Comparisons of Soil Moisture Simulations from the VB95 Land Surface Model Against Observations

H. Richter[a,b], A.W. Western[a,c] and F.H.S. Chiew[a,c]

[a]Cooperative Research Centre for Catchment Hydrology
[b]Bureau of Meteorology Research Centre
[c]Department of Civil and Environmental Engineering, University of Melbourne
h.richter@bom.gov.au

Abstract: Numerical Weather Prediction (NWP) models are sensitive to predictions of soil moisture and evapotranspiration at the land surface. This paper compares simulations of the stand-alone VB95 land surface model with various soil and vegetation parameter sets against soil moisture and soil temperature observations across the Murrumbidgee River catchment. The results indicate that the simulations are sensitive to the soil and vegetation parameters. In general, VB95 can model the temporal fluctuation in soil moisture, and therefore the moisture fluxes, realistically. However, the model exhibits a significant bias in the absolute soil moisture and soil temperature, highlighting the need to improve the model formulation or our estimates of soil and vegetation properties for modelling applications.

Keywords: *Soil moisture; Land surface model; Water budget; NWP model; Australia*

1. INTRODUCTION

Soil moisture plays an important role in the exchange of water and energy between the land surface and the atmospheric boundary layer. For example, the initiation of moist convection can be heavily influenced by the distribution of soil moisture in the region (Pielke Sr., 2001; Weaver and Avissar, 2001). Numerical experiments have shown that the soil moisture pattern over Victoria can alter the movement of wind shift lines significantly (Mills, 1995), which, in an Australian context, is particularly relevant for the prediction of fire behaviour some hours ahead. Fog and low cloud prediction, as another threshold process, is also very sensitive to the surface fluxes controlled by soil moisture (Bergot and Guedalia, 1994).

The land surface model developed by Viterbo and Beljaars (1995) (hereafter VB95) is used in some of the operational Bureau of Meteorology numerical weather prediction models (NWPs). Although VB95 has been tested in various climatic regimes, its performance under Australian climate, soil and vegetation conditions is unknown. In its present application, the same globally uniform parameter values are used for all the NWP modelling grids.

This paper compares the stand-alone VB95 simulations using the globally uniform parameter values and parameter values derived from spatial soils and vegetation data for ten locations in the Murrumbidgee catchment in southeast Australia. The paper also compares the modelled soil moisture and soil temperature with continuous observations from a field monitoring program.

2. THE BOM NWP MODEL SUITE AND THE VB95 LAND SURFACE MODEL

VB95 is likely to become the land surface scheme of the entire suite of operational NWP models in Australia. The three primary operational NWP models (for the extra-tropics) are the Global Assimilation and Prediction System (GASP) global model, the Limited Area Prediction System (LAPS) and its mesoscale companion model Meso-LAPS (Seaman et al., 1995; Puri et al., 1998). GASP has an approximate spatial resolution of 75 km and runs out to 7 days. LAPS extends from 65^{O}S – 17.125^{O}N and 65^{O}E – 184.625^{O}E with an approximate spatial resolution of 37.5 km. Meso-LAPS covers the domain 55^{O}S - 4.875^{O}N and 95^{O}E-169.875^{O}E with an approximate spatial resolution of 12.5 km. LAPS runs to 60 hours, while Meso-LAPS runs out to 36 hours. Fields in the LAPS and Meso-LAPS model are defined on 29 sigma-levels (a terrain-following coordinate) between the ground and ~20 km (10 m–2 km resolution. The dynamic time step is 40 seconds, while physics packages (including the land surface scheme) are called every 6 minutes. The initialization of the soil moisture field in the Meso-LAPS model, for example, is currently a 12-hour nudging process, which uses observed screen-level specific humidity to correct the root-zone layer soil moisture (Mahfouf, 1991; Viterbo, 1996). Operationally, VB95 coupled to Meso-LAPS only runs out to 36 hours, placing the main emphasis on the latent and sensible heat fluxes produced by VB95 in the 0-36 h time period.

The VB95 land surface model is forced by the following Meso-LAPS fields: large-scale rainfall, convective rainfall, shortwave radiation (down), thermal radiation (down), specific humidity, temperature, wind speed and wind direction (the last four fields all taken at the lowest model level). The most important quantities estimated by VB95 for the atmospheric model are the latent and sensible heat fluxes, which strongly influence the boundary layer of the atmospheric model.

VB95 is a prognostic scheme for soil moisture and soil temperature in four soil levels, along with a skin temperature (see Figure 1). It solves the Richard's equation for vertical water exchanges between the soil layers. Rainfall first fills an interception reservoir (W_l) before infiltration into the topmost soil layer occurs. Evapotranspiration can occur from the interception reservoir, the bare soil in the top soil layer and through dry vegetation with roots in the top three soil layers.

3. SOIL MOISTURE MONITORING PROGRAM

The Murrumbidgee River catchment is a large (~100,000 km^2), predominantly east-west oriented catchment in the southern part of New South Wales in southeast Australia (see Figure 5). Rainfall across the Murrumbidgee varies from about 330 mm per year in the western part to about 1900 mm per year in the mountainous eastern part. Elevations range from 50 m to 1900 m, also from West to East. Soils are made up largely of loam and sandy loam, except for the western third where heavier soils dominate (Western et al. 2002; McKenzie et al. 2000). Pasture and crops are prevalent in most of the catchment while the mountain areas are largely covered by forests (Barson et al. 2000).

A total of 18 monitoring stations have been collecting soil moisture, soil temperature and soil suction data since September 2001. Ten of these stations have been clustered into groups of 5 stations in each the Kyeamba Creek and Adelong Creek sub-catchments. Soil moisture is measured as an average over the 4 layers 0-7 cm, 0-30 cm, 30-60 cm and 60-90 cm. Soil temperature and soil suction are measured at the midpoints of each layer (see Figure 1). Soil moisture and soil suction are measured every 30 minutes, while soil temperature and rainfall are recorded every 6 minutes. The CS615 determined soil moisture values used in this study have been calibrated against time domain reflectometry (TDR) sensors.

4. PARAMETER VALUES AND FORCING DATA FOR VB95

In the current operational NWP modelling runs, VB95 assumes a globally uniform medium-textured soil and a globally uniform leaf area index in the vegetated fraction, but temporally constant and spatially varying fractional vegetation coverage ("default" values in Table 1). The "variable" soil and vegetation

Site	θ_{pwp}	θ_{cap}	θ_{sat}	γ_{sat}	vfrac	LAI	AEP	b
Default	*0.171*	*0.323*	*0.472*	*4.57x10^{-6}*	*0.87*	*4.0*	*-0.338*	*6.04*
Kyeamba	0.230	0.296	0.343	8.33x10^{-8}	0.6121	2.48	-0.323	15.3
Adelong	0.239	0.301	0.341	8.33x10^{-6}	0.6815	2.80	-0.441	16.2
Cooma	0.120	0.241	0.523	8.33x10^{-6}	0.5865	2.05	-0.047	5.5
Canberra	0.187	0.263	0.377	8.33x10^{-7}	0.6545	2.31	-0.060	11.2
Cootamundra	0.196	0.283	0.436	8.33x10^{-6}	0.5713	2.50	-0.040	10.3
West Wyalong	0.230	0.296	0.343	8.33x10^{-8}	0.3797	1.30	-0.323	15.3
Yanco	0.274	0.344	0.374	2.78x10^{-6}	0.5228	1.82	-0.785	16.9
Griffith	0.274	0.344	0.374	2.78x10^{-6}	0.3596	1.24	-0.785	16.9
Hay	0.274	0.344	0.374	2.78x10^{-6}	0.4201	1.41	-0.785	16.9
Balranald	0.310	0.386	0.450	2.78x10^{-8}	0.4319	1.25	-0.279	16.9

Table 1. Soil and vegetation parameters used in the "default" and "variable" soil/vegetation runs using VB95 at 10 different sites throughout the Murrumbidgee catchment. The soil water content at wilting point (θ_{pwp}), field capacity (θ_{cap}) and saturation (θ_{sat}) are specified volumetrically (m^3 m^{-3}). The hydraulic conductivity at saturation (γ_{sat}) is specified in ms^{-1}. The fractional vegetation cover (**vfrac**) and the leaf area index (**LAI**) are annual averages of monthly varying values. In the operational models **vfrac** is a spatially varying field following Wilson and Henderson Sellers (1985). **AEP** is the air entry potential (m) and **b** is the Campbell b parameter.

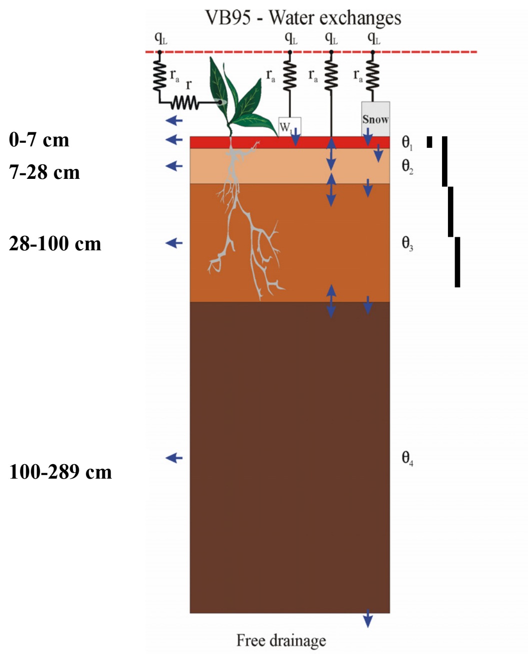

Figure 1. Water fluxes in the VB95 land surface scheme. The four soil layers have depths of 7 cm, 21 cm, 72 cm and 189 cm. The black vertical bars on the right indicate the four depths in which soil moisture observations are taken (see Section 3).

parameter values, estimated from spatial soils and vegetation data, for the ten locations in the Murrumbidgee catchment, are also given in Table 1.

The "variable" soil and vegetation parameters used in VB95 were derived as follows. Soil properties were obtained by extracting the soil landscape type from the digital Atlas of Australian Soils (Bureau of Rural Sciences after Commonwealth Scientific and Industrial Research Organisation, 1991), and then obtaining the dominant soil type within that soil landscape using (McKenzie et al., 2000) interpretations of soil properties for each (Northcote, 1979) soil type. McKenzie et al. (2000) give estimates of thickness and properties of the A and B horizons. The wilting point (1.5MPa), field capacity (10kPa) and porosity were depth averaged for these two horizons and used to calculate depth averaged effective (Campbell, 1974) parameters for solving Richard's Equation. The "field capacity" in Table 1 is used in the transpiration estimation, and it is defined as the moisture content at a suction of 33kPa. This was calculated from the effective Campbell parameters. The saturated hydraulic conductivity was set equal to the B horizon value given by McKenzie et al. (2000).

The percentage vegetation cover and the LAI of the canopy were specified using data from Lu et al. (in press) who estimated annual average woody LAI and fraction cover and monthly average herbaceous LAI and fraction cover for a thirteen year period on a 0.05º grid across Australia. The woody and herbaceous estimates were combined to estimate a monthly average total fraction of (green) vegetation cover and total LAI. Obviously these averages will be somewhat different to the actual conditions encountered at any time due to significant interannual variations in vegetation cover in response to variations in precipitation.

The forcing data used to run the stand-alone VB95 in this study is compiled from the BOM Automatic Weather Stations (AWS) and climate stations (see Siriwardena et al., 2003).

5. VB95 SENSITIVITY AND COMPARISONS WITH OBSERVATIONS

Four types of model experiments were performed: a control run (CTRL) using the default values for soil and vegetation as applied in the operational NWP models, and three cases (a-c). Case a) had default soil and variable vegetation, b) had variable soil and default vegetation and c) had variable soil and vegetation.

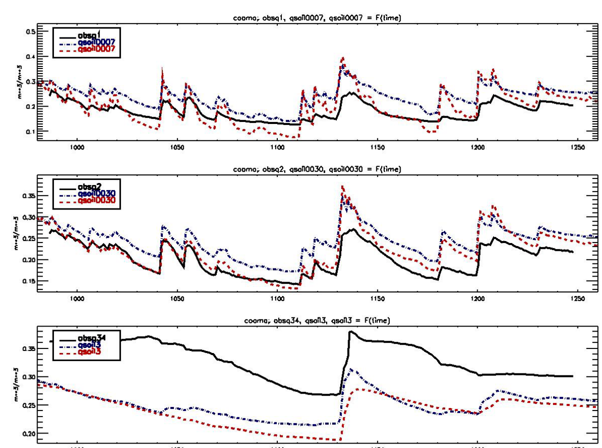

Figure 2. Volumetric soil moisture comparisons at Cooma between 11 September 2001 (day 985) and 31 May 2002 (day 1247). The three panels show results for the soil layers 0-7 cm (top panel), 0-30 cm (center panel) and 30-90 cm (bottom panel). The solid (black) line is the observed volumetric soil moisture, the dot-dash (blue) line the model moisture for the CTRL run, and the dashed (blue) line the model moisture for variable soil and variable vegetation (case c).

Figures 2 and 3 show comparisons between observed soil moisture and modelled values from the CTRL and case c runs for Cooma (one of the best) and Yanco (typical), respectively. At many sites there is a marked wet bias over the whole profile in the simulations, while at Canberra (not shown) the average soil moisture is simulated well. At some other sites (Cooma, Yanco, Cootamundra, Hay) the average moisture content of specific layers is well simulated. There is a greater tendency for a wet bias in the surface layers, and there is a mix of wet and dry biases for the deeper layers. In general, VB95 is able to simulate the temporal dynamics of soil moisture in terms of timing and amplitude well at nearly all sites (Figures 2 and 3).

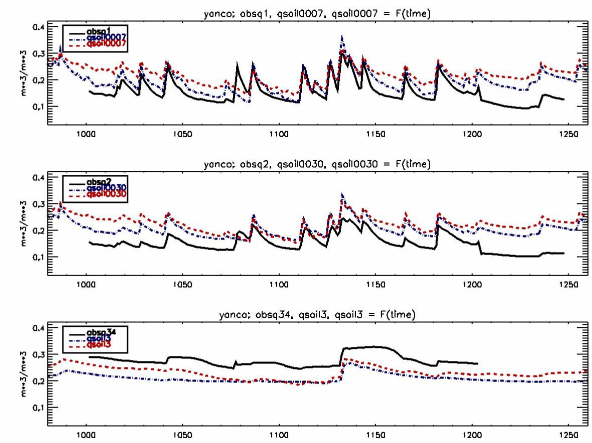

Figure 3. Same as Figure 2, but for Yanco.

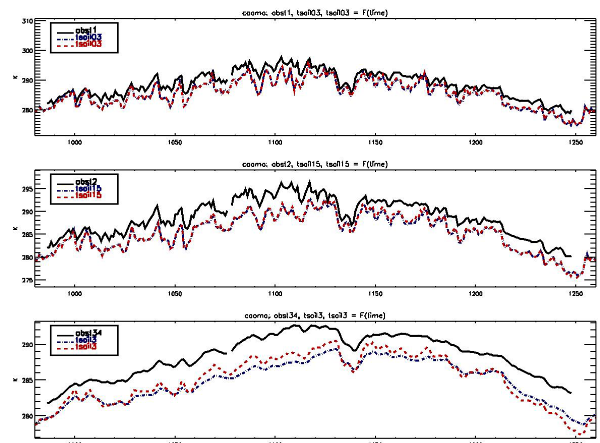

Figure 4. Same as Fig.2, but for Cooma soil temperatures at levels 3.5 cm (top panel), 15 cm (middle) and 60 cm (average of 30-60 and 60-90 cm; lower panel).

Figure 4 shows typical comparisons of the modelled and observed soil temperature averaged over 24 hours at Cooma around the levels 3.5, 15 and 60 cm. Compared to soil moisture, the modelled soil temperature is relatively insensitive to variations in soil type and vegetation (compare CTRL and c) simulations). The model is too cool in all soil levels, in particular the deeper level (30-90 cm).

Figure 5 illustrates the effect of variable soil texture and vegetation on the water budget at ten different Murrumbidgee sites for the time period 01 December 2000 – 30 November 2002. Each site-specific histogram shows the annual precipitation (first column) and the annual evapotranspiration (ET; from VB95) for the control run (second column) and each of the runs with modified parameters (cases a-c being columns 3-5, respectively).

For 25 out of the 40 simulations shown in Fig. 5 the soil water loss through evapotranspiration (ET) outweighs the water input through precipitation. The additional water needed for the ET equates to the storage depletion. This may indicate that running the model for about a 2-year period (prior to 01 December 2000) is insufficient to remove the effect of initial conditions. There are clear differences between simulations with each parameter set, and it is clear the soils parameters (compare columns 2 and 4) cause greater changes in simulated annual evapotranspiration than the vegetation parameters do (compare columns 2 and 3).

The sensitivity of the model ET to changes in soils and vegetation is slightly larger in terms of absolute changes in ET depth in the east (by about 25 mm/year), but the sensitivity in terms of proportional changes is greatest in the west due to the much lower rainfall and ET rates.

6. DISCUSSION

It is clear from Figures 2 to 5 that changing the soil and vegetation parameters has a significant impact on simulated soil moisture and the annual ET, but not on soil temperature. The impact of the changed soils parameters was greater than the impact of the changed vegetation characteristics in nearly all cases for these simulations. These results indicate that the parameterisation of surface properties is important for VB95 and numerical weather predicition models.

For soil moisture there are changes in the amount of bias, and more subtle changes in the temporal dynamics between the parameter sets. The bias in the soil moisture is likely to be primarily related to the parameters that control the impact of soil moisture on ET, which are θ_{cap} and particularly (given the dry conditions here) θ_{pwp}. Thus the results indicate that θ_{pwp} is generally set too high. The tendency for the wet bias to reduce with depth is probably also related in that real soils tend to become more clayey with depth, indicating a higher θ_{pwp}. The model, however, assumes that soils do not vary with depth.

The bias in absolute soil moisture has some important implications. If one were to initialise VB95 with measured soil moisture at the start of a forecast, serious errors in flux predictions are almost guaranteed. For example, at both Griffith and Kyeamba Creek the measured soil moisture is nearly always less than θ_{pwp} as specified in the model, implying that the simulated ET would be very low, but the behavior of the measured soil moisture clearly shows periods of significant ET (not shown).

It is also clear that we do not have adequate soil property information at our disposal to correct these biases. While using soil parameters based on the Atlas of Australian soils led to differences in soil moisture and ET, it did not lead to a consistent improvement in the soil moisture simulations presented here. This means that if we want to simulate fluxes or soil water availability to plants, we need an initialization approach that utilizes information on soil water availability rather than the absolute value of soil moisture.

It is evident from Figures 2 and 3 that using soil properties derived from the Atlas of Australian soils led to only subtle changes in the temporal pattern of the simulated soil moisture. This is probably because the forcing, particularly rainfall events, is largely responsible for the temporal variation in soil moisture. There are, however, some significant differences in the dry-down rates following rainfall. These are probably partly related to the direct effect of plant available water storage and vegetation cover on ET and the effect of unsaturated flow parameters on the transfer of water to deeper layers, which indirectly affects ET via the simulated soil moisture control on transpiration and the amount of bare soil evaporation.

Figure 5 shows the impact of various changes in soil and vegetation parameters on the annual ET. The variation of the model vegetation has different effects at each site. At the drier (western) sites the substantial reduction in leaf area index fraction cover are associated with a significant reduction in root extraction (less transpiration), but an even larger increase in bare soil evaporation. The reverse is true for the five eastern sites where a significant reduction in root extraction generally dominates an increase in bare soil evaporation resulting in lower total ET.

The changes to soil parameters led to a decrease in ET at six sites and an increase at four sites. Generally the decrease ET was due to less depletion in soil storage due to the reduction in the difference between field capacity and wilting point. At some sites (Kyeamba, Adelong, Canberra, West Wyalong) there was also a marked increase in runoff due to a reduction in θ_{sat}, resulting in a higher unsaturated hydraulic conductivity and increased drainage. At three dry sites (Yanco, Griffith, Hay) there was a marked increase in ET. Here θ_{sat} reduced substantially and θ_{pwp} increased substantially forcing the model to operate at a point with greater moisture diffusivity. These dry sites had an upward gradient and the additional ET was supplied by depleting the 1.89m thick deep layer.

7. CONCLUSIONS

This study presented comparisons between observed and modelled soil moisture and soil temperature as well as sensitivity of the VB95 land surface model to variations in soil texture and vegetation. Although the absolute values of soil moisture simulated by the model were often biased, the temporal dynamics of the soil moisture were well simulated. Correspondingly, the moisture fluxes simulated by the model are likely to be unaffected by model soil moisture bias. Utilising spatially variable soil and vegetation properties led to changes in the simulated soil moisture and ET, but it did not improve significantly the model predictions of soil moisture overall, indicating that obtaining correct parameter values is still a significant challenge. The bias in model predictions makes use of measured soil moisture for model initialization challenging. In general VB95 was more sensitive to soil properties than to vegetation cover, and vegetation appeared to have different effects in wet and dry climates.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

Barson, M., L. Randall and V. Bordas, 2000: Land cover change in Australia. Results of the collaborative Bureau of Rural Sciences – state agencies' project on remote sensing of agricultural land cover change, Bureau of Rural Sciences, Canberra.

Bergot, T. and D. Guedalia, 1994: Numerical forecasting of radiation fog. Part I: Numerical model and sensitivity tests. *Mon. Wea. Rev.,* **122,** 1218-1230.

Bureau of Rural Sciences after Commonwealth Scientific and Industrial Research Organisation, 1991. Digital Atlas of Australian Soils (ARC/INFO® vector format). [Online] Available HTML: http://www.brs.gov.au/data/datasets.

Campbell, G.S., 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Science, 117: 311-314.

Lu, H., Raupach, M.R., McVicar, T.R. and Barrett, D.J., in press. Decomposition of vegetation cover into woody and herbaceous components using AVHRR NDVI time series. Remote Sensing of Environment.

Mahfouf, J. F., 1991: Analysis of soil moisture from near-surface parameters: A feasibility study. *J. Appl. Meteor.,* **30,** 1524-1547.

McKenzie, N.J., D. W. Jacquier, L. J. Ashton and H. P. Cresswell, 2000: Estimation of soil properties using the Atlas of Australian Soils. 11/00, CSIRO Land and Water, Canberra.

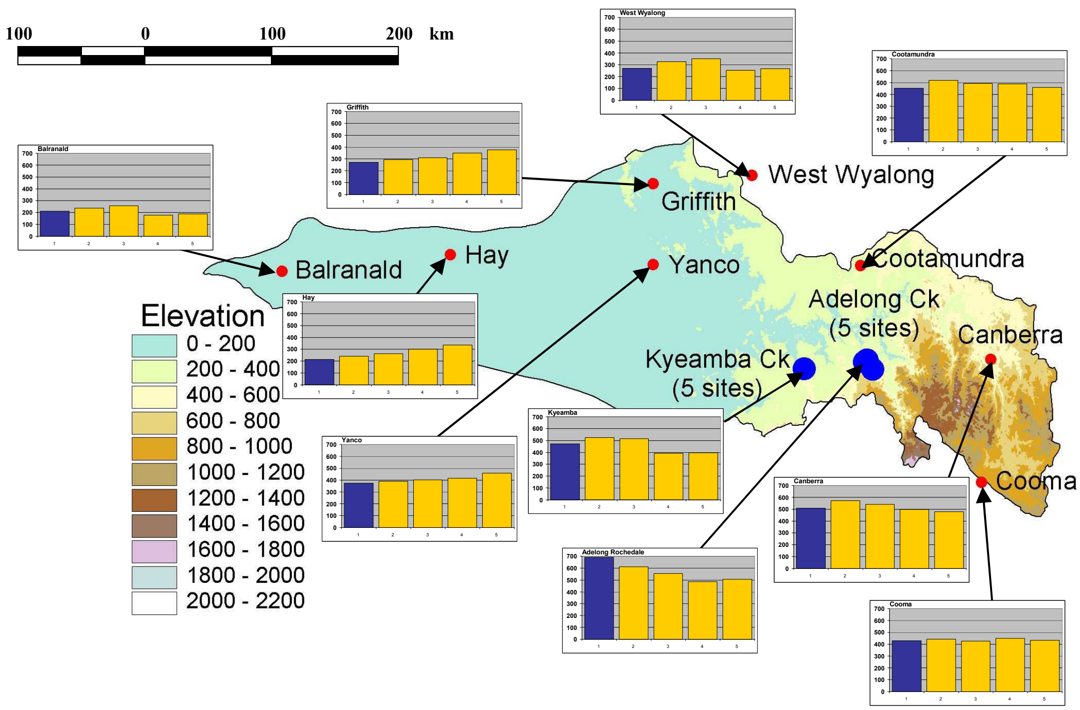

Figure 5. The eighteen sites where measurements of soil moisture, temperature and suction are recorded. The blue dots mark clusters of 5 individual sites in gauged catchments. The column charts show the dominant components of the annual water budget for 10 individual soil moisture stations in the Murrumbidgee averaged over the period 01 Dec 2000 to 31 Nov 2002. The first (blue) column in each histogram marks the measured precipitation (in mm), columns 2-5 represent simulated evapotranspiration for (2) default soil and vegetation, (3) default soil and variable vegetation, (4) variable soil and default vegetation and (5) variable soil and vegetation.

Mills G.A., 1995: The Enfield fire – LAPS model results. Proceedings, 6th Fire Weather Workshop, Hahndorf, South Australia, 18-22 June 1995. Bureau of Meteorology, PO Box 1289K, Melbourne VIC 3001, Australia.

Northcote, K.H., 1979. A factual key for the recognition of Australian Soils. Rellim Technical Publications, Coffs Harbour, NSW, Australia, 123 pp.

Pielke Sr, R. A., 2001: Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Rev. Geophys.,* **39,** 151-177.

Puri, K., G. S. Dietachmayer, G. A. Mills, N. E. Davidson, R. A. Bowen, and L. W. Logan, 1998: The new BMRC Limited Area Prediction System, LAPS. *Aust. Met. Mag.,* 47, pp. 203-223.

Seaman, R., W. Bourke, P. Steinle, T. Hart, G. Embery, M. Naughton, and L. Rikus, 1995: Evolution of the Bureau of Meteorology's Global Assimilation and Prediction System. Part I: Analysis and initialisation. *Aust. Met. Mag.,* **44**, 1-18.

Siriwardena, L., F. Chiew, H. Richter and A. Western, 2003: Preparation of a climate dataset for the Murrumbidgee River Catchment. Cooperative Research Centre for Catchment Hydrology, Working Document 03/01.

Viterbo, P., and A. C. M. Beljaars, 1995: An improved land surface parameterization scheme in the ECMWF model and its validation. *J. Climate,* **8,** 2716-2748.

Viterbo, P., 1996: The representation of surface processes in general circulation models. Ph. D. thesis, University of Lisbon, 201 pp. [Available from ECMWF, Shinfield Park, Reading, Berkshire RG28AX, United Kingdom.]

Weaver, C. P., and Avissar, R., 2001: Atmospheric disturbances caused by human modification of the landscape. *Bull. Amer. Met. Soc.,* **82,** 269-281.

Western, A. W., H. Richter, F. H. S. Chiew, R. I. Young, G. Mills, R. B. Grayson, M. Manton and T. A. McMahon, 2002: Testing the Australian Bureau of Meteorology's land surface simulations using soil moisture observations from the Murrumbidgee Catchment. Hydrology and Water Resources Symposium 2002 [CD-ROM], IE Aust, Melbourne, Australia. 10pp.

Wilson, M. F., and A. Henderson-Sellers, 1985: A global archive of land cover and soil data sets for use in general climate models. *J. Climatol.,* **5,** 119-143.