	20-25	43	30	13	26	45	1.31	**46**	**49**
Timmering loam (KR)	20-25	55	32	27	50	19	1.47	**48**	**11**
Tragowel clay (HE)	20-25	50	41	6	15	44	1.27	**55**	**29**
Cornella clay (KE)	20-25	42	29	13	26	45	1.34	**67**	**17**
Binabbin clay (MW)	20-25	49	37	10	22	42	1.35	**95**	**18**

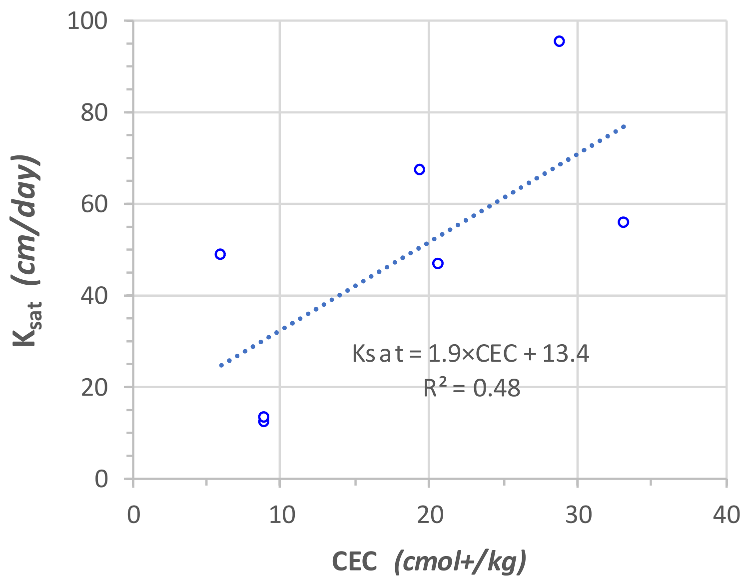

Figure 4. The relationship between measured K_{sat} and cation exchange capacity at seven of the 2019-20 tomato monitoring sites.

Soil water characteristic curves

Duplex RBE – Bunnaloo loam

There was a significant difference between the θ-ψ relationships for the 10 cm, the 20 cm and the 30 cm depths in the duplex RBE, but no significant difference between the 30, 40 and 50 cm depths. Separate moisture characteristics were therefore assessed in RETC for 10 cm, 20 cm and a combined curve for 30, 40 and 50 cm depths. Values of θs, θr and K_{sat} used as input in RETC to model the soil moisture characteristic curves of the three horizons in the duplex RBE are shown in Table 3. Data was fitted to the van Genuchten model with m = 1-2/n as this model gave the best fit to the data based on the R^2 of the regression and the standard error and T-value of the predicted coefficients (van Genuchten *et al.*, 1991). θr was set to 0 for all three horizons as modelled values were always < 0.01 and θs was determined from the average volumetric water content of saturated soils (ψ = 0 kPa).

Table 3. Parameters describing the hydraulic properties of the duplex RBE (Bunnaloo loam) determined from least-squares fitting in RETC (θs is saturated water content, θr is residual water content and α and *n* are fitting parameters). Soil water retention data was fitted to the van Genuchten model with m = 1 – 2/n using soil water content data obtained from soil cores (Gravimetric) and from calibrated EnviroPro sensor readings (Logger).

Depth (cm)	θ_v data source	θ_s	θ_r	K_{sat} ($cm\ d^{-1}$)	α (cm^{-1})	*n*	R^2
10	Gravimetric	0.38	0.0	76	0.0122 *(0.0035 – 0.0209)*	2.328 *(2.190 – 2.466)*	0.88
	Logger				0.0105 *(0.0091 – 0.0119)*	2.354 *(2.320 – 2.389)*	0.86
20	Gravimetric	0.36	0.0	12	0.0181 *(0.0065 – 0.0296)*	2.148 *(2.105 – 2.190)*	0.94
	Logger	0.35			0.0060 *(0.0054 – 0.0066)*	2.204 *(2.189 – 2.220)*	0.93
30,40,50	Gravimetric	0.35	0.0	12	0.0113 *(0.0050 – 0.0176)*	2.121 *(2.086 – 2.155)*	0.83
	Logger				0.0045 *(0.0040 – 0.0050)*	2.224 *(2.200 – 2.247)*	0.86

Separate model runs were done with the gravimetric core data and the logger data to check the calibration of the EnviroPro sensors. The results showed the soil moisture characteristics modelled from the two data sets at 10 cm were similar (Table 3). However, the modelled best-fit curves obtained from the gravimetric data were different to the curves from the logger data at the 20 cm and the 30-50 cm depths (Figure 5), particularly at the drier end of the curve. All curves obtained from the gravimetric data had greater 95% confidence limits compared to the curves fitted using the logger data. Based on the 95% confidence intervals from the gravimetric data (Table 3), the values obtained for α at the 20 depth and for both α and *n* at the 30-50 cm depth using the gravimetric data were significantly different to the values obtained from the logger data. It can be seen in Figure 5 (bottom right) that the curves for the 20 cm and 30-50 cm depths derived from the logger data were similar, whereas those from the gravimetric data were appreciably different.

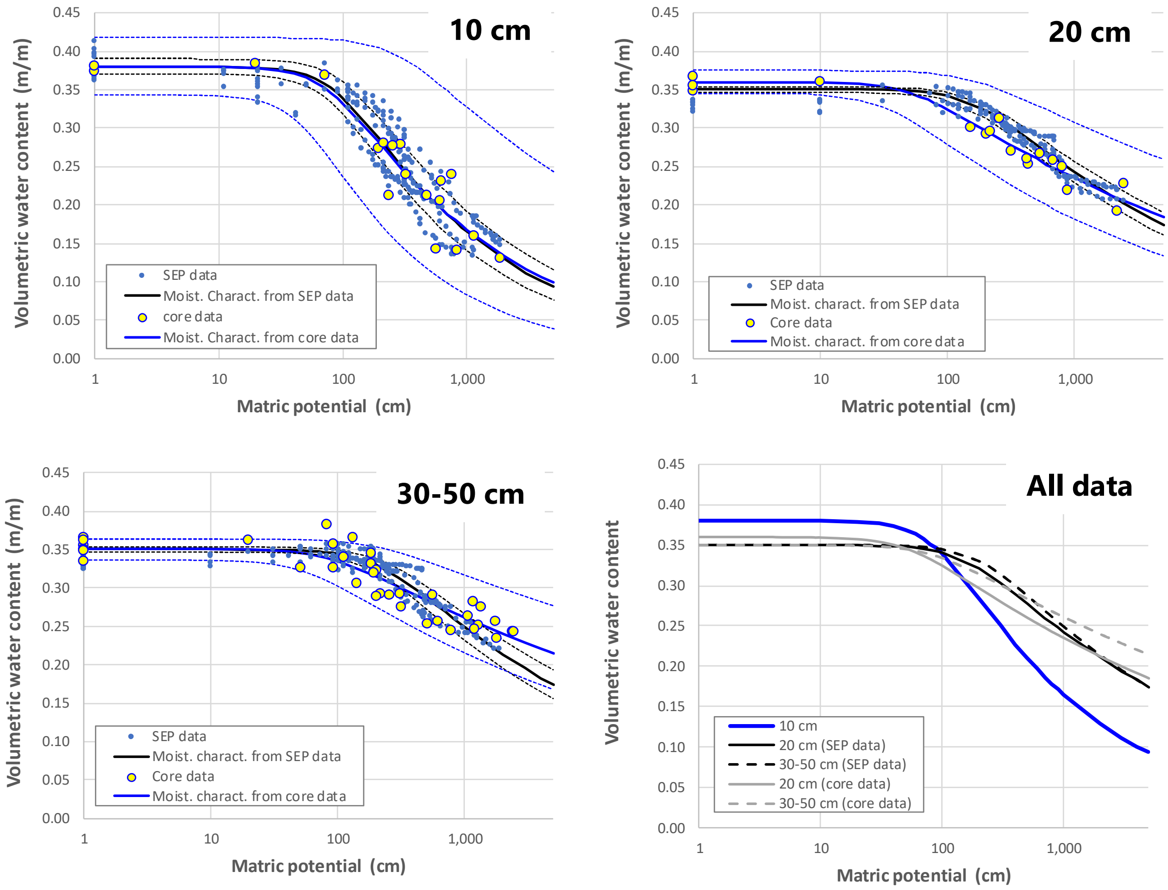

Figure 5. Volumetric water contents from the gravimetric cores (core data - yellow circles) and the calibrated, standardised EnviroPro sensors (SEP data - blue dots) plotted against simultaneous readings of matric potential in the duplex RBE (Bunnaloo loam) in each soil horizon. The best-fit soil moisture characteristic curves obtained from RETC using the core data (solid blue lines) and the EnviroPro sensor data (solid black lines) are also shown. Dashed lines indicate the upper and lower 95% confidence intervals for these fitted curves. The best-fit soil moisture characteristic curves from each horizon and for the two data sets (SEP and core data) are shown together at bottom right (All data) for comparative purposes.

Uniform clay – Rochester clay

The fine texture of the Rochester clay meant the profile did not drain quickly or by much after it had been saturated prior to the start of the measurement period (12 March 2021). To obtain θv-ψ measurements over a wider soil moisture range, the covers were taken off the rings on 21 April 2021 to allow evaporation. While this resulted in drying to a ψ of -800 cm at the 10 cm depth, there was little change in moisture content/potential at 20 cm depth and almost no change at 30, 40 or 50 cm. Plotting the θv measurements from the gravimetric core samples at the five depths against the paired matric potential readings showed that a common moisture characteristic fitted to all depths in this soil would be acceptable over the range of moisture contents observed (Figure 6). Because the data from the 10 cm depth had the widest range in moisture contents, the data from this depth was used to derive this common moisture characteristic curve for the Rochester clay.

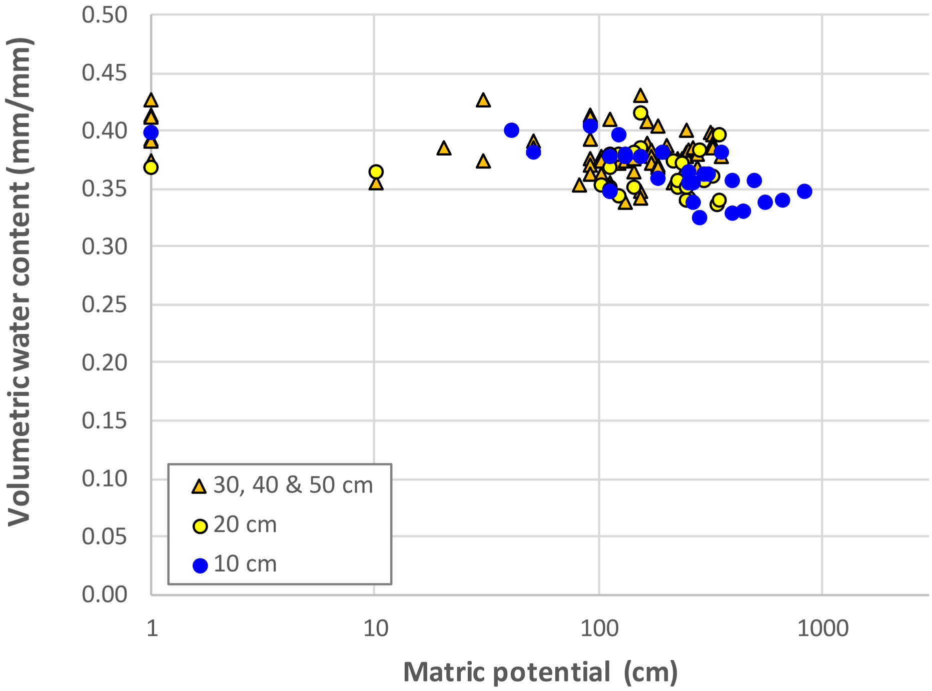

Figure 6. Volumetric water contents from gravimetric soil cores plotted against matric potential readings from Watermark sensors made at the time the cores were sampled to calibrate the EnviroPro sensors at 10, 20, 30, 40 and 50 cm depths in the Rochester clay.

Values of θs, θr and K_{sat} used as input to RETC to model a common soil moisture characteristic curve for the top 0.5 m of the Rochester clay are shown in Table 4. Like the duplex soil, data was fitted to the van Genuchten model with m = 1-2/n as this model gave the best fit to the data. θr was set to 0.09 for a clay soil (Rawls and Brakensiek, 1982) and θs was determined from the average volumetric water content of readings in saturated soil (ψ > -6 kPa). Separate model runs were done using the gravimetric core data and the calibrated, standardised EnviroPro readings to check correspondence and ensure the EnviroPro sensors were properly calibrated. The results showed poor correspondence between the curves derived from gravimetric and EnviroPro sensor data, even though the two data sets overlapped (Table 4 and Figure 7 left). This is attributed to the scatter in the data and the narrow soil moisture range that during the measurement period.

Data from paired EnviroPro and Watermark sensors was collected from this site in 2019-20 whilst monitoring a tomato crop. These EnviroPro readings could not be standardised because full scale readings in air and water were not made at the time, so the logarithmic calibration equation and default parameters recommended by EnviroPro (EnviroPro Dielectrics, 2014) were used to convert EnviroPro readings to θv. Comparison of this data set with the gravimetric core and logger datasets from 2021 showed the θv-ψ curves from the two logger data sets were almost identical (Figure 7 right), whereas the curve obtained from the gravimetric core data was not (Figure 7 left). Based on this, it was assumed the best fit relationship obtained using the logger data at 10 cm (Table 4, middle row) was representative of the soil moisture characteristic of the top 0.5 m of the Rochester clay at Strathallan.

Table 4. Parameters describing the hydraulic properties of the uniform clay (Rochester clay) determined from least-squares fitting in RETC to data from 10 cm depth (θs is saturated water content, θr is residual water content and α and n are fitting parameters). Soil water retention data was fitted to the van Genuchten model with m = 1 – 2/n using soil water content data obtained from soil cores (Gravimetric); from calibrated EnviroPro sensor readings (Logger); and logger readings obtained in 2019-20.

θ_v data source	θ_s	θ_r	K_{sat} *(cm d^{-1})*	α *(cm^{-1})*	n	R^2
Gravimetric	0.40			0.0242 *(-0.0028 – 0.0511)*	2.078 *(2.032 – 2.123)*	0.50
Logger	0.38	0.09	46	0.0086 *(0.0053 – 0.0119)*	2.121 *(2.082 – 2.160)*	0.56
Logger (2019-20 crop data)	0.39			0.0099 *(0.0092 – 0.0106)*	2.128 *(2.124 – 2.133)*	0.99

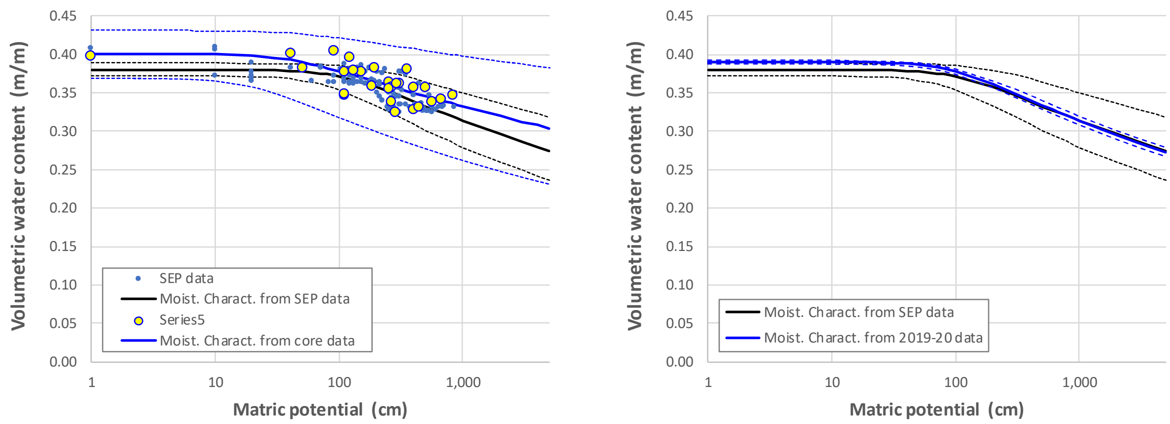

Figure 7. Left - volumetric water contents from gravimetric cores (Core data - yellow circles) and calibrated, standardised EnviroPro sensors (SEP data - blue dots) plotted against simultaneous readings of matric potential in the uniform clay (Rochester clay) at 10 cm depth, and the best-fit curves from RETC to the core data (solid blue line) and the EnviroPro sensor data (solid black line). Right – curves fitted by RETC to the θ-ψ data from under the tomato crop in 2019-20 and from the EnviroPro (SEP) data at the measurement site in 2021. Dashed lines indicate the upper and lower 95% confidence intervals.

Soil hydraulic properties

The unsaturated hydraulic conductivity functions obtained from RETC for the duplex RBE show that the curves for the A horizon (10 cm) and B horizon (20 cm and 30-50 cm) are different, with the A horizon having a higher hydraulic conductivity in wetter soil (Figure 8 left). The hydraulic conductivity functions for the 10 cm depth derived from both the logger and the gravimetric core data were similar because the moisture characteristic curves for the two data sets were similar. In the B horizon, however, slight differences in the soil moisture characteristics fitted to the two data sets (logger and gravimetric data) resulted in quite different hydraulic conductivity functions. The gravimetric data also produced different hydraulic conductivity functions for the 20 cm and the 30-50 cm depths, whereas these two depths had similar hydraulic conductivity functions when modelled from the logger data (Figure 8 left).

The unsaturated hydraulic conductivity functions obtained from the logger data for the uniform clay (Figure 8 right) and for the B horizon of the duplex RBE (Figure 8 left) were similar, though with slightly higher hydraulic conductivity in wet soil for the uniform clay. The functions obtained using the gravimetric data indicate a lower hydraulic conductivity than the functions derived from the logger data in both soils. This is attributed to the prediction of higher volumetric water contents at greater soil suctions in the moisture characteristic curves derived from the gravimetric data.

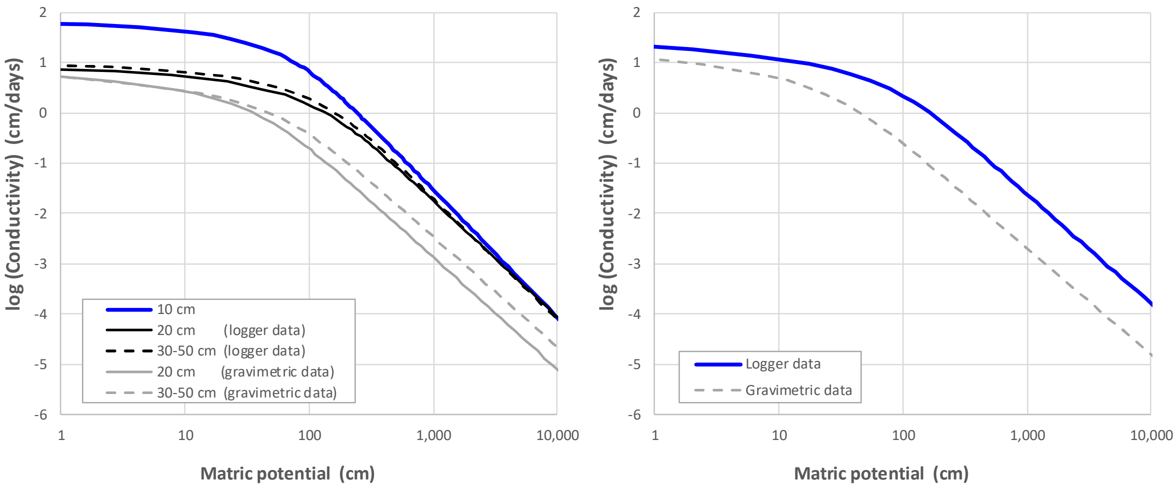

Figure 8. Unsaturated hydraulic conductivity functions predicted from soil moisture characteristic curves for the duplex RBE (left) and the uniform clay (right) by RETC. In the duplex RBE, relationships were modelled for each of the three depths examined (10, 20 and 30-50 cm) while a common curve was modelled for the uniform clay using the data from the 10 cm depth. Separate lines in each graph show functions modelled from the logger data and from the gravimetric core data.

Discussion

The greater amount of data able to be collected from the logged sensors resulted in narrower confidence intervals and better definition of the shape of the moisture characteristic at the drier end compared to what could be obtained from the smaller number of physically sampled soil cores. The unsaturated hydraulic conductivity functions obtained from the logged EnviroPro and Watermark data may be the better of the two choices in cases such as this when there is only a small range in measured water contents/potentials. However, without validation of the modelled hydraulic conductivity functions, the question remains as to which data set best captures the soils' hydraulic properties.

Greacen (1981) found that at higher suctions in duplex RBE the hydraulic conductivity of the B horizon was always greater than that of the A horizon. This would support the use of the logger data for determining the hydraulic conductivity function of the B horizon of the duplex RBE, as this is the pattern exhibited for this data set (Figure 8 left). However, data collected from 112 Group 2 soils in the Shepparton Irrigation Region (Mehta and Wang, 2005) contradicts this, with the hydraulic conductivity function of the B horizon lower than that of the A horizon across the full range of suctions when this data was input to RETC (Figure 9).

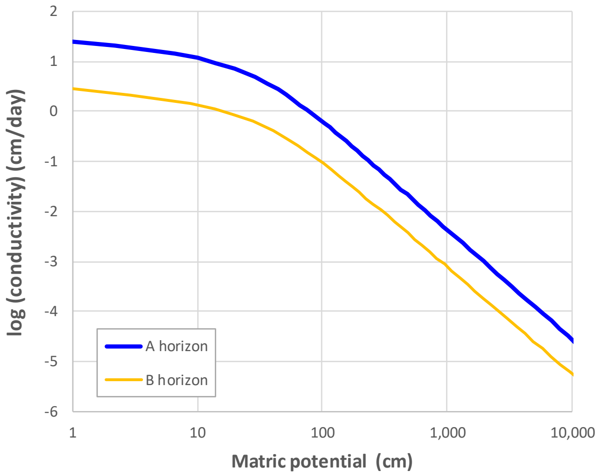

Figure 9. The unsaturated hydraulic conductivity functions for the A and B horizon predicted by RETC from moisture characteristic data from of 112 Group 2 soils in the Shepparton Irrigation Region.

All data was fitted to the van Genuchten model with m = 1-2/n as this model gave the best fit to the data. This differs from Cote *et al.* (2003) in their study of sub-surface drip for Australian soils as they used m = 1-1/*n*. Kosugi *et al.* (2002) state that the specific mathematical form of the soil water retention function has no influence on the conductivity prediction as long as it describes the data accurately. The largest question raised by this study is whether the moisture characteristic curves obtained for the two soil adequately describe their hydraulic properties. The best test of the hydraulic characteristic functions obtained in this study will be if the measured water distribution within the beds at these two sites, as shown in Figure 10, matches the water distribution modelled in HYDRUS.

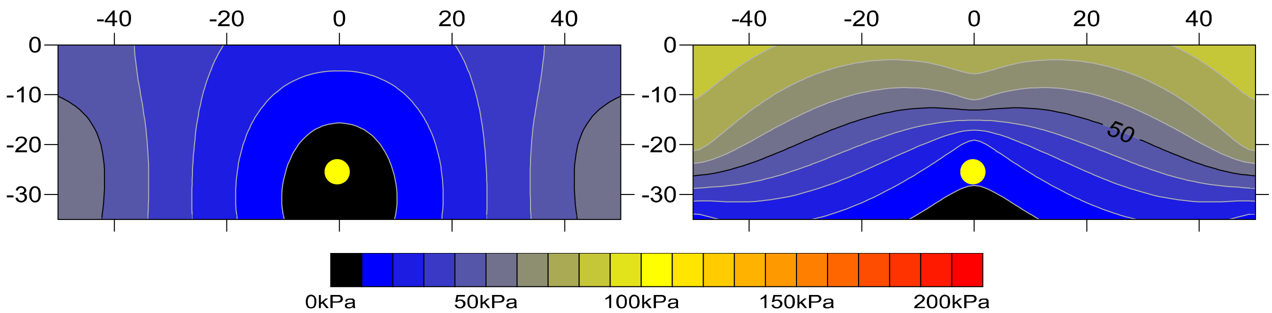

Figure 10. Average matric potential (kPa) during January 2020 in a cross-section through raised beds under tomatoes growing in the duplex RBE (Bunnaloo loam - left) and the uniform clay (Rochester clay - right). The position of the drip tape is indicated (yellow circle). Distance (cm) from the bed centre is shown on the x-axis and depth on the y-axis.

Conclusions

The moisture characteristics fitted to the data obtained from calibrated EnviroPro sensors and from Watermark matric potential sensors gave narrower 95% confidence limits and covered a wider range of soil water content/potential readings than was possible when using manual gravimetric sampling. The hydraulic parameters obtained from this logger data (Table 5) are recommended for use in modelling water flows from sub-surface drip in these two soils.

Table 5. Hydraulic parameters for use in modelling flows in the duplex RBE and uniform clay obtained from paired, calibrated standardised EnviroPro readings and Watermark matric potential readings.

Parameter	Units	Duplex RBE		Uniform clay
		10 cm	20-50 cm	0-50 cm
θ_s	*(m/m)*	0.38	0.35	0.38
θ_r	*(m/m)*	0	0	0.09
α	(cm^{-1})	0.0105	0.0060	0.0086
n		2.354	2.204	1.121
R^2		0.86	0.93	0.56
K_{sat}	*(cm/day)*	76*	12	46

** this Ksat value is a modelled value from particle size and bulk density data input to Rosetta*

References

Amoozegar, A. (1989). A compact constant-head permeameter for measuring saturated hydraulic conductivity of the vadose zone. *Soil Science Society of America Journal* 53: 1356-1361.

Barber, S. A., Katpiya, A. & Hickey, M. (2001).Effects of long-term subsurface drip irrigation on soil structure. In "*Science and technology: delivering results for agriculture?*" *Proceedings of the 10th Australian Agronomy Conference, January 2001*(Eds B. Rowe, D. Donaghy and N. Mendham). Hobart, Tas: Australian Agronomy Society.

Brown, P. (2016). Aerated water irrigation for increased water productivity, yield and quality of processing tomato. *Australian Processing Tomato Grower* 37(September): 31-33.

Cote, C. M., Bristow, K. L., Charlesworth, P. B., Cook, F. J. & Thorburn, P. J. (2003). Analysis of soil wetting and solute transport in subsurface trickle irrigation. *Irrigation Science* 22: 143-156.

EnviroPro Dielectrics (2014).User Manual. EnviroPro Soil Moisture Sensor. Moonta, South Australia: EnviroPro Dielectrics Pty Ltd.

Greacen, E. L. (1981).Physical properties and water relations. In *Red-brown earths of Australia.*, 83-96 (Eds J. M. Oades, D. G. Lewis and K. Norrish). Adelaide: Waite Agricultural Institute & CSIRO Division of Soils.

Isbell, R. F. & National Committee on Soil and Terrain (2016). *The Australian Soil Classification*. Australia: CSIRO Publishing.

Johnston, E. J. (1952).Soils of Deniboota Irrigation District and their classification for irrigation. In *Soils and Land Use Series No. 5*Melbourne, Australia: CSIRO.

Kosugi, K., Hopmans, J. W. & Dane, J. H. (2002).Parametric models. In *Methods of soil analysis. Part 4: physical methods*(Eds J. H. Dane and G. C. Topp). Madison, USA: Soil Science Society of America.

Lanyon, D. M. & Kelly, J. (2010). Long term impacts of sub surface irrigation on soil health. *Australian Processing Tomato Grower* 31: 23-24.

Mehta, B. & Wang, Q. J. (Eds) (2005). *Soil Hydraulic Properties of the Shepparton Irrigation Region*. Tatura, Vic.: Department of Primary Industries.

Minasny, B. & McBratney, A. B. (2001). The Australian soil texture boomerang: a comparison of the Australian and USDA/FAO soil particle-size classification systems. *Australian Journal of Soil Research* 39: 1443-1451.

North, S. H. (2020). Investigation of factors limiting processing tomato yields. *Australian Processing Tomato Grower* 41: 10-15.

Rawls, W. J. & Brakensiek, D. L. (1982). Estimating soil water retention from soil properties. *Journal of Irrigation and Drainage Engineering (ASCE)* 105(2): 166-171.

Simunek, J., van Genuchten, M. T. & Sejna, M. (2012). HYDRUS: Model use, calibration and validation, Special issue on Standard/Engineering Procedures for Model Calibration and Validation. *Transactions of the ASABE* 55(4): 1261-1274.

Skene, J. K. M. & Harford, L. B. (1964).Soils and land use in the Rochester and Echuca Districts, Victoria. Melbourne.

van Genuchten, M. T., Leij, F. J. & Yates, S. R. (1991).The RETC code for quantifying the hydraulic functions of unsaturated soils. Riverside, California: US Salinity Laboratory.

van Genuchten, M. T., Simunek, J., Leij, F. J. & Sejna, M. (1998).RETC version 6.02. Code for quantifying the hydraulic function of unsaturated soils. California, USA: PC-Progress.

Yong, M., Doyle, R., Fisher, P. & Mann, L. (2015). Sub-surface drip irrigation with Gyp-Flo in processing tomatoes. *Australian Processing Tomato Grower* 36: 24-26.