The Tarrawarra Project: High resolution spatial measurement and analysis of hydrological response

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Abstract Specialised equipment enables us to collect high resolution ground based measurements of the spatial patterns of soil moisture. Data collection on a 10 m by 20 m grid over a 10.5 ha agricultural catchment in SE Australia has been undertaken on 13 occasions, along with additional data at higher spatial or temporal resolutions collected from 0.6 to 1.7 ha areas on several occasions. Meteorological and runoff measurements were also made and 250 soil cores have been collected enabling detailed descriptions of soil type and depth. Seventy four piezometers and 20 access tubes for a Neutron Moisture meter are regularly read to provide information on subsurface dynamics. In addition, overpasses by the European Space Agency satellites ERS1/2 and an overflight by a specially equipped NASA plane collected Synthetic Aperture Radar (SAR) images coincident with ground measurements. These provide the opportunity for the most detailed ground truthing of SAR estimates of soil moisture estimation yet undertaken. The data are being used to explore the spatial hydrological response of the catchment to particular runoff events and longer-term patterns of streamflow generation. This is being done both through direct analysis of the data and by using distributed parameter hydrological models. The use of terrain based wetness indices for predicting soil moisture patterns is also being explored, as are several conceptual developments related to the spatial and temporal behaviour of soil moisture over various scales. This paper provides an overview of the field and remotely sensed data, a summary of the analyses to date, and prospects for future use of the data and development of the concepts arising from the analyses.

1 INTRODUCTION

In 1995, an experiment began to collect and analyse one of the most comprehensive sets of spatial soil moisture measurements over a small catchment, yet undertaken. The data include high resolution spatial patterns, detailed moisture profile data, and some remotely sensed images from both airborne and satellite based instruments. The project was undertaken on a 10.5 ha pasture catchment, known as Tarrawarra, situated approximately 60 km east of Melbourne in the Yarra Valley. The experimental phase of the project is now complete and a range of analyses have been undertaken or are in progress. This paper presents an overview of the project, beginning with its motivation, briefly describing the experimental methods employed and presenting a precis of some of the key findings to date in terms of hydrological process, geostatistical characterisation and implications for the representation of spatial soil moisture behaviour in general.

The data set also provides an excellent opportunity for the testing and development of spatially distributed hydrological models. While we will not discuss this aspect of the work in this paper, the following paper in this publication presents some of the results from preliminary modelling.

2 MOTIVATION FOR THE TARRAWARRA PROJECT

The primary scientific motivation for the Tarrawarra project was to investigate the spatial organisation of hydrological processes, particularly soil moisture. This information was to be used to test and develop concepts about spatial organisation and methods for its description and representation in hydrological models (Western et al., 1996).

Near-surface soil moisture is a major control on hydrological processes at both the storm event scale and in the long term. It influences the partitioning of precipitation into infiltration and runoff and is important in evapotranspiration because it controls water availability to plants and thus affects the partitioning of latent and sensible heat. Soil moisture is also a key state variable in hydrological models. While the spatial resolution of modern distributed parameter models is impressive, our ability to test the spatial performance of these models is severely limited by a lack of suitable data (eg., Beven, 1989; Grayson et al., 1992). Measured soil moisture patterns provide such suitable data.

The absence of detailed spatial measurements has required alternative representations of spatial variability to be developed for modelling purposes. These range from the application of geostatistical techniques to deterministic representations such as wetness indices which are generally based on topographic information (eg., Beven and Kirkby, 1979; O'Loughlin, 1986), and remote sensing methods (eg., Engman, 1995). The extent to which any of these approaches are applicable has rarely been tested due to a lack of ground data, despite the importance to hydrological simulations (eg., Grayson et al., 1995). The Tarrawarra experiment was designed to address that deficiency.

3 EXPERIMENTAL DESIGN AND RESULTS

3.1 Design

The Tarrawarra catchment is 10.5 ha in area with two main drainage lines, an overall relief of 30 m and slopes up to 15% (Figure 1). Average annual rainfall is 1000 mm and class A pan evaporation is 1200 mm. The major soil type is duplex with a clay-loam A horizon of 20 to 40 cm and a clay B horizon from 50 to over 150 cm deep. The base of the depressions have much higher levels of silt and clay and are more gradational. The primary measurement period was from September 1995 to March 1997.

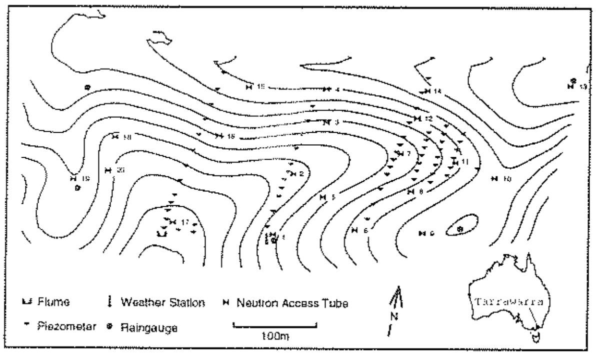

Figure 1 Tarrawarra catchment and sampling sites

The catchment has a weather station with a pluviometer, net and global radiation, wind speed and direction, wet and dry bulb temperature, soil temperature at 5 depths and soil surface temperature. All atmospheric data are logged at 6 minute intervals. A calibrated flume measures runoff at the catchment outlet and five collecting raingauges provide information on the spatial variability of rainfall. Twenty access tubes for a Neutron Moisture Meter are installed to depth of refusal (75-150 cm) and measured approximately fortnightly (more often during rain) to provide soil moisture profile data (accurate to ± 2.5% volumetric water content). Figure 2 shows the time series of NMM measurements over the top 60 cm, scaled by the wettest and driest readings during the measurement period. Seventy four piezometers were used in the wet periods to measure the water table that developed in the A horizon.

On 13 occasions during the experimental period, soil moisture measurements in the top 30 cm were obtained using Time Domain Reflectrometry (TDR) on a 10 m by 20 m grid over the whole catchment. This represents approximately 520 individual measurements on each occasion. The data were collected using a specially designed all terrain vehicle incorporating a differential GPS guidance system (accurate to ± 0.5m), hydraulic insertion of TDR probes and logging of all data. On one of these occasions, a 10 m by 10 m sampling grid was used (over 1000 points); on another, four measurements were taken at each site on the 10 m by 20 m grid (over 2000 points); and on another, a subsection of the catchment was sampled on a 2 m by 2 m grid, imbedded in a standard run. Table 1. provides a summary of the dates and soil moisture conditions during each of these sampling exercises and Figure 3 shows some of the measured data (note that each "pixel" represents one measurement). The TDR measurements were made at the rate of 50 to 100 per hour, depending on the experimental arrangement, and moisture measurements are accurate to ± 1.7% v/v.

The main data sets are discussed in detail in Western and Grayson (1997) and the data will be available at http://www.civag.unimelb.edu.au/data/ in early 1998.

Table 1 Summary of Tarrawarra TDR data sets

Date	No. of samples	Mean (%v/v)	Variance $(\%v/v)^2$
27/9/95	502	37.7	24.1
14/2/96	498	26.2	10.6
23/2/96	518	20.8	5.31
28/3/96	501	23.9	7.06
13/4/96*	507	35.2	12.3
22/4/96	513	40.5	14.6
2/5/96*	2056	41.4	19.4
3/6/96	505	45.0	14.0
2/9/96	515	48.5	13.9
20/9/96*	512	47.3	15.2
25/10/96*	490	35.0	19.2
10/11/96*	1008	29.3	10.8
29/11/96*	514	23.9	6.28

The TDR sampling runs noted with an asterisk in Table 1 were timed to coincide with the overpass of the European Space Agency's ERS satellites. The first two dates were when both ERS1 and ERS2 were operational (the so called "tandem mission") while the later dates were ERS2 only. The two satellites carry C-band (5.3 GHz) Synthetic Aperture Radar (SAR) sensors that theoretically have the capacity to measure dielectric constant of the earth surface and hence enable estimation of soil water content in a similar manner to TDR. It should be noted that the ERS SAR instruments were not specifically designed for measuring soil moisture, are known to be affected by surface roughness and vegetation, and have a depth of penetration limited to approximately 5 cm. Nevertheless, this is the only space platform with microwave sensors in a wavelength suitable for soil moisture measurement, and the small pixel size (25 m) enables spatial detail to be resolved. On the occasions of the satellite overpasses, surface roughness and vegetative measurements were made to help interpret the SAR signal. Figure 4 shows a SAR image for Tarrawarra, without any corrections.

In November 1996, a NASA DC8 overflew the site with SAR instruments measuring in the C, L and P bands, with a ground resolution of approximately 6 m. On this occasion the ground sampling included a 5 km long transect across the Yarra Valley at a 20 m spacing and with TDR measurements at both 15 and 30 cm.

In order to properly interpret the soil moisture measurements and for modelling purposes, detailed sampling and characterisation of the soils is underway. In May 1996, 125 soil cores were taken on a 20 by 40 m grid to a depth of approximately 75 cm. These were used for the definition of horizon depths, basic textural analysis and preliminary description of soil types. In July 1997, another 125 soil cores of the top 30 cm were taken for the characterisation of bulk density, soil hydraulic properties and particle size analyses.

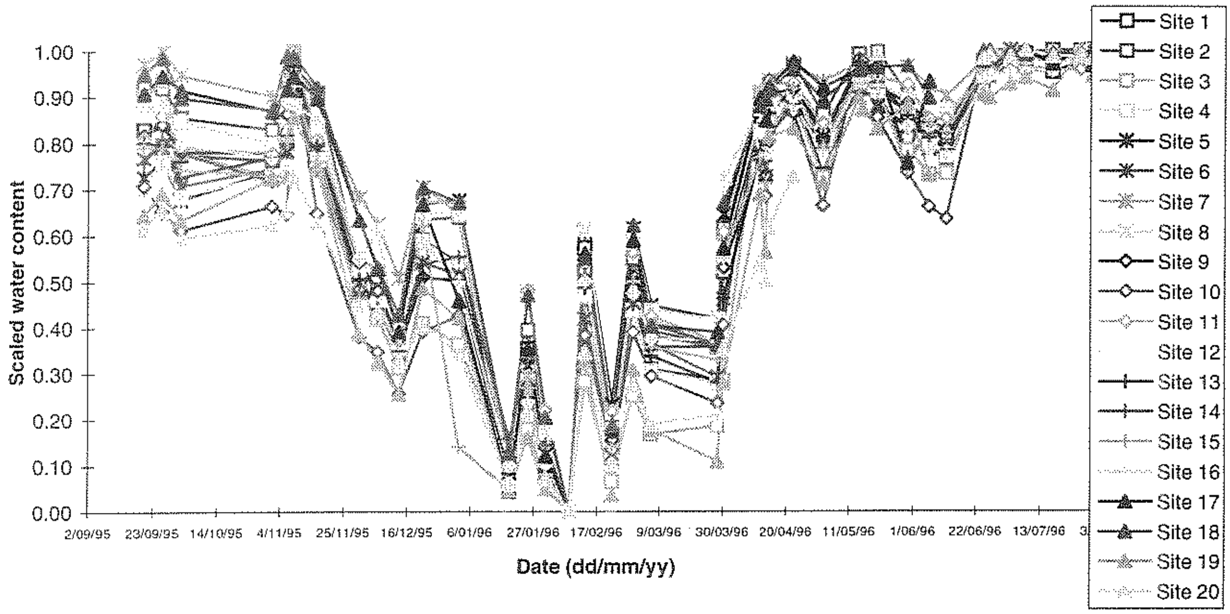

Figure 2 NMM data from 20 sites at Tarrawarra

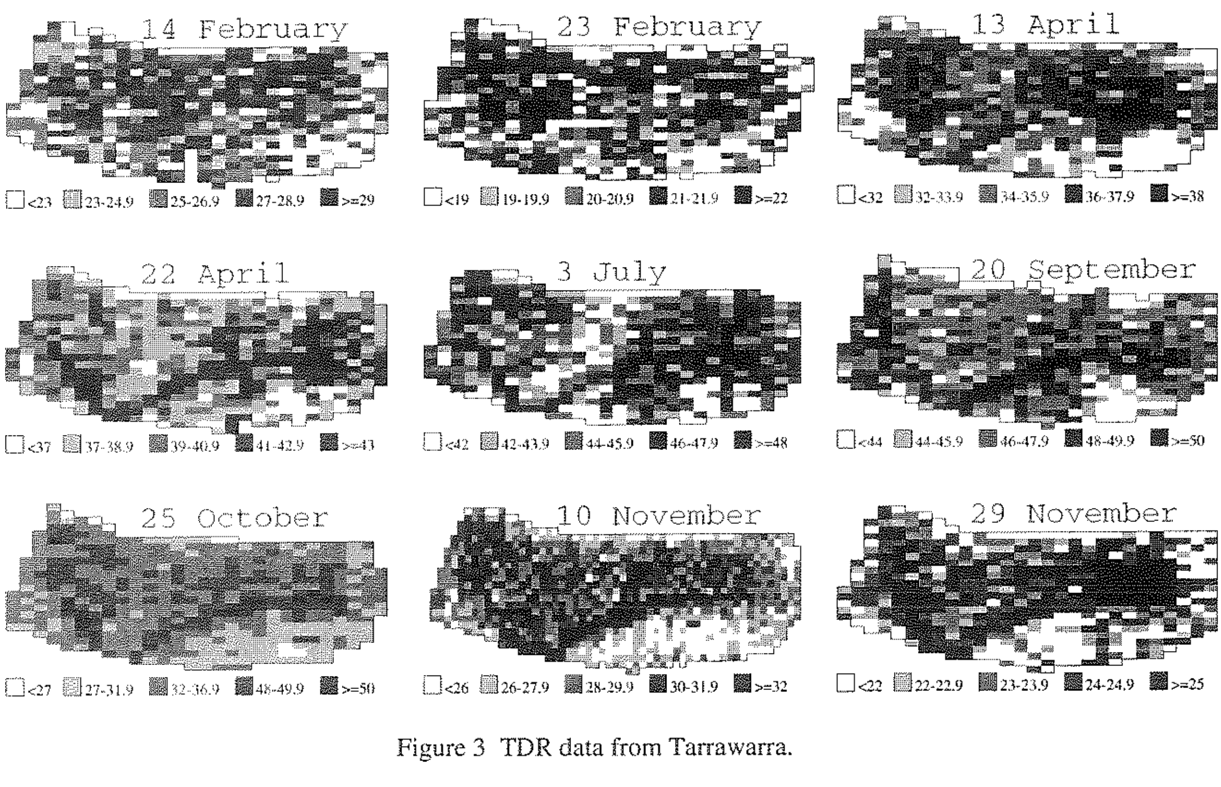

Figure 3 TDR data from Tarrawarra.

4 KEY FINDINGS

The following section presents a summary of some of the more important findings from the study so far. These are presented in three sections. The first concentrates on issues of basic hydrological understanding and representation, the second discusses the remotely sensed data and the third focuses on geostatistical properties of the data sets and the extent to which geostatistical techniques can be used to represent patterns of hydrological significance. These results are more fully discussed in a series of papers listed in the references.

4.1 Hydrological understanding

A striking feature of the patterns in Figure 3 is the difference in apparent organisation between the summer and winter data. During the wetter periods, the soil moisture patterns appear dominated by topography while in summer the patterns appear much more random. In addition, Figure 2 indicates that the temporal variation between primarily wet and dry periods occurs rather quickly. This observation, along with analysis of data from some other locations, forms the basis of a hypothesis that spatial soil moisture patterns in temperate regions switch between two "preferred states", each dominated by different hydrological fluxes (Grayson et al., 1997). The premise is that in the summer, vertical fluxes dominate, with precipitation being rapidly evaporated and little opportunity for lateral redistribution. As evaporation declines in autumn, soil moisture levels rise and lateral redistribution begins to become important, particularly in areas of high local convergence. These areas are the first to become saturated (April 13 in Figure 3; see also Barling et al., 1994). Once runoff occurs from these "source areas", the drainage lines rapidly wet up both from above (surface flow) and due to subsurface flow as the non-linearity of hydraulic conductivity with moisture content ensures more rapid subsurface lateral redistribution. Under these conditions, topography dominates the soil moisture patterns. During spring, evaporation increases and once soil moisture levels drop below 70 to 80% of saturation, lateral redistribution is limited and the dry pattern becomes established. Grayson et al. (1997) show that this behaviour is not unique to Tarrawarra and that it has important implications for the way spatial patterns of soil moisture are represented in models, particularly those that use topographically based wetness indices for spatially distributing bulk estimates of soil moisture.

The preceding analysis indicates that while these index based methods may be applicable to wet winter conditions, they a poor descriptors of drier conditions. It is proposed that different indices be developed to describe wet and dry patterns, along with a switching criterion to determine which index is appropriate.

Western et al. (1997a) assess the performance of common terrain based indices using the TDR data. Table 2 shows the coefficients of determination for a range of dates, indicating that, at best, 50 % of the variation in measured soil moisture is explained by common indices during the wetter periods and that none perform well during drier conditions. Work is continuing in the development of modified indices that will enable the basic elegance and parsimony of index-based modelling to be preserved, but provide better representations of the spatial organisation of soil moisture.

Table 2 R^2 for selected TDR data sets.

Date	ln(a/tanβ)	ln(a)	tangent curvature	cos(aspect)
27/9/95	0.42	0.50	0.31	0.21
23/2/96	0.02	0.05	0.02	0.04
13/4/96	0.14	0.23	0.14	0.15
2/5/96	0.50	0.55	0.21	0.00
3/5/96	0.12	0.14	0.12	0.00

While the soil moisture patterns during the drier periods appear to be random, it is highly likely that they reflect, at least in part, soil characteristics. Deeper soil profiles and those with finer texture will hold more moisture and for longer under dry conditions than shallow, or coarser textured profiles. Qualitative relationships between the spatial patterns of saturation deficit and soil properties have been observed but are yet to be quantified. Similarly, there appear to be relationships between features of the terrain and soil characteristics; however, these require results from analysis still in progress to substantiate these observations. These analyses include more extensive textural descriptions, soil moisture characteristic definition and measurements of soil structural properties.

4.2 Remotely Sensed Data

To date, four ERS SAR images have been analysed and compared to the ground based measurements of soil moisture. The base pixel size of ERS 1 and 2 data is 12.5 m which is aggregated to 25 m. A number of small farm dams around the Tarrawarra site provided excellent reference points in the SAR images enabling georeferencing to be accurate to less than 25 m. The raw SAR signal was converted to dB using standard parameters provided by the European Space Agency, and moisture content was computed using an inversion algorithm based on soil type and surface roughness. The SAR signal is influenced by moisture in the top few cm of soil, whereas the TDR measurements are over the top 30 cm. Given the relatively wet soil profile, this is not considered a problem for the images processed to date. The results of pixel to pixel comparisons were poor with R^2 less than 6%. It can be concluded that the combined influences of terrain, surface roughness and vegetation conspire to confound the ERS SAR signal such that it is not useful for individual site measurement of moisture content.

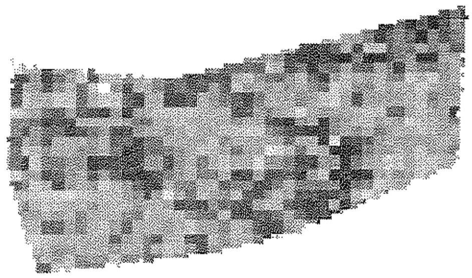

Figure 5 Raw SAR signal for Tarrawarra 13/4/96

Other researchers have found that multi-temporal analysis (comparison of images taken at different times) can be useful because it can remove some of the noise due to extraneous influences (eg., De Troch et al., 1996). In a similar style of analysis, multifrequency measurements, taken at the same time, as was the case with the NASA data in November 1996, should provide better estimates because the influence of vegetation and surface roughness can be computed out of the signal. These analyses are yet to be performed and are unlikely to be complete until mid 1998.

At present, we may conclude that remote sensing of soil moisture using microwave sensors is some way off being an operational tool (see also Ulaby et al., 1996; De Troch et al., 1996; Engman, 1995).

4.3 Geostatistical Analyses

In the absence of spatial data to explicitly represent variability in features such as soil moisture or saturation deficit, it is common to use geostatistical methods to generate spatial patterns with particular types of variability and spatial correlation. This approach is widely used in groundwater investigations and is central to stochastic approaches for the representation of uncertainty. If geostatistical methods can capture the fundamental features of spatial patterns that are important hydrologically, they will be powerful tools for spatial modelling. If however, they are poor representations of these features, application of the methods will distort the subsequent simulation results.

The most common tool to use is the variogram which describes the spatial correlation between measurements as a function of separation. Western et al (1997b) present a geostatistical analysis of the TDR data sets and conclude that soil moisture patterns for dry conditions have lower variance, longer correlation lengths and higher nugget relative to the sill, than patterns for wet conditions. They also concluded that the number of samples required for accurate estimation of the variogram was approximately 300. This is substantially greater than the number of samples used in most published studies of the geostatistics of soil moisture.

It is important to recognise that, from a hydrological perspective, the variogram does not capture all the important features of soil moisture patterns. Grayson et al. (1995) show that patterns of saturation deficit which have the same variogram can give extremely different results when used in modelling. This is because variograms do not provide information on the connectivity of patterns. In terms of soil moisture and runoff, how well the wet areas are connected to the catchment outlet is crucial to runoff response.

It has been proposed in the literature that indicator variograms may be able to capture features of connectivity (Anderson, 1997; Journel, 1983). An indicator variogram is based on a binary classification of the spatial pattern at a specific threshold. Comparing indicator variograms for different thresholds provides information on how the spatial continuity changes as a function of moisture content. Substantial differences in the correlation lengths of indicator variograms for different thresholds have been interpreted in the literature as evidence for connectivity. Western et al. (1997c) present an application of indicator geostatistics to the TDR data set. They show that the these techniques *cannot* capture the connectivity features that are important hydrologically.

Work is progressing on other connectivity measures, and preliminary analysis using the work of Journel and Alabert (1989) indicates that these measures can differentiate between patterns in terms that are relevant to hydrological response. This work is incomplete and it is as yet unclear how these measures can be used to generate patterns with equivalent statistics.

5. FURTHER WORK

A number of components of the work presented are yet to be completed. These include the remote sensing analysis and the work on representation of soil characteristics and their relationship to the patterns of soil moisture and terrain. In addition, a range of modelling studies are planned and underway, some details of which are provided in the following paper.

The main thrust of ongoing work is to extend to larger scales, looking particularly at the estimation of areal soil moisture behaviour and the role of spatial variability on measured hydrological response. This work involves a 50 km^2 catchment in New Zealand that has 30 nested gauging stations and a series of soil moisture monitoring sites as well as an extended region around Tarrawarra. Amongst other things, this work will look at the applicability of the idea that CASMM (Catchment Average Soil Moisture Monitoring) sites exist in the landscape. We define CASMM sites as *certain parts of the landscape which consistently exhibit mean behaviour irrespective of the overall wetness.* The idea is based on the notion of time stability, first introduced by Vachaud et al. (1985). Preliminary analysis of the Tarrawarra data and data from Kalma et al. (1985) and Loague (1992) indicate that CASMM sites do exist in landscapes (Grayson and Western, 1997). If this can be proven over a wider range of terrain and climatic conditions, and if these locations can be identified apriori, it may provide a method for interpreting point measurements in an areal context. It would therefore provide a framework for the testing of large footprint remote sensing devices and for developing a network of routine sampling sites that could be used for the quantification of areal soil moisture status.

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