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Towards SMOS validation in south-eastern Australia

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Abstract: The upcoming Soil Moisture and Ocean Salinity (SMOS) mission of the European Space Agency will be the first satellite dedicated to the measurement of soil moisture. It will measure soil moisture for the top 5 cm at a spatial resolution of 35 to 50 km. Comparison of the soil moisture data from SMOS with in-situ monitoring network measurements across areas the size of a SMOS footprint will play a vital role in the validation of this new data stream. Possible validation sites in south-eastern Australia include the monitoring networks located in the Goulburn Catchment of the upper Hunter and Yanco area of the Murrumbidgee Catchment.

This study has assessed the suitability of these two networks for the validation of SMOS soil moisture measurements using L-band passive microwave aircraft observations obtained from the National Airborne Field Experiments (NAFE) of 2005 and 2006. Here the soil moisture content for the entire SMOS sized area of each site has been estimated from validated aircraft observations across the region, providing a measurement that is not readily achieved by traditional ground-based sampling. This spatial average is then compared with averages from ground-based point measurements of the soil moisture taken at approximately 2 km spacing, as well as the existing in-situ networks on a number of dates and moisture conditions. From this assessment, both the number of point measurements required to accurately obtain the average soil moisture for the area and the suitability of the existing monitoring networks in each of the sites has been assessed.

Using three days of extensive regional soil moisture data from the Goulburn catchment with coincident airborne soil moisture data covering a range of soil moisture conditions from wet to dry, it was found that 5 to 15 point measurements were needed to obtain the spatially averaged surface soil moisture for the area within a root mean square error of 0.04 m^3/m^3; the greater number of points were required in wetter conditions. However, the current monitoring station networks in the Goulburn River catchment and the Yanco region were found to not yield accurate estimates of average soil moisture of their respective areas when using all available station data (13 stations in the Goulburn and 9 stations at Yanco). Moreover, the error in average soil moisture for the areas did not asymptotically decrease as more measurements were included. This demonstrated that several of the monitoring stations installed are not representative of the broader area. However, through comparison of monitoring station combinations that produced the smallest error in average soil moisture, representative monitoring stations were identified for each area. Specifically, it was found that stations K3, M5, M6 and S1 produced a spatially averaged soil moisture estimate with a RMSE of less than 0.07 m^3/m^3 for the Goulburn catchment, and that stations Y5, Y7, Y10 and Y12 produced a spatially averaged soil moisture estimate with a RMSE of less than 0.04 m^3/m^3 for the Yanco area. An explicit assumption in the RMSE estimates is that both the aircraft and point measurements of soil moisture are error free.

Keywords: *Remote Sensing, Soil Moisture, SMOS*

1 INTRODUCTION

The European Space Agency will soon launch the first-ever dedicated soil moisture satellite; the Soil Moisture and Ocean Salinity (SMOS) mission. This satellite will use L-band passive microwave measurements to yield information on the top 5cm moisture content with a spatial resolution of about 50 km and design accuracy of 0.04 m^3/m^3 (Kerr *et al*., 2001). It is widely recognised that passive microwave is the most promising remote sensing method for soil moisture measurement, due to its ability to penetrate cloud, its direct relationship with soil moisture through the soil's dielectric constant, and a reduced sensitivity to land surface roughness and vegetation cover as compared to active microwave (Njoku *et al*., 2002). However, as SMOS uses a new-generation synthetic aperture sensor, the derived data must first be calibrated and independently verified for a range of environmental conditions before it can be used to address science questions. Likewise, the soil moisture retrieval algorithms developed by the European Space Agency need to be verified and potentially refined (Bosch *et al*., 2001). While very detailed airborne campaign data are limited in duration and spatial extent, and the spatially and temporally extensive soil moisture models are limited in their ability to provide realistic soil moisture estimates, in-situ soil moisture monitoring networks can provide long term records with a high degree of accuracy. Consequently, SMOS will use data from a range of soil moisture monitoring networks globally in its calibration and validation activities (Delwart *et al.*, 2008), including the networks within the Goulburn River and Murrumbidgee catchments, Australia. However, the use of point measurements from these networks must first be verified for this purpose.

The number of stations required to accurately represent the spatially averaged soil moisture is the main limitation with these monitoring networks, as the measurements may not be representative of the average soil moisture within the scale of a satellite footprint. Consequently, knowledge of how many stations are required to represent a SMOS-sized area with sufficient accuracy also needs to be answered. Previous studies have generally been for areas that are too small for the validation of SMOS. For example, Jacobs *et al.* (2004) found that 3 to 32 point measurements were needed to estimate the soil moisture for an agricultural field of 4 km^2, while Cosh *et al.* (2006) found 6 point measurements were sufficient for a 625 km^2 area. Both of these studies estimated the spatially averaged soil moisture to within 0.02 m^3/m^3. However, using a Monte Carlo simulation of four 50 km x 50 km areas Hansen *et al.* (In Review) found that 9 to 22 samples were required to estimate the average soil moisture to within 0.03 m^3/m^3. Moreover, these previous studies on the number of sampling stations for average soil moisture have typically used only the existing network of soil moisture stations, thus assuming that the average of all available stations already yields an accurate average of the study area. Consequently, this paper takes a novel approach, estimating the average soil moisture from independently verified 1 km resolution airborne soil moisture maps that give complete coverage of a SMOS sized pixel. This study also makes an assessment of the accuracy with which SMOS can be validated using the existing Australian soil moisture monitoring networks, and identifies which stations yield the most representative measurements. Given that SMOS aims to produce soil moisture with an error less than 0.04 m^3/m^3, this study makes its assessment of the Goulburn and Murrumbidgee networks against this target.

2 STUDY AREAS

This study assesses the two soil moisture monitoring networks in Australia (Figure 1) that have each been the subject of a National Airborne Field Experiment (NAFE). Specifically, the NAFE'05 study area (Panciera *et al.*, 2008) of the Goulburn River experimental catchment (Rüdiger *et al*., 2007) and the Yanco NAFE'06 study area (Merlin *et al.*, 2008) of the Murrumbidgee experimental catchment (Smith *et al*., In Review) are used. Together with the large number of top 5 cm soil moisture measurements in each, the heterogeneous land cover, soil texture and topography make them very suitable candidate SMOS validation sites, since these characteristics have been identified as priority issues for SMOS validation (Delwart *et al*., 2008). Specifically, the sites are typical of much of Australia, and include varied land covers and standing water effects that need to be addressed by SMOS retrieval algorithms. Further, the existing soil moisture

Figure 1. Location of Goulburn River and Murrumbidgee catchments in south-eastern Australia.

monitoring networks each occupy areas larger than 50 km, allowing for the validation of SMOS.

2.1 The Goulburn catchment

The 40 km x 40 km NAFE'05 study area of the Goulburn River catchment (Figure 2) is located approximately 200 km west of Newcastle, New South Wales. Here 13 of the 26 soil moisture monitoring stations in the Goulburn catchment could be used to represent the NAFE'05 study area. This area was additionally measured with an airborne Polarimetric L-band Multi-beam Radiometer (PLMR) over four dates, coinciding with regional ground soil moisture sampling with up to 181 point measurements (Figure 3).

The Goulburn River catchment has been chosen for remote sensing studies for its varied vegetation cover, soil type distribution, and topography (Rüdiger *et al.*, 2007). The soil type in the NAFE'05 study area consists of clays in the north and sands in the south. Moreover, land cover is mostly cleared and predominantly used for pasture and crops, including wheat, barley, sorghum and oats, but with some forest in the south (Panciera *et al.*, 2009).

2.2 The Murrumbidgee catchment

The 40 km x 55 km NAFE'06 study area of the Yanco region is located within the Murrumbidgee catchment (Figure 4). This area has 13 soil monitoring stations that are evenly spread through the region in a grid like manner, and distributed between the three main land uses of pasture, dryland crops and irrigated crops. Moreover, the area was measured with PLMR over eleven dates, with 9 of the soil moisture monitoring stations contained with the NAFE'06 study area.

Unlike the Goulburn study area, the Yanco region has flat topography. Of significant interest is that about one-third of the Yanco region is occupied by the Coleambally Irrigation Area, which includes rice, maize and soybean crops over summer, and wheat, barley, oats and canola crops over the winter. This irrigation district makes the site particularly well suited for the study of standing water on SMOS data. The remainder of the Yanco area is used for dryland crops and grazing.

3 DATA

Data used in this study was acquired as part of NAFE, with i) airborne derived soil moisture of the top 5 cm, and ii) ground based soil moisture data for the top 5 cm from point based regional soil moisture maps (Goulburn site only) and permanent monitoring stations.

3.1 Airborne soil moisture data

Airborne soil moisture maps of the two monitoring networks were made with PLMR, which measured the H- and V-polarised brightness temperatures at 1 km resolution (Panciera *et al.*, 2008; Merlin *et al.*, 2008). Flights were conducted from 6am to 10am. The 1 km resolution soil moisture maps for the Goulburn and

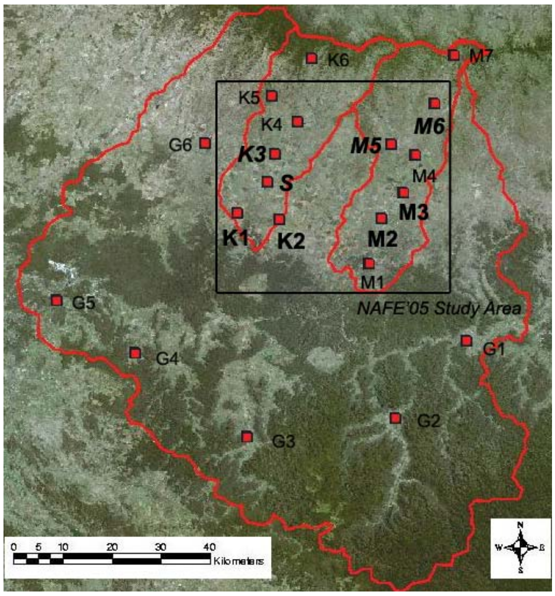

Figure 2. Monitoring stations in the NAFE'05 study area and Goulburn catchment. Merriwa and Krui subcatchments are outlined in red. Stations in bold font were operational during NAFE'05 and stations in italics were identified as representative.

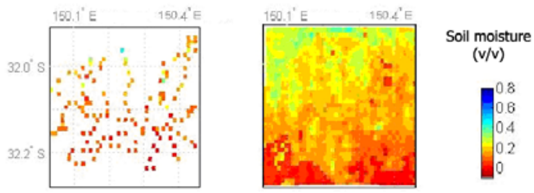

Figure 3. Example of airborne and regional ground-based soil moisture measurements for 21 November over the NAFE'05 study area.

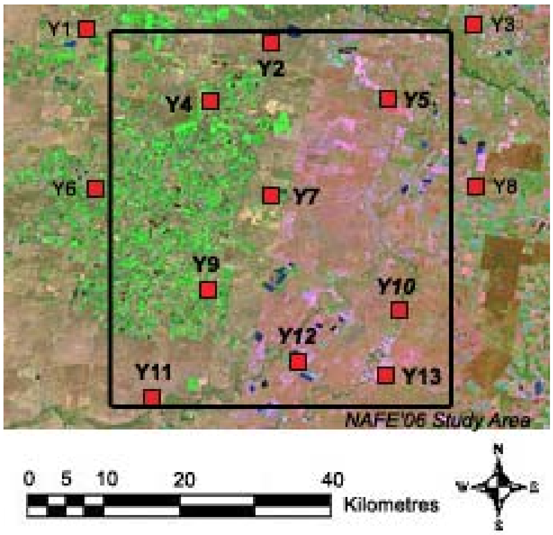

Figure 4. Monitoring stations in the NAFE'06 study area (black outline) of the Yanco region in the Murrumbidgee. Stations in bold font were operational during NAFE'06 and stations in italics were identified as representative of the area.

Table 1. Summary of SMOS scale soil moisture for the Goulburn and Yanco study areas. Averages were obtained from the airborne measurements, ground-based measurements along road networks, and from monitoring stations. A subset of monitoring stations was identified as representative of the area, with the average calculated and error compared to the airborne measurements described. Values with * were used for station selection.

Area	Date	Average soil moisture (m^3/m^3) for each data source. Numbers in brackets are standard deviations.			Soil moisture (m^3/m^3) estimated from a subset of monitoring stations	
		Airborne PLMR	Regional samples	Monitoring stations	Monitoring stations	Error
Goulburn	7-Nov-05	0.378 (0.142)	0.364 (0.131)	0.325 (0.096)	0.403	0.028
	14-Nov-05	0.178 (0.112)	0.186 (0.099)	0.193 (0.106)	0.289	0.111
	21-Nov-05	0.161 (0.088)	0.110 (0.073)	0.102 (0.063)	0.162	0.000
Yanco	31-Oct-06	0.044 (0.049)	-	0.050 (0.026)	0.031	0.012
	2-Nov-06	0.028 (0.041)	-	0.048 (0.028)	*	*
	3-Nov-06	0.166 (0.054)	-	0.142 (0.051)	0.104	0.062
	4-Nov-06	0.110 (0.046)	-	0.122 (0.039)	*	*
	5-Nov-06	0.065 (0.046)	-	0.102 (0.034)	0.078	0.013
	7-Nov-06	0.042 (0.044)	-	0.075 (0.030)	0.052	0.011
	9-Nov-06	0.038 (0.043)	-	0.062 (0.028)	*	*
	13-Nov-06	0.192 (0.049)	-	0.236 (0.079)	0.180	0.012
	14-Nov-06	0.113 (0.038)	-	0.181 (0.050)	*	*
	16-Nov-06	0.105 (0.045)	-	0.151 (0.053)	*	*
	18-Nov-06	0.059 (0.046)	-	0.120 (0.052)	0.090	0.031

Yanco study areas were produced using the L-band Microwave Emission of the Biosphere model as per Panciera *et al*. (2009) and Merlin *et al*. (2009). The accuracy of the PLMR derived soil moisture data has been quantified at 0.04 m^3/m^3 (R. Panciera, pers. comm.) for the Goulburn area, and 0.03 m^3/m^3 for pixels with pasture and non-irrigated crops in the Yanco region (Merlin *et al.*, 2009) by direct comparison with averaged high resolution ground measurements of soil moisture. The 1 km resolution airborne soil moisture product was arithmetically averaged to obtain a SMOS equivalent value of soil moisture for each study area and date (Table 1).

3.2 Ground-based soil moisture

Ground-based measurements of soil moisture were all obtained using a Stevens Water Hydraprobe for the top 5 cm of soil (Panciera *et al*., 2008; Merlin *et al.*, 2008). These soil moisture measurements were calibrated to an accuracy of 0.033 m^3/m^3 as described by Merlin *et al*. (2007) and are summarised in Table 1. No area-weighting of any of the ground-based soil moisture measurements was performed, nor was any constraint applied to limit the use of point measurements within a particular distance to each other.

Regional ground-based soil moisture measurements for the top 5 cm were only obtained for the Goulburn area on three dates. These regional sampling measurements were made in fields abutting the existing road networks at an approximate spacing of 2 km with single soil moisture measurements at each location.

Both the Goulburn River catchment and the Yanco area have soil moisture monitoring stations which measure the moisture throughout the top 5 cm (and root zone). Daily soil moisture values were calculated for each station based on the average of measurements taken every 20 minutes from 6am to 10am to coincide with airborne measurements. In the Goulburn catchment, 13 monitoring stations within the study area mapped by PLMR could be used (Figure 2). Of these, 6 are located in the 150 ha microcatchment called "Stanley". In the Yanco region, 9 monitoring stations are within the study area mapped by PLMR (Figure 4).

4 RESULTS AND DISCUSSION

The general approach for this study was to use the airborne data to obtain a spatial average value of soil moisture for the SMOS sized study areas, and to compare this to the average soil moisture from ground-based measurements. First the number of stations needed to obtain the spatial average was determined. Then existing monitoring networks were assessed for their ability to correctly estimate the spatial average.

4.1 Number of sample points required?

The number of sample points required to obtain the spatial average for a SMOS sized pixel was determined from the large number of measurements obtained at the Goulburn study area during regional sampling. This was determined by creating pseudo "networks" using the sample points. One thousand networks of up to 50 sample points each were created by random sampling, ensuring that each sample point was only used once per network. A general trend for all sampling dates is that the use of more point measurements results in a smaller error (Figure 5). The airborne soil moisture value is reached with a root mean square error (RMSE) of 0.04 m^3/m^3 when using about 15 samples for 7 and 14 November. However, the samples from 21 November do not reach this target regardless of the number of points averaged. This was due to the distribution of the samples not capturing the full variability of soil moisture in the area, particularly in the far north and south (Figure 3 and Table 1).

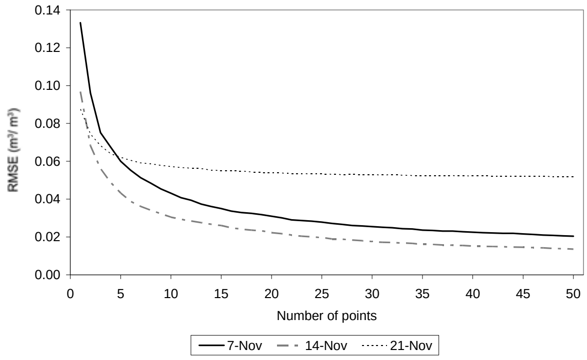

Figure 5. RMSE of mean soil moisture from sample sets using up to 50 of the ground-based measurements when compared to the airborne measured soil moisture of the Goulburn area on separate days. The RMSE was calculated from 1,000 random sets of 139 to 181 ground measurements depending on the sampling date.

It was also found that the variability of point measurements is larger when soil moisture is greater and decreases as the area becomes drier (Table 1). Figure 5 shows that a greater number of samples is required on the wetter day (7 November) to represent the average within an RMSE of 0.04 m^3/m^3, compared to the drier day (14 November). This analysis suggests that 5 (dry) to 15 (wet) point samples are required to obtain the average soil moisture for a 50 km area, provided that the distribution of the samples are such that they capture the spatial variability of soil moisture in the area.

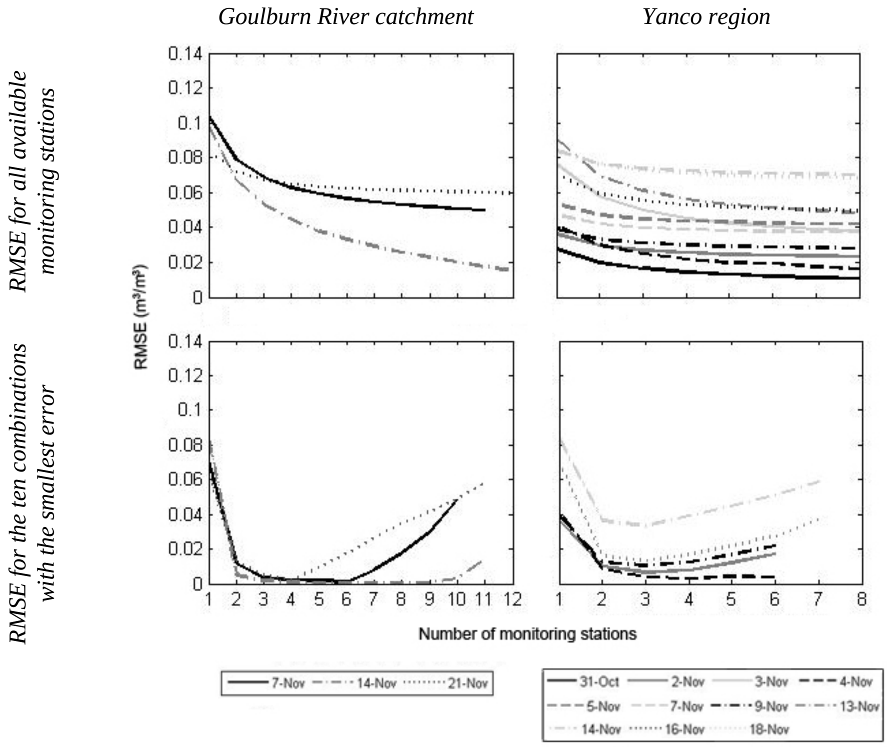

Figure 6. RMSE for soil moisture estimates in the two study areas using measurements from existing monitoring networks and airborne measured soil moisture. Top row depicts mean from all possible combinations of all stations; bottom row depicts mean from the ten combinations that produced the smallest error.

4.2 Accuracy of existing monitoring network in the Goulburn River catchment study area?

In the Goulburn Catchment, only 13 (stations shown in bold) of the possible 18 monitoring stations within the NAFE'05 study area measured the soil moisture for the top 5 cm during the campaign, due to unexpected instrument failures (Figure 2). The average soil moisture from all possible combinations of these monitoring stations was calculated for each date. Similar to the regional sampling, a greater number of samples reduced the error between the average soil moisture from point measurements and the airborne soil moisture (Figure 6). However, similar to the regional sampling, the error did not decrease significantly after about 5 stations, with the error remaining above 0.06 m^3/m^3 for two of the days. This suggests that some of the installed stations may not be representative of the area and consequently introduce errors in the area average.

To further investigate this, the ten combinations that produced the smallest error were identified and compared. As shown in Figure 6, the error initially decreased, but then increased beyond about 4 to 8 stations, with the actual number varying each day. This shows further that inclusion of particular monitoring stations degrades the spatial average.

Evaluation of the occurrence of each station in these combinations (Table 2) revealed that stations K3, M5, M6 and S1 all occur the most often across the three dates, and using these 4 stations alone the area averaged soil moisture is estimated with an RMSE of less than 0.06 m^3/m^3. However, these stations are not necessarily those that occur the most often within a date. For example, S7 is used in all ten of the best combinations on 7 November, but only in three combinations on 14 November. Consequently, a station that is representative on a given day is not always representative of the area; note that only one Stanley site is in this combination, showing no bias to the relatively densely populated microcatchment.

Stations K3, M5, M6 and S1, being the sites that give the best average, are all situated on sites that are generally wetter than other monitoring stations for the NAFE sampling period. This suggests that the overall current network is based on sites that are drier than the area average and thus not representative of the area.

4.3 Accuracy of existing monitoring network in the Yanco study area?

In the Yanco area, average soil moisture in the top 5 cm was estimated from all possible combinations of the 9 monitoring stations for each date. Again, use of a greater number of samples reduced the error between the average soil moisture from the monitoring stations and the airborne measurements (Figure 6), with little additional improvement when including more than 5 stations.

Given the greater number of sampling dates available for this study site, the samples were randomly split by date. Using monitoring data from half of the dates (2, 4, 9, 14 and 16 November) representative monitoring stations were identified using the approach outlined for the Goulburn area. As per the Goulburn area, errors initially decreased as more stations are considered, but then increased beyond about 3 stations (Figure 6).

For the Yanco region, stations Y5, Y7, Y10 and Y12 were found to be most representative (Table 3), with an average RMSE of less than 0.04 m^3/m^3 on any of the calibration dates. Using the four selected stations, the five remaining dates were assessed (Table 1), with an RMSE of 0.03 m^3/m^3.

5. CONCLUSIONS

This study has investigated the suitability of existing Australian soil moisture monitoring networks for their direct use in SMOS calibration and validation using ground-based point measurements and an airborne soil moisture product. Specifically, the northern part of the Goulburn catchment and the Yanco region of the Murrumbidgee catchment have been assessed. Although the various data sets used in this study were each accurate to within 0.04 m^3/m^3, they were assumed error free when performing analyses.

While it was found that up to 15 randomly selected point measurements were required to yield an estimate of the average moisture content for the top 5 cm of soil in the Goulburn area with an RMSE of less than 0.04 m^3/m^3, as few as 5 point measurements typically gave a RMSE of less than 0.06 m^3/m^3. Moreover, more accurate estimates could be achieved by using carefully

Table 2. Occurrence of each monitoring station in the ten combinations with least absolute error compared to airborne measured soil moisture in the Goulburn area.

	07-Nov	14-Nov	21-Nov
K1	4	6	10
K2	n/a	6	0
K3	8	8	8
M2	0	8	0
M3	8	6	7
M5	10	6	10
M6	8	6	10
S1	10	8	10
S3	0	6	0
S4	9	5	5
S5	8	6	5
S6	5	6	7
S7	10	3	8

selected sites. Specifically, it was found that stations K3, M5, M6 and S1 produced a spatially averaged soil moisture estimate to within 0.07 m^3/m^3 for the Goulburn catchment, and that stations Y5, Y7, Y10 and Y12 produced a spatially averaged soil moisture estimate to within 0.04 m^3/m^3 for the Yanco area. While this suggests that current monitoring station locations in the Goulburn area are unsuitable for SMOS validation on their own, the limitations of the data used for this analysis should not be forgotten. Specifically, this assessment for the Goulburn area was based on only three dates, while the Yanco assessment was based on eleven dates.

Table 3. Occurrence of each monitoring station in the ten combinations with least absolute error compared to airborne measured soil moisture in the Goulburn area.

	02-Nov	**04-Nov**	**09-Nov**	**14-Nov**	**16-Nov**
Y2	3	5	4	0	0
Y4	3	2	3	3	3
Y5	8	8	8	7	6
Y7	10	7	9	10	9
Y9	1	1	0	0	0
Y10	6	7	7	7	6
Y11	0	0	0	7	9
Y12	7	5	7	3	5
Y13	2	5	2	3	2

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