Comparison of Methods for the Calculation of Root Zone Readily Available Water in Irrigated Vineyards

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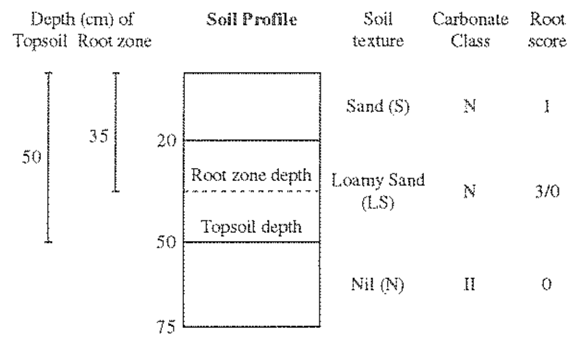
Abstract Readily available water (RAW) is the parameter used in assessing the water holding capacity of a soil. The depth and texture of the various soil layers which are measured in a soil survey are the main determinants of this: each soil texture encountered having a readily available water determined from a soil moisture retention curve. In addition, the root development and the amount of rubble within the layers are scored and these affect the calculated readily available water. In 1994 a simplified formula for the calculation, based upon a different scoring system, was introduced by the Irrigated Crop Management Service of Primary Industries (SA). This paper compares the results for calculations of root zone readily available water and root zone depth for an irrigated vineyard near Waikerie, SA. The simplification changes root zone RAW values by more than 20% in a fifth of the sites. Changes greater than 40% occur in about 8% of the sites. The consequences for the semivariogram, the function describing spatial variability of readily available water across the vineyard, are also significant. Spherical models are better defined and their use gives kriged estimates for irrigation valve areas which are more accurate.

1. INTRODUCTION

The Riverland is an important agricultural area in South Australia and is planted to many varieties of crops, principally grapes, citrus and vegetables. The objective is to grow a high yield of quality crops with the minimum of expense. With irrigation being a significant cost, appropriate system development and scheduling is necessary to reduce the associated expenses without affecting crop production. Detailed soil information is necessary to achieve this.

The Irrigated Crop Management Service (ICMS) of Primary Industries (SA) provides an on-farm approach to improving irrigation management. It was established in 1985 and is available to growers primarily within the Murray-Darling Basin. For a new property, attention is directed first to understanding the soil, crops are matched to this and an appropriate irrigation system is designed. On developed properties assessment of the performance of the irrigation system, in conjunction with an understanding of the soil types and crops present, allows appropriate modifications to be suggested. Preparation of the irrigation scheduling plan follows in both cases.

To obtain relevant soil information and determine where the variations in soil properties occur, the ICMS carries out a detailed soil survey. Typically this involves the excavation of a pit with a backhoe, to a safe working depth of up to 1.8 metres, so that the undisturbed *in-situ* soil profile can be examined. From each soil profile a number of soil characteristics are recorded (Figure 1). These include the depth (cm) and hand assessed texture (McDonald et.al., [1990]) of each soil layer, the class of each carbonate layer encountered (Wetherby and Oades, [1975]) and the depth (cm) of the topsoil. In the Riverland the carbonate layers tend to lie near the base of the soil profile. The other overlying layers comprise the topsoil. A further two soil



Root score - quantification of root abundance and development
1 : Few roots; slight root development.
3/0 : Abundant roots; maximum development before the cessation of root growth at a depth of 35 cm.
Carbonate class classification
N : Nil. II : Sheet of boulder calcrete.

Figure 1 A typical soil profile description.

characteristics are also recorded for developed properties. These are the extent of root activity (root score) within each soil layer (McDonald et.al., [1990]) and the depth (cm) of the effective root zone. Other variables which may be measured include pH, the fine earth carbonate content and the geology of the soil layers, the salinity and the depth to a watertable if present, but these will not be discussed in this paper.

For the assessment of the water holding capacity of a soil, the parameter readily available water (RAW) is calculated. This is defined as the reservoir of soil water (in mm) which can be stored between -8 kilopascals (full point) and -60 kilopascals (refill point). These suction pressures correspond to a soil water depletion range which maintains maximum crop production for a broad range of horticultural crops in the Riverland. The depth and the texture of the various soil layers are the main determinants of readily available water: each soil texture encountered having a readily available water value (mm/cm of soil) determined from a soil moisture retention curve. This curve is experimentally calculated from cores using a range of suction pressures, as described by Loveday [1974]. The readily available water value for the whole profile is obtained by summing the values within each soil layer. For crops which penetrate into the carbonate layers, the amount of rubble contained in the layers as well as the root abundance within each layer, affect the calculated readily available water values, and this will be outlined later. Readily available water is always calculated for the topsoil, however developed properties can also have the root zone readily available water calculated as this reflects the actual depth to which roots are able to absorb water.

Accurate mapping of the readily available water makes for appropriate irrigation system design and aids in preparation of the irrigation scheduling plan. The method of root zone RAW was revised during 1994. With it being an extremely important parameter in vineyard management, the consequences of this new method must be investigated. An existing vineyard near Waikerie, surveyed by the ICMS in 1990 and the subject of a geostatistical analysis by Brooker et.al., [1993], provides a study area to compare the methods for root zone RAW calculation.

2. CALCULATION OF READILY AVAILABLE WATER (RAW)

2.1 Calculation of Topsoil RAW

Topsoil RAW is calculated according to equation (1).

$$TSRAW\ (\text{mm}) = \sum_{i=1}^{N} \left(\text{STRAW}_i\,(\text{mm / cm})\ \text{x}\ \text{LT}_i\,(\text{cm})\right) \qquad (1)$$

where LT_i stands for the thickness of the ith layer, STRAW_i is the readily available water of the soil texture of that layer, and N is the number of layers in the topsoil. As explained above, the amount of water a soil retains is governed by its texture. Table 1 gives the values of RAW for some common soil textures.

Table 1
Readily available water (RAW) stored between -8 kPa and -60 kPa for some Riverland soil textures

Soil Texture	*Code*	*RAW* (mm/cm)
Sand	S	0.38
Loamy Sand	LS	0.55
Sandy Loam	SL	0.64
Light Sandy Clay Loam	LSCL	0.65
Sandy Clay Loam	SCL	0.62

For the profile of Figure 1 the topsoil RAW is *24* mm.

2.2 Calculation of Root Zone RAW

Calculation of root zone RAW may be more involved than that described above. If the roots terminate in the topsoil but not at a layer boundary, (1) must be modified to allow the actual depth of roots to be used, as shown in equation (2).

$$RZRAW\ (\text{mm}) = \sum_{i=1}^{n} \left(\text{STRAW}_i\,(\text{mm / cm})\ \text{x}\ \text{LT}_i\,(\text{cm})\right) + \left(\text{STRAW}_{pp}\,(\text{mm / cm})\ \text{x}\ \text{RD}_{pp}\,(\text{cm})\right) \qquad (2)$$

where n is the number of layers completely penetrated by roots, RD is the depth extent of roots within the partially penetrated (pp) soil layer.

Figure 1 illustrates such a scenario and the calculated value of root zone RAW is *16* mm.

2. 3 Root Zone Readily Available Water and the Involvement of Carbonate Layers

Wetherby and Oades [1975] classified the types of carbonate layers found within the Riverland into classes I, II, IIIA, IIIB, IIIC, or IV. The basis for their distinction is a combination of colour difference, the extent of the very high fine earth carbonate content, and the varying degrees in their texture and structure. This classification leads to two important properties in so far as crop development is concerned; drainage ability and the degree to which root development can be established.

Class I and II carbonates are very restrictive. Class I comprises a very high accumulation of fine earth carbonate in a clay matrix. It has the worst drainage ability and it is rare to find extensive root development in this layer. Class II carbonate is sheet or boulder calcrete and is only slightly more conducive to root development than Class I.

Class III carbonate layers consist of high accumulations of fine earth carbonate in a loam matrix combined with a rubble content. The extent and size of the rubble leads to further subdivision (Table 2). Drainage and root penetration through Class III carbonates generally varies from fair to good with increase in rubble content, although texture is also important in the case of Class IIIA. Class IV carbonate comprises a weak accumulation of fine earth carbonate in a sandy matrix which provides excellent drainage and seldom restricts or affects root development. For this reason, Class IV carbonate is treated as any other natural soil layer.

Vines may penetrate the carbonate layers and so the amount of water that may be stored within these layers needs to be considered. The essence of the calculation is expressed in equation (2), however the class of the carbonate layers and the root activity within them have traditionally had weighting factors associated with them to modify the values calculated from these layers.

To allow for the presence of rubble in the carbonate layers, the carbonate weighting factor, CWF, was introduced. Table 2 lists the range.

Table 2
Carbonate class classification and weighting factors applied in the calculation of root zone RAW, pre-1994

Carbonate Class	*Rubble content*		*CWF*
	Max size	Percentage	
I	-	0 - 10%	1
II	-	90 - 100%	0
IIIA	1 cm	0 - 30%	0.75
IIIB	10 cm	30 - 60%	0.50
IIIC	30 cm	> 60%	0.25

Similarly, a root score weighting factor, RWF, is applied depending upon the extent of root activity within the carbonate layers (Table 3). It should be noted that for the topsoil layers no such factors were ever applied.

Table 3
Root scores, root activity and weighting factors applied in the calculation of RAW from carbonate layers, pre-1994

Score	*Root abundance*	*Root development*	*RWF*
1	Few	Slight (poor to fair)	0.50
2	Common	Some (fair to good)	0.75
3	Abundant	Maximum (excellent)	1

Thus for any carbonate layer the contribution to the root zone RAW can be expressed by;

$$\begin{gathered}\textit{Carbonate layer RAW}\ (\text{mm})\ \text{pre - 1994} = \\ \text{STRAW}\ (\text{mm / cm})\ \text{x}\ \text{RD}\ (\text{cm})\ \text{x}\ \text{CWF}\ \text{x}\ \text{RWF}\end{gathered} \quad (3)$$

where RD is the depth extent (cm) of roots within the layer.

For the soil profile of Figure 2 the root zone RAW is calculated to be *41* mm.

3. CHANGES TO THE WEIGHTING FACTORS FOR CARBONATE LAYERS AND THE TREATMENT OF ROOT SCORES POST-1993

During 1994 the formula for the calculation of root zone RAW was changed. The carbonate weighting factor, which was only representative, was replaced with a fragment percentage which is now measured in the field. This parameter more accurately reflects the percentage of soil unable to directly absorb any water infiltrating through. It may, of course, vary from site to site for a particular carbonate class, unlike the weighting factor which was applied universally to a particular layer. The treatment of the root score for each soil layer has changed more fundamentally. Now all layers from the base of the root zone which have a root score of 1 are removed from the calculation. All other layers, regardless of their root score,

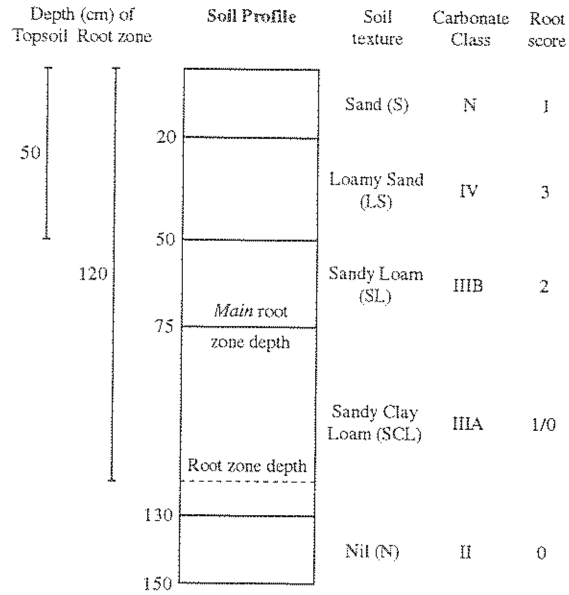


Figure 2 A soil profile involving carbonate layers.

are weighted 100% in the calculation of root zone RAW. This change leads to definition of the *main* root zone depth as the depth of roots scored either 2 or 3. For the soil profile in Figure 2, the main root zone is seen to be 75 cm.

If the main root zone lies within the topsoil, equation (2) applies (with the implication that only the main root zone depth is used). For any carbonate layer included in the calculation the new RAW calculation is expressed by;

$$\begin{gathered}\textit{Carbonate layer RAW}\ (\text{mm})\ \text{post - 1993} = \\ \text{STRAW}\ (\text{mm / cm})\ \text{x}\ \text{RD}\ (\text{cm})\ \text{x}\ (1\ -\ \text{Fragment}\ \%)\end{gathered} \quad (4)$$

To illustrate the changes brought by the new formula, the value of root zone RAW for the profile of Figure 2 has been recalculated using fragment percentages which are representative of rubble percentages for the carbonate classes from a vineyard near Waikerie, SA, (set 1 in Table 4). The fragment percentages implied in the former carbonate weighting factors (set 2) are also presented for comparison.

Table 4
The representative and CWF fragment percentages

Carbonate Class	*Rubble %*	*Rep Frag %* (set 1)	*CWF Frag %* (set 2)
I	0 - 10%	0.05	0
II	90 - 100%	0.95	1
IIIA	0 - 30%	0.05	0.25
IIIB	30 - 60%	0.30	0.50
IIIC	> 60%	0.60	0.75

For the profile of Figure 2, the new root zone RAW value is *35* mm. This compares with *41* mm calculated previously; a 15% variation.

If the fragment percentage (50%) corresponding to the CWF (0.5) is used, the RAW value is *32* mm; a 22% variation. The difference between the original, *41* mm, and this value, is purely the result of root score treatment changes. The smaller fragment percentage for the representative value when compared to the CWF fragment percentage for the Class IIIB layer, allows for an additional *3* mm.

4. CASE STUDY

4.1 Changes to Root Zone RAW

The above example illustrates that significant changes in RAW may occur with the change in calculation method. To further investigate this, calculations have been made for a vineyard located about 15 kilometres from the South Australian town of Waikerie. The vineyard is a few hundred metres south of the River Murray and covers an area of about 6 square kilometres. It is planted to several different varieties of vines of various ages. Soil profile descriptions were collected from 926 sites using a sample grid of 75 m x 75 m. Typically, if a restrictive layer (normally Class II carbonate) was intersected, the hole was terminated. There is some vacant ground in the property and only 764 of these sites give information on root growth.

The data from this property did not contain fragment percentage values for each carbonate layer at each site. Consequently, representative fragment percentages, chosen in retrospect by ICMS staff who surveyed the property, have been applied to all sites. These are the values (set 1) in Table 4 which were used in the illustrative example above. As well, the fragment percentages (set 2), which are implied in the carbonate weighting factors, CWF, are used for comparison. Use of this set allows for the effect of root scoring increases in the carbonate layers (root score 2 treated as 3), and layer removals (root scores of 1 at the base of the soil profile) to be considered against the previous calculation. It is worth emphasising that the changes in treatment of the root scores can contribute both positively and negatively to root zone RAW. When a layer with a root score of 1 has been removed then the contribution to RAW from this layer is absent. However, an overlying carbonate layer with common root abundance is now deemed able to take in all the water absorbed and so there is an increased contribution to the resultant RAW.

The irrigation system in place on the property has been designed to accommodate an upper limit of 65 mm for RAW, and 62 pre-1994 values were cut to this. In the new calculations any RAW value greater than 65 mm has been similarly cut to 65 mm. Of the 62, 25 now show a smaller value using both the CWF and representative fragment percentages.

With the CWF fragment % (set 2) a total of 234 sites (30.6% of 764) have a different root zone RAW value (Table 5). At 141 sites the value changes by more than 20%, and 57 sites change in value by more than 40%. At 30 sites there is an increase in RAW value, the average being 4.3 mm and standard deviation 2.1 mm. This increase has been because of Class IIIA and Class IIIB carbonate layers. The other 204 sites are reduced in root zone RAW by up to 68% with the average being 14.6 mm and standard deviation 9.4 mm. This reduction is primarily because of the removal of layer(s) from the base of the soil profile with root score 1. However, the change in treating layers with root score 2 as if 3, at five sites, has moderated this reduction to some extent.

For the representative fragment % (set 1) the number of sites with a variation in root zone RAW increases from 234 to 293 (38.4% of 764). At 158 sites the value changes by more than 20%, and at 58 sites the change is greater than 40%. Now 59 sites previously showing no variation using set 2 values are increased in value. This is attributed to the reduction in rubble content in the carbonate layers in going from set 2 to set 1.

For the 90 sites showing an increase in root zone RAW, the average increase is 6.0 mm and the standard deviation is 3.9 mm. The average reduction at 203 sites which show smaller values, drops marginally to 14.3 mm with standard deviation of 9.6 mm.

Table 5

Distribution of the variation in new root zone RAW values involving the CWF and representative fragment percentages

Variation	*CWF Frag %*			*Rep Frag %*		
	No.	*Ave.* (mm)	*Std. Dev.*	*No.*	*Ave.* (mm)	*Std. Dev.*
$0 \leq 10$ % increase	10	2.50	0.71	16	2.94	1.12
$0 \leq 10$ % reduction	16	3.56	1.31	22	3.32	1.43
$10 \leq 20$ % increase	19	5.42	1.80	50	4.70	1.53
$10 \leq 20$ % reduction	48	7.17	2.21	47	7.11	2.25
$20 \leq 30$ % increase	1	8.00	-	14	8.36	3.20
$20 \leq 30$ % reduction	45	10.84	3.69	41	11.05	3.73
$30 \leq 40$ % increase	0	-	-	8	13.63	3.74
$30 \leq 40$ % reduction	38	16.18	4.91	37	16.51	5.00
$40 \leq 50$ % increase	0	-	-	2	15.50	0.71
$40 \leq 50$ % reduction	32	21.41	5.03	31	21.23	5.01
> 50 % reduction	25	31.32	7.94	25	31.32	7.94

4.2 Reduction in Root Zone Depth

Removal of layers with a root score of 1 at the base of the soil profile results in the definition of the main root zone depth (Figure 2), which has a smaller value than the root zone depth. There is such a reduction at 220 sites (28.8% of 764). Table 6 details the distribution of this reduction. For 191 sites there is a reduction by more than 20%, and 109 sites were reduced by more than 40%. The average reduction is 43.9 cm, and the standard deviation is 21.4 cm.

For this vineyard the main layers removed are Class IV (105) and Class IIIA (98) carbonates. For only ten topsoil

Table 6
Distribution of the reduction in root zone depth

Reduction	*Samples*	*Ave.* (mm)	*Std.Dev.*
$0 \leq 20$ %	29	16.72	5.71
$20 \leq 30$ %	40	29.00	8.41
$30 \leq 40$ %	42	38.45	8.80
$40 \leq 50$ %	62	50.08	12.40
> 50 %	47	70.21	19.75

layers (other than Class IV carbonate) are vines terminating with slight root development. Table 7 shows the summary statistics associated with the reduction in root zone depth by the removal of individual layers, and links this to the reduction in root zone RAW coming from such removals.

Table 7
Descriptive statistics for the reduction in root zone depth (top) and root zone RAW (bottom) with reference to the specific soil layers removed

Removed soil layer	*No.*	*Reduction in RZD* (top) *and RZRAW* (below) *Range*	*Ave.*	*Std.Dev.*
Class IV	105	5-100 cm	44.65 cm	20.69
		2-44 mm	19.03 mm	9.95
Class IIIA	73	10-110 cm	40.42 cm	20.10
		2-26 mm	9.51 mm	4.83
Class IIIB	24	5-115 cm	44.17 cm	25.14
		1-18 mm	6.89 mm	3.94
Natural	10	20-95 cm	42.50 cm	25.07
		11-33 mm	20.27 mm	7.01
Class I	5	30-50 cm	38.00 cm	8.37
		8-14 mm	10.64 mm	2.34

4.3 Geostatistical Analysis

The values of root zone readily available water show considerable variation from site to site. Figure 3 shows RAW values for 21 sites from the pre-1994 data and at the same sites the new RAW involving the CWF fragment %. Since irrigation involves watering a certain area (in this case about 1.3 hectares) by turning on appropriate irrigation valves, it is important to properly map the value of this variable for these areas throughout the property. The geostatistical process of kriging [Brooker, 1991] is used to estimate the average value for individual irrigation valve areas. It is written as a weighted linear sum of surrounding sample values and the process generates optimal weights and a measure of the accuracy of the estimate; the kriging variance which may be converted to a confidence interval for the estimate. The technique first defines the variation structure of root zone RAW by calculation of its semivariogram and this function, together with the sample and irrigation valve geometry, is the fundamental input to the estimation process.

51	65	65	49	65	61	47
19	25	65	25	53	38	30
42	34	36	42	42	46	46
30	34	42	42	25	46	46
19	50	50	38	58	65	47
19	50	50	38	19	38	47

Figure 3 Pre-1994 root zone RAW values (top) and the post-1993 values (below) surrounding the 225 m x 75 m irrigation value area.

Brooker et.al., [1993] described the use of this technique to estimate values of root zone readily available water and topsoil depth for the irrigation valve units of this property. That study identified a marked degree of geometric anisotropy in the semivariograms for root zone RAW, reflecting the fact that there is an underlying sand dune system striking E-W through the property. A spherical model was chosen for the semivariogram and its parameters, the nugget effect, C_0, the sill, $C_0 + C$, and the range a, are given in Table 8.

Table 8
Semivariogram models for root zone RAW

Root zone RAW	*Spherical model parameters* C_0	C_0+C	a(N-S)	a(E-W)
pre-1994	100 cm^2	230 cm^2	200 m	650 m
post-1993	95 cm^2	175 cm^2	180 m	775 m

For the irrigation valve area of Figure 3 the estimated root zone RAW value was calculated to be 44.9 mm and the 95% confidence interval was (37.3 mm, 52.4 mm).

Similar anisotropy is found using the new values of root zone RAW. A spherical model is chosen to model the spatial variability and the parameters are also shown in Table 8. Using this semivariogram to estimate the irrigation valve area value gives an estimate of 37.8 mm and a 95% confidence interval (31.0 mm, 44.5 mm). These values are rather different from those calculated previously, reflecting the extent of the changes in RAW data values. Maps of such kriged estimates for root zone RAW over the whole property can be produced to assist in vineyard management.

The semivariograms for both the former root zone RAW values and the new values are plotted in Figure 4 after scaling distances E-W by the ratio of the range N-S to the range E-W to produce isotropic models. There is a somewhat lower level of overall variation in the post-1993 semivariograms and this manifests in the smaller size of the confidence interval in that case.

Similar calculations can be made for the same irrigation valve area for both the root zone depth and the new *main* root zone depth values shown in Figure 5. The parameters of the spherical semivariogram models are given in Table 9.

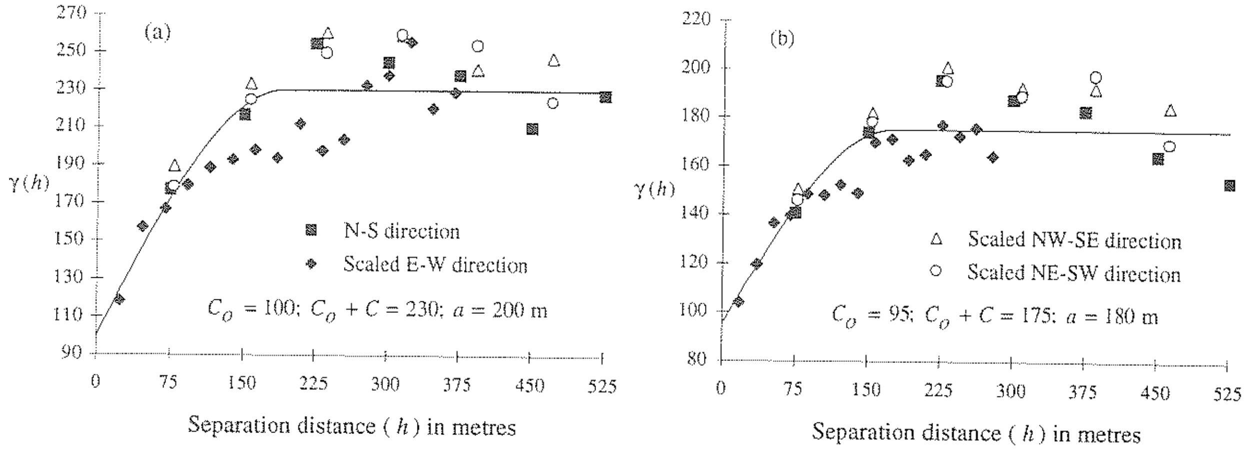


Figure 4 Scaled experimental semivariograms and the isotropic spherical model for; (a) the pre-1994 root zone RAW (Brooker et.al., [1993]) and; (b) the post-1993 root zone RAW involving the CWF fragment %.

100	150	170	110	140	160	150
50	65	170	65	100	100	80
110	90	110	110	110	120	120
80	90	110	110	65	120	120
30	90	110	100	120	100	100
30	90	110	100	50	100	100

Figure 5 Root zone depth values (top) and new *main* root zone depth values (below) surrounding the 225 m x 75 m irrigation valve area.

Table 9
Semivariogram models for root zone depth

Variable	*Spherical model parameters*			
	C_0	C_0+C	a (N-S)	a (E-W)
Root zone depth	490 cm^2	1220 cm^2	190 m	660 m
Main root zone depth	530 cm^2	1020 cm^2	175 m	850 m

The estimate and confidence interval for average root zone depth over the irrigation valve area of Figure 5 are 113.0 cm and (95.6 cm, 130.3 m), whilst for the main root zone depth the values are 95.6 cm and (79.3 cm, 111.8 cm).

5. SUMMARY AND DISCUSSION

The new method of root zone RAW calculation relies on the main root zone depth to reflect the appropriate irrigation depth and soil water reserve which may be utilised between irrigations, and considers that slight root development over any depth below this provides insufficient influence. It is expected that the majority of the water retained by the soil in the main root zone will be absorbed by the abundance of roots that exist. In contrast, very little of the water retained by the soil layer with a few roots can be expected to be absorbed. In addition the fragment percentage of the carbonate layers which is now measured in the field, site by site, gives a better measure of the extent of the layer unable to absorb water rather than a universally applied factor.

The results for calculations of root zone readily available water and root zone depth for an irrigated vineyard near Waikerie, SA, show changes in readily available water values by more than 20% in a fifth of the sites. Changes greater than 40% occur in about 8% of the sites. The consequences for the spatial variability across the vineyard are also significant. Experimental semivariograms give better defined spherical models which are used to calculate more accurate kriged estimates for irrigation valve areas.

In the vineyard near Waikerie, topsoil layers make up 50% of the total number of layers removed with slight root development. Comparing the new calculations with the former shows that the average reduction in root zone RAW from these layers is around 19 mm. Carbonate layers are also removed in 50% of the cases. Their contribution is of the order of 9 mm.

6. REFERENCES

Brooker, P.I., *A Geostatistical Primer*, World Scientific Publishing, 95pp., Singapore, 1991.

Brooker, P.I., Winchester, J.P., and A.C. Adams, A geostatistical study of soil data from the Riverland, S.A., in *International Congress on Modelling and Simulation, 4*, edited by M. McAleer and A. Jakeman, pp 1461-1466, Uniprint, University of W.A., Perth, 1993.

Loveday, J., *Methods for Analysis of Irrigated Soils*, Wilke and Co., 208pp., Clayton, Victoria, 1974.

McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J., and M.S. Hopkins, *Australian Soil and Land Survey Field Handbook*, Inkata Press, 83-126, Melbourne, 1990.

Wetherby, K.G., and J.M. Oades, Classification of Carbonate Layers in Highland Soils of the Northern Murray Mallee, S.A., and their Use in Stratigraphic Land Use Studies. *Australian Journal of Soil Research, 13*, 119-132, 1975.