CHAPTER ELEVEN

11. FIELD APPLICATION: 3D SOIL MOISTURE PROFILE ESTIMATION

The one-dimensional studies in Chapters 6 and 10 have highlighted some important issues that require careful consideration for estimating the soil moisture profile from near-surface soil moisture observations. However, estimation of the spatial distribution of soil moisture profiles will no doubt have its own special set of requirements, over and above those from the one-dimensional studies, to ensure satisfactory estimates of the soil moisture profile using the soil moisture profile estimation algorithm. Hence, this chapter evaluates the ability to estimate both the spatial distribution and temporal variation of soil moisture profiles throughout a catchment, by applying the Modified Kalman-filter developed in Chapter 8 and the ABDOMEN3D soil moisture profile forecasting model developed in Chapter 7, to the Nerrigundah experimental catchment during the intensive field campaign (Chapter 9). This is a more realistic application of the soil moisture profile estimation algorithm than Chapter 10, as the effects from lateral redistribution of soil moisture on the soil moisture profile estimation are accounted for.

11.1 CALIBRATION OF ABDOMEN3D

Soil moisture profiles were monitored in the Nerrigundah catchment using the connector TDR soil moisture sensors from August 22 1997 until October 20 1998, with the intensive soil moisture mapping campaign being from August 27 1997 until September 22 1997 (see section 9.3.2). These 13 point measurements of the soil moisture profile, distributed throughout the 6 ha catchment (see Figure 9.4), have provided the necessary data for calibration and evaluation of the soil moisture forecasting model ABDOMEN3D. As the soil moisture model was to be applied to data collected during the intensive field campaign, calibration of the model was performed for the period from October 14 1997 until July 22 1998 (see Figure B.2, Figure B.3 and Figure B.10). This meant that the forecasting model was calibrated to a data set that was independent of the data used for application of the model.

11.1.1 OBSERVED MODEL PARAMETERS

In calibrating the ABDOMEN3D model, both residual soil moisture content and soil porosity could be inferred from measurements of the soil moisture profile. In addition, soil porosity could be estimated from the soil cores taken throughout the catchment (see Table B.5). Other model parameters, such as total soil depth (see Figure 9.44), saturated hydraulic conductivity (see Table B.7) and depression storage (see Table D.1), could be inferred from field measurements. Hence, the only model parameters requiring calibration were the maximum gradient parameter *MGRAD* and the van Genuchten soil parameter n (when using the van Genuchten hydraulic conductivity relationship). The model assumed isotropic soil properties within each grid element.

Soil layers were defined, consistent with observed soil horizon thicknesses, as determined from the proportion of total soil depth (Figure 9.46). The soil layer representing the A1 horizon was divided into two model layers, consisting of a 1 cm near-surface layer and the remainder, making a total of five model layers. However, the two model layers making up the A1 horizon were considered to have the same soil properties, while all other layers and grid cells were allowed to have different soil properties. The soil horizon depths and the connector TDR soil moisture measurements used to estimate the soil moisture content over that depth are given in Table 11.1, for the 13 locations where soil moisture profiles were monitored (see Figure 11.1).

To reduce the number of soil parameters used by the ABDOMEN3D model, the Nerrigundah catchment was divided into a number of “uniform” soil type areas. These soil type areas allowed different soil properties for the different model layers, but enforced the same soil layer properties for all grid cells within the uniform soil type area. Delineation of the catchment into uniform soil type areas was based on the estimates of soil porosity, residual soil moisture content and saturated hydraulic conductivity within the four soil horizons. The residual soil moisture content was estimated from each of the 13 soil moisture profiles,

Table 11.1: Soil horizon depths (mm) at soil moisture profile monitoring sites; connector TDR probe length measurements used for estimation of soil moisture content over that depth are given in parenthesis (mm).

Moisture Profile	**Soil Horizons**			
	A1	***A1 – A2***	***A1 – B1***	***A1 – B2***
1	45 (50)	113 (av. 100 & 150)	225 (200)	450 (400)
2	45 (50)	113 (av. 100 & 150)	225 (200)	450 (400)
3	32 (50)	80 (100)	160 (150)	320 (300)
4	45 (50)	113 (av. 100 & 150)	225 (200)	450 (400)
5	35 (50)	87 (100)	175 (av. 150 & 200)	350 (300)
6	32 (50)	80 (100)	160 (150)	320 (300)
7	52 (50)	130 (av. 100 & 150)	260 (av. 200 & 300)	520 (500)
8	130 (av. 100 & 150)	325 (300)	650 (av. 500 & 800)	1300 (1000)
9	85 (av. 50 & 100)	213 (200)	425 (400)	850 (800)
10	40 (50)	100 (100)	200 (200)	400 (400)
11	52 (50)	130 (av. 100 & 150)	260 (av. 200 $ 300)	520 (500)
12	32 (50)	80 (100)	160 (150)	320 (300)
13	34 (50)	85 (100)	170 (150)	340 (300)

while soil porosity was estimated from the 13 soil moisture profiles in addition to the 19 soil core locations.

The residual soil moisture content and soil porosity were the two most important soil parameters for modelling of the soil moisture profile, as they set the bounds on the dynamic range for soil moisture content. Thus a residual soil moisture content which is set too high will restrict the model from ever reaching a soil moisture content below that value, and likewise a soil porosity which is set too low will restrict the model from ever reaching a soil moisture content above

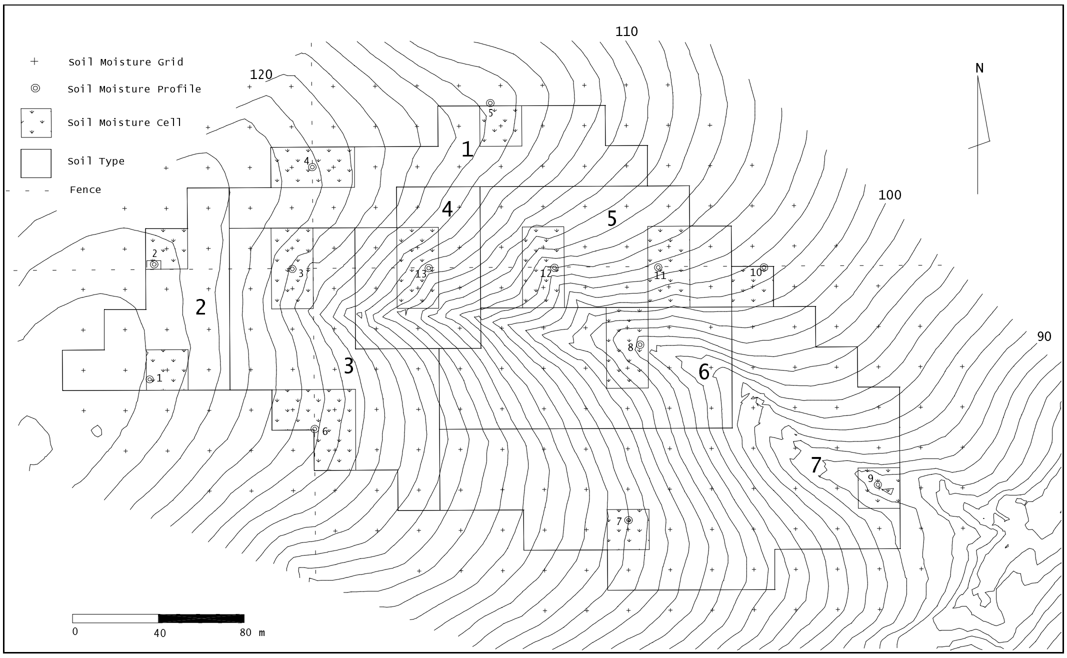

Figure 11.1: Plan of the Nerrigundah catchment showing the 7 uniform soil type areas, 13 soil moisture profile monitoring sites, and the model grid cells used for comparison with soil moisture profile observations.

that value, even with data assimilation. Hence, a conservative approach was to set the lowest possible residual soil moisture content and highest possible soil porosity.

Saturated hydraulic conductivity was estimated for the A1 horizon from double ring infiltrometer measurements at the 19 soil core locations (Figure 9.43), while saturated hydraulic conductivity for deeper depths was estimated from Guelph permeameter measurements made at the selected soil core locations. Using this data for each soil horizon, the catchment was divided into the uniform soil type areas shown in Figure 11.1, and the residual soil moisture content, soil porosity and saturated hydraulic conductivity estimates averaged for each soil horizon of the uniform soil type area (see Table 11.3). A spatially uniform value of 5 mm was taken as being representative of the depression storage across the Nerrigundah catchment, and a Manning's *n* value of 0.2 was used as being representative for pasture (Streeter and Wylie, 1983). The calibration period was initiated with soil moisture values interpolated from the soil moisture profile measurements made on October 14 1997.

11.1.2 CALIBRATED MODEL PARAMETERS

The most rigorous calibration procedure is a Monte-Carlo based approach, which involves multiple runs of the forecasting model for the entire simulation period with different model parameter values. Using this procedure, the optimum parameter set is chosen based on an objective function that compares the forecast state values with the observed state values. However, simulation of the soil moisture profile distribution with the three-dimensional model ABDOMEN3D was computationally too intensive for such a calibration approach, which requires several thousand runs with the forecasting model to determine the optimum parameter set.

One alternative is to manually “tune” the model parameters to obtain a reasonable comparison between simulated and observed states, but this is labour intensive and does not always provide a satisfactory calibration. As calibration using the Monte-Carlo based approach was desired, calibration of the three-dimensional model was undertaken using a series of one-dimensional calibrations. In this way, each soil moisture monitoring site was considered as being a one-dimensional soil profile, and the unknown soil parameters calibrated from the one-dimensional soil moisture model ABDOMEN1D. This calibration was undertaken by matching simulated soil moisture content with the connector TDR depth integrated soil moisture measurements using the Bayesian non-linear regression program NLFIT.

The assumption made was that the effects from lateral redistribution were negligible in respect to vertical redistribution. Apart from soil moisture profiles located in the main drainage lines and steeper sections of the catchment, this assumption was found to be valid. As soil moisture measurements with the 5 cm connector TDR probes had a wide range of variation when compared with thermogravimetric measurements (see Figure 9.17), calibration was only performed for soil moisture measurements of horizons A1 and A2, A1 to B1 and A1 to B2 (ie. model layers 1 to 3, 1 to 4 and 1 to 5). The calibrated model parameter values for *MGRAD* and *n* are given in Table 11.2, along with the averaged soil parameters from field measurements. The averaged soil parameters assigned to each of the uniform soil type areas are given in Table 11.3.

Table 11.2: Calibrated soil parameters for the 13 monitored soil moisture profiles.

Moisture Profile	**Soil Horizon**	ϕ (% v/v)	θ_r (% v/v)	K_s (mm h^{-1})	*MGRAD* (mm)	*n*
1	A1	60	6	35	500	2.5
	A2	45	8	10	490	2.2
	B1	42	12	3	28	2.1
	B2	40	15	1	26	1.6
2	A1	60	6	35	480	2.5
	A2	45	8	10	317	1.7
	B1	42	12	3	257	1.8
	B2	40	15	1	73	2.4
3	A1	60	4	25	227	2.4
	A2	54	4	20	68	1.2
	B1	38	4	15	86	1.7
	B2	36	6	5	10	2.2
4	A1	50	5	80	348	2.1
	A2	46	7	20	124	1.1
	B1	32	8	5	19	1.7
	B2	32	10	0.5	383	2.4
5	A1	50	5	80	330	2.1
	A2	46	7	20	14	1.2
	B1	32	8	5	5	2.1
	B2	32	10	0.5	314	1.7
6	A1	60	4	25	405	2.2
	A2	54	4	20	48	2.4
	B1	38	4	15	1	2.5
	B2	36	6	5	258	2.1
7	A1	60	6	35	500	2.5
	A2	46	8	15	1	1.2
	B1	44	9	2	276	1.5
	B2	34	16	0.1	279	2.1
8	A1	60	10	15	500	2.5
	A2	37	13	3	104	1.2
	B1	34	16	1	2	1.4
	B2	32	20	0.5	88	2.5
9	A1	60	6	35	500	2.5
	A2	46	8	15	1	1.7
	B1	44	9	2	376	1.1
	B2	34	16	0.1	360	1.8
10	A1	60	6	35	498	2.5
	A2	46	8	15	2	1.9
	B1	44	9	2	377	1.2
	B2	34	16	0.1	327	2.2
11	A1	60	5	20	438	2.5
	A2	50	6	3	491	2.1
	B1	38	10	0.5	496	1.2
	B2	38	18	0.3	345	1.1
12	A1	60	5	20	202	2.4
	A2	50	6	3	3	1.2
	B1	38	10	0.5	24	1.5
	B2	38	18	0.3	370	2.5
13	A1	50	9	30	497	2.4
	A2	47	9	5	9	2.5
	B1	42	9	3	119	1.2
	B2	31	11	1	34	2.0

Table 11.3: Soil properties used for the 7 uniform soil type areas.

Soil Type	**Soil Horizon**	ϕ **(% v/v)**	θ_r **(% v/v)**	K_s **(mm h^{-1})**	***MGRAD*** **(mm)**	***n***
1	A1	50	5	80	340	2.1
	A2	46	7	20	70	1.2
	B1	32	8	5	15	1.8
	B2	32	10	0.5	350	2.0
2	A1	60	6	35	490	2.5
	A2	45	8	10	400	1.9
	B1	42	12	3	145	2.0
	B2	40	15	1	50	1.9
3	A1	60	4	25	315	2.3
	A2	54	4	20	58	1.6
	B1	38	4	15	40	2.0
	B2	36	6	5	130	2.1
4	A1	50	9	30	497	2.4
	A2	47	9	5	9	2.5
	B1	42	9	3	119	1.2
	B2	31	11	1	34	2.0
5	A1	50	60	5	320	2.4
	A2	46	50	6	245	1.5
	B1	32	38	10	260	1.3
	B2	32	38	18	360	1.5
6	A1	60	10	15	500	2.5
	A2	37	13	3	104	1.2
	B1	34	16	1	2	1.4
	B2	32	20	0.5	88	2.5
7	A1	60	6	35	500	2.5
	A2	46	8	15	1	1.7
	B1	44	9	2	375	1.3
	B2	34	16	0.1	320	2.0

In contrast to the calibration results from one-dimensional modelling in Chapter 10, the calibration results for the *MGRAD* parameter in Table 11.2 have shown a general decrease with soil depth, rather than an increase with depth. In Chapter 10, it was noted that under most situations the *MGRAD* parameter should intuitively increase with depth, as a result of increased clay content in lower soil layers. This is because the *MGRAD* parameter accounts for the maximum matric suction of the soil.

It was also shown in Chapter 10 that the ABDOMEN1D model failed to yield good comparisons of total soil moisture storage during the summer of 1997/98, as a result of there being no root water uptake term in the model (see section 10.2). Since the forecasting model ABDOMEN3D was actually calibrated to the soil moisture measurements made during the summer of 1997/98 in this instance, the calibration of the *MGRAD* parameter resulted in a decreased value with depth, to account for the neglect of a root water uptake term in the model. By taking on a larger *MGRAD* value for near-surface layers than deeper layers, a greater moisture suction was imposed in the near-surface layers than for deeper layers. The effect of this was a greater flux of soil moisture to the soil surface in order to supply the demand of evaporation, which was taken from the soil surface. In this way, the model parameter *MGRAD* was given a non-physical value to account for the model structural error.

In the following sections, figures presented in the body of this thesis only show the results from modelling of soil moisture content at soil moisture profile number 7. However, for the interested reader, graphical modelling results for other soil moisture profiles are given in Appendix F. Soil moisture profile number 7 was chosen for illustration, as it was typical of the results from the other profiles, with it having a mid range soil depth (520 mm) and being located at mid-slope (see Figure 11.1).

Figure 11.2 shows a comparison of calibration results with connector TDR observations at soil moisture profile number 7. Simulation results from the one-dimensional model ABDOMEN1D, using the calibrated parameters from Table 11.2, are compared with results from ABDOMEN1D using the averaged soil parameters in Table 11.3, and results from the three-dimensional model ABDOMEN3D using the uniform soil type parameters in Table 11.3. These results show only a slight difference between the three simulations (approximately 5% v/v), and a very good agreement with the connector TDR soil moisture observations, particularly for deeper depth comparisons. The poorer agreement for the A1 horizon is a result of the noisy connector TDR measurements for the 5 cm probe lengths (see Figure 9.17).

The good comparisons between one-dimensional simulations when using both the calibrated and averaged soil parameters in ABDOMEN1D, indicated that averaging of the soil moisture profile monitoring site calibrations within a uniform soil type area, had a minimal impact on the calibration of the one-

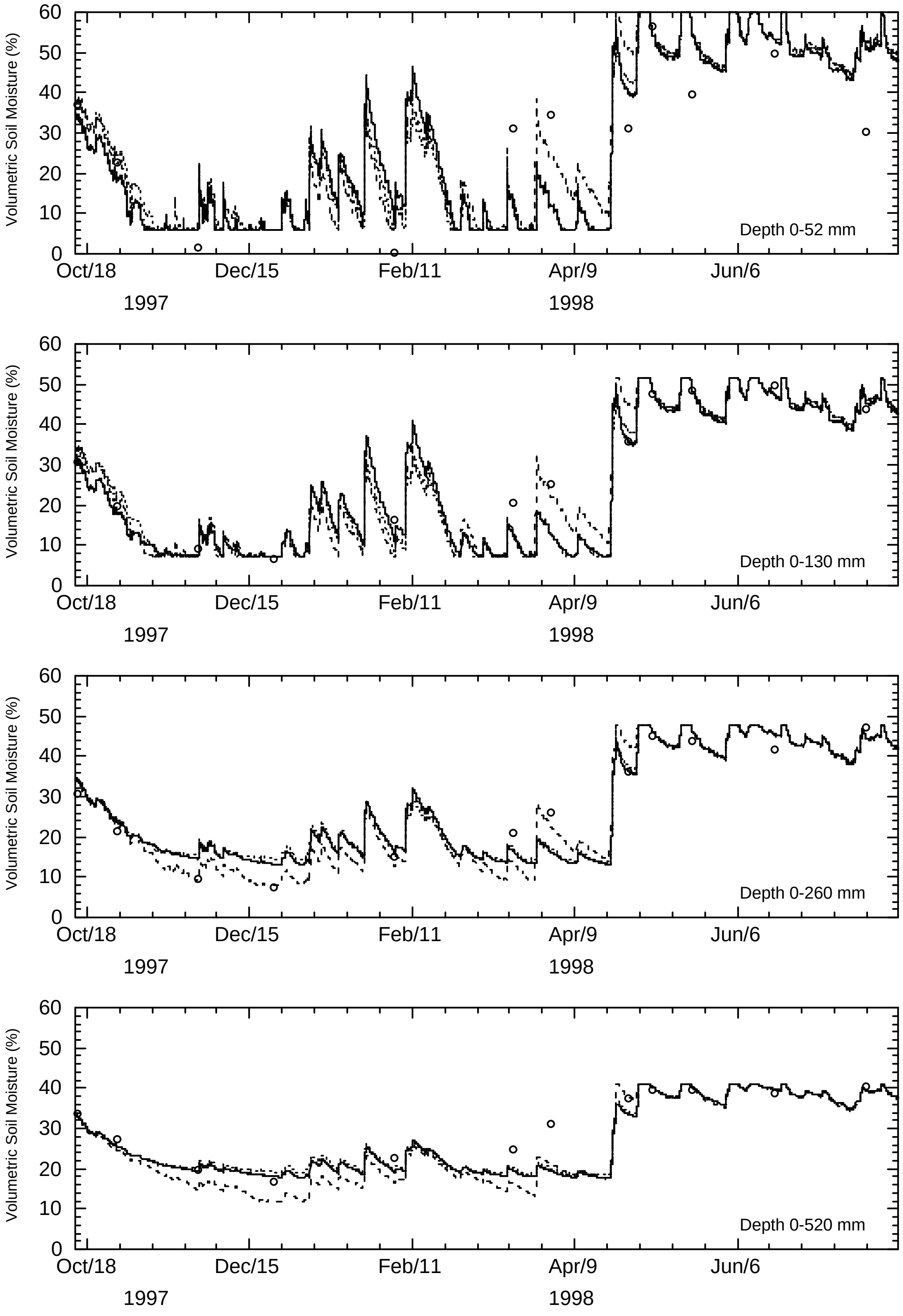

Figure 11.2: Calibration results from soil moisture profile number 7, situated in uniform soil type number 7. Connector TDR observations (open circles) are compared against one-dimensional simulation results with calibrated parameters (solid line) and averaged parameters (short dashed line), and three-dimensional simulation results with averaged parameters (long dashed line). The difference between the solid line and the short dashed line is the effect of averaging calibrated soil parameters for the uniform soil type, while the difference between short dashed and long dashed lines is the effect of lateral redistribution.

dimensional model. Moreover, the good comparison between the one-dimensional model simulations using averaged soil parameters and the three-dimensional simulations using the uniform soil type parameters, indicated that neglecting the lateral redistribution of soil moisture in the model calibration had a minimal impact on the calibration results, with the exception of soil moisture profiles located in the main drainage lines and steeper sections of the catchment. The implication of this was that vertical redistribution was more important than lateral redistribution in the Nerrigundah catchment. However, if a non-isotropic hydraulic conductivity was used in the three-dimensional model, the conclusions may have been different.

11.2 EVALUATION OF ABDOMEN3D CALIBRATION

Using the calibrated model parameters for the uniform soil type areas in Table 11.3, the three-dimensional soil moisture model ABDOMEN3D was evaluated for the period from August 22 1997 to September 22 1997. This is the 1 month period for the intensive field campaign, being the period for which soil moisture profiles are estimated with the soil moisture profile estimation algorithm. This is a true evaluation of the model calibration, as this data was not used for calibration of the model. Initialisation of the model was performed using an interpolated field of soil moisture content from the 13 soil moisture profile measurements made on August 22 1997.

The results from modelling of the soil moisture profile at soil moisture profile number 7 are given in Figure 11.3, where a good agreement can be seen between the model simulation and connector TDR observations of soil moisture content. The poorer agreement with the A1 horizon is again a reflection of the noisy measurements with 5 cm connector TDR probe lengths. Whilst there was only a limited range of soil moisture contents during this relatively short modelling period, the evaluation has confirmed that the calibration of ABDOMEN3D was adequate for forecasting the soil moisture profiles, and hence estimation of the spatial distribution and temporal variation of soil moisture profiles using the soil moisture profile estimation algorithm.

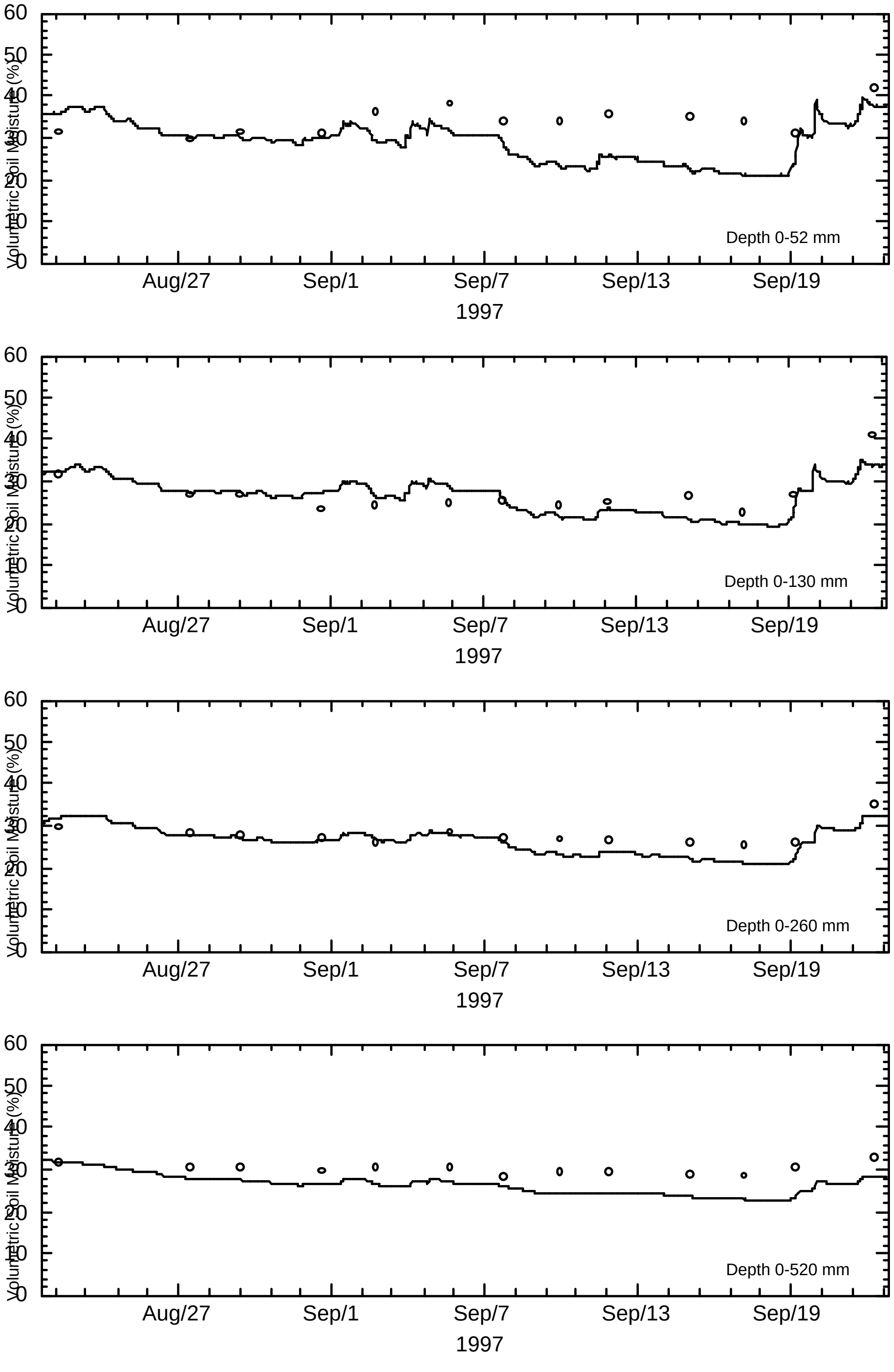

Figure 11.3: Evaluation of soil moisture profile simulation at soil moisture profile number 7. Connector TDR observations (open circles) are compared against three-dimensional simulation results with calibrated parameters (solid line).

Table 11.4: Comparison of rms errors (%v/v) of soil horizons at soil moisture profile monitoring sites during model evaluation.

Moisture Profile	***Soil Horizons***			
	A1	***A1-A2***	***A1-B1***	***A1-B2***
1	6.8	3.1	2.0	4.0
2	13.3	6.7	2.4	1.5
3	7.3	3.4	4.4	4.7
4	2.8	4.4	1.9	1.1
5	6.4	2.4	2.3	3.5
6	8.2	5.5	4.8	4.8
7	7.8	3.4	2.5	4.1
8	4.5	6.1	2.9	3.2
9	3.8	2.2	1.6	4.8
10	10.3	6.1	6.1	5.7
11	11.7	7.4	3.7	3.7
12	20.2	13.4	11.0	6.2
13	8.3	3.5	4.7	5.9
All Profiles	9.6	5.9	4.6	4.3

A comparison of the rms errors for the evaluation of ABDOMEN3D against the observed soil moisture profiles is given in Table 11.4. These results have indicated that there is a good agreement between the model simulation of total soil moisture profile storage and the field observations, with a rms error generally less than about 5% v/v. The rms errors for total soil moisture profile storage had a range from 1.1% v/v to 6.2% v/v. Simulation of soil moisture content in the A1 horizon had the highest rms error, as a result of the noisy observations using 5 cm connector TDR probes. Profile 12 had the largest rms error across all depths. This is a result of the monitoring site being located in a depression line, which due to the grid resolution used by the model, is not identified as being in a depression line (see Figure 9.7a and Figure 11.1).

11.3 SOIL MOISTURE PROFILE ESTIMATION

The ability to estimate the spatial distribution and temporal variation of soil moisture profiles from near-surface soil moisture observations under field conditions using ABDOMEN3D and the Modified Kalman-filter assimilation scheme within the frame work of the soil moisture profile estimation algorithm, was evaluated from August 22 1997 to September 22 1997. This is the period that encompasses the intensive field campaign (see section 9.3.2), commencing on August 27 1997 and continuing until September 22 1997. Soil moisture profile observations were made at soil moisture profile monitoring sites on August 22, but observations of near-surface soil moisture using the TDAS were not made until August 27 (see section 9.3.2.1). Hence updating of the forecasting model ABDOMEN3D could not commence until August 27. Furthermore, near-surface soil moisture observations on September 19 were not used for updating of the model, due to the rainfall that fell during the observing period (see Figure 9.28). However, the soil moisture profile observations made on this day were still used for comparison with the estimated soil moisture profiles.

11.3.1 INITIALISATION USING OBSERVED PROFILES

An interpolation of the soil moisture profile measurements made on August 22 was used for initialisation of the forecasting model ABDOMEN3D. This is the same initialisation that was used for the evaluation of the forecasting model calibration in the previous section.

11.3.1.1 Updating With Original TDAS Observations

Upon initialisation of the forecasting model with the soil moisture profile observations, the soil moisture profiles were forecast, and the forecasting model updated. The near-surface soil moisture observations used were the 15 cm connector TDR measurements made with the TDAS (see section 9.3.2.1) on a 20 m × 20 m grid. The 15 cm connector TDR observations of near-surface soil moisture content have been applied as observations of the top 15 cm of the soil profile, as Chapter 10 has illustrated the importance of applying near-surface soil moisture observations to the depth for which they relate. However, results from updating with an observation depth of 15 cm can be considered indicative of the results that would be obtained from observations over a much shallower depth, as Chapter 6 has illustrated that soil moisture profile estimation with the Kalman-filter was insensitive to the near-surface soil moisture observation depth. Updating of the forecasting model was performed for each set of TDAS near-surface soil moisture observations (excluding September 19). In updating the forecast model, a system state standard deviation of 5% v/v and an observation error of 2% v/v of the near-surface soil moisture observation were used.

Ideally, updating of the forecasting model ABDOMEN3D with near-surface soil moisture observations should improve the overall estimation of the

Table 11.5: Comparison of rms errors (%v/v) of soil horizons at soil moisture profile monitoring sites during estimation of the soil moisture profile using the observed initial soil moisture profile and original TDAS near-surface soil moisture observations.

Moisture Profile	***Soil Horizons***			
	A1	***A1-A2***	***A1-B1***	***A1-B2***
1	8.8	7.3	6.2	6.9
2	19.5	12.7	8.0	6.2
3	8.0	4.7	6.1	7.2
4	7.1	10.3	5.8	3.5
5	9.7	6.8	6.5	6.6
6	4.6	8.1	7.1	7.8
7	9.8	5.8	5.9	6.7
8	8.5	9.9	7.3	7.2
9	12.9	12.5	11.4	13.1
10	14.8	9.9	4.3	6.6
11	6.7	5.1	8.2	7.1
12	6.1	3.6	3.6	2.5
13	13.9	6.0	6.6	8.0
All Profiles	10.8	8.4	6.9	7.3

spatial distribution and temporal variation in the soil moisture profile. However, the simulation results given in Figure 11.4 for soil moisture profile number 7 have shown that the soil moisture profile estimation using the Modified Kalman-filter was poor in comparison with the open loop simulation (no updating of the forecasting equation). From an observation of the rms errors in Table 11.5, it may be seen that with the exception of soil moisture profile number 12 and the near-surface layers of a few soil moisture profile locations, all rms errors were slightly greater than rms errors for the open loop simulation (see Table 11.4). Soil moisture profile number 12 is the profile located in the depression line that was not identified for the grid resolution used by the model. Hence, the improvement seen in the estimation of this soil moisture profile was a result of the poor open loop simulation. This poor performance of updating when compared with the open loop simulations, was a result of the good model calibration and an accurate knowledge of the initial soil moisture profiles for both simulations.

The simulation results for the upper 130 mm soil layer of soil moisture profile number 7 (Figure 11.4) gave the best representation of the forecast soil moisture, for comparison with the actual observation depth used for assimilation of the near-surface soil moisture observations. However, it can be seen in a number of instances that the updated soil moisture content in this figure did not compare closely with the connector TDR observations of soil moisture content shown. The reason for this was found to be that 15 cm connector TDR

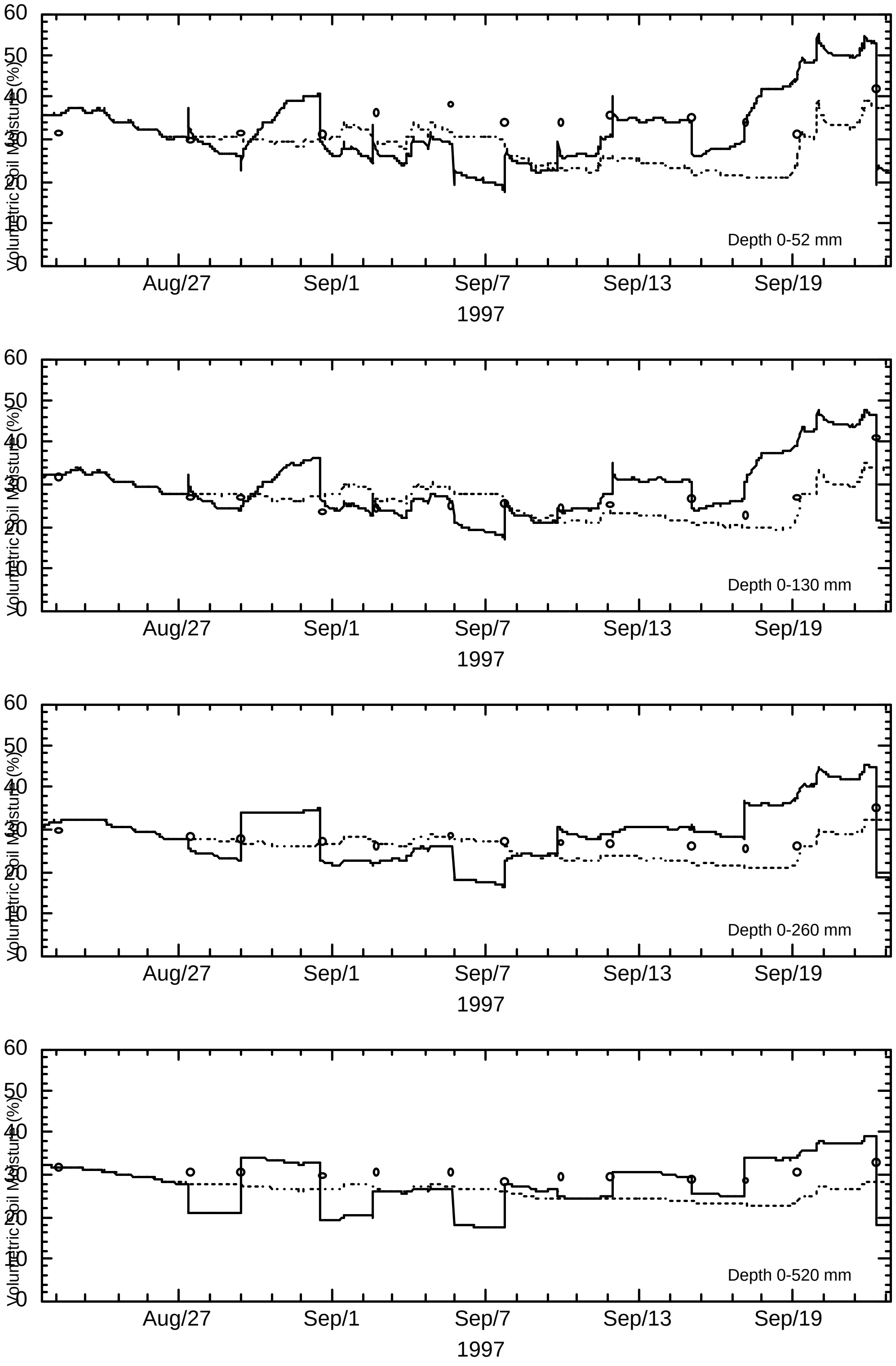

Figure 11.4: Evaluation of soil moisture profile estimation at soil moisture profile number 7. Connector TDR observations (open circles) are compared against the estimated soil moisture profile (solid line) and open loop simulation results (dashed line), for simulations initiated with the observed soil moisture content.

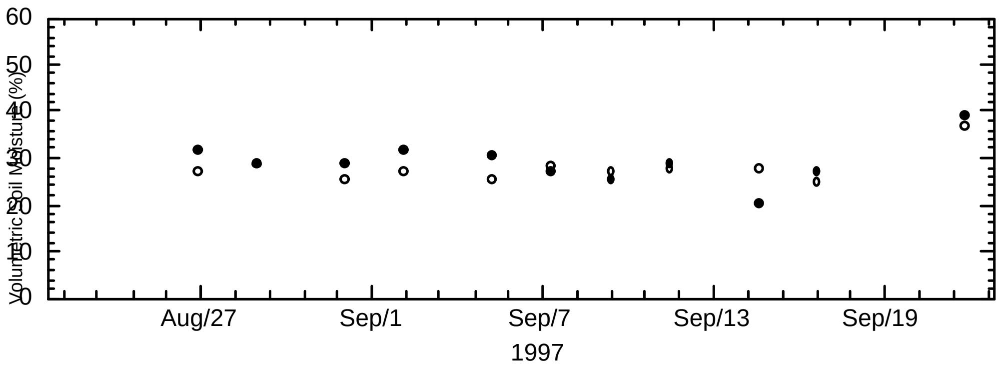

Figure 11.5: Comparison of TDAS (solid symbols) and profile monitoring (open circles) 15 cm connector TDR soil moisture measurements for soil moisture profile number 7.

measurements made at the soil moisture profile monitoring site did not correspond with the connector TDR measurements made with the TDAS for the corresponding grid cell(s) shown in Figure 11.1. This was not surprising, given that TDAS near-surface measurements and soil moisture monitoring site measurements were not made at precisely the same location, having a separation of approximately 5 m for profile number 7.

A comparison of TDAS and profile monitoring 15 cm connector TDR soil moisture measurements is made in Figure 11.5. When comparing the data in Figure 11.5 to the update results in Figure 11.4, it may be seen that the updates on August 27, September 1, September 3 and September 15 were due to the differences in soil moisture observations made by the TDAS and at the profile monitoring site. However, the poor updates on September 6, September 13, September 17 and September 22 were not explained by Figure 11.5. These updates were obviously a result of lateral correlations in the forecast system state covariance matrix and noise in the surrounding near-surface observations, resulting in a difference between observed and forecast soil moisture contents at the surrounding grid cells. With a difference in observed and forecast soil moisture contents, and lateral correlations, this allows updating of the surrounding profiles with the Kalman-filter.

Figure 11.5 is indicative of the sub-grid variability and hence noise in near-surface soil moisture observations. Similar plots are given in Appendix F for the other soil moisture profile monitoring locations. These plots have shown that on average there was between 5 and 10% v/v difference in 15 cm depth soil moisture observations for the TDAS and profile monitoring locations, with differences being as great as 15% v/v. This is about two to three times greater than the sub-grid variability indicated by Figure 9.30a, which may be a result of the small area over which the sub-grid variability was previously estimated. These results highlight the difficulty of taking point measurements of soil moisture content as being an estimate of the spatially averaged soil moisture content that would be measured using remote sensing.

11.3.1.2 Updating With Modified TDAS Observations

To make the comparisons of soil moisture profile estimation with soil moisture profile observations more comparable, the above simulation was repeated for a modified set of near-surface soil moisture observations. In this simulation, the TDAS near-surface soil moisture observations of grid cells used for comparison with soil moisture profile observations (see Figure 11.1) were replaced with the 15 cm connector TDR measurements made at the profile monitoring locations. The results from this simulation at soil moisture profile number 7 are given in Figure 11.6, where there was an obvious improvement in estimation of the soil moisture profile for the upper 130 mm layer when compared to the simulation results in Figure 11.4. However, updates on September 3, September 17 and September 22 were still poor. This is likely to be a result of lateral correlations imposing an update as a result of model predictions for adjacent grid elements having a poor comparison with near-surface soil moisture observations.

Updates for these dates may be improved by using a non-constant system state variance and a spatially uniform observation error. With the current assimilation scheme, the state forecast error was always greater than observation error, which was not necessarily the case. Also, observation error was a function of the soil moisture observation, with wetter observations having a higher variance than drier observations. The meaning of this is that all model estimates of soil moisture content were assumed to have the same error, and near-surface soil moisture observation were assumed to be more accurate when the soil was drier. Hence, an improved assimilation scheme may be to use a system state variance that is a function of the separation between model predictions and observations of

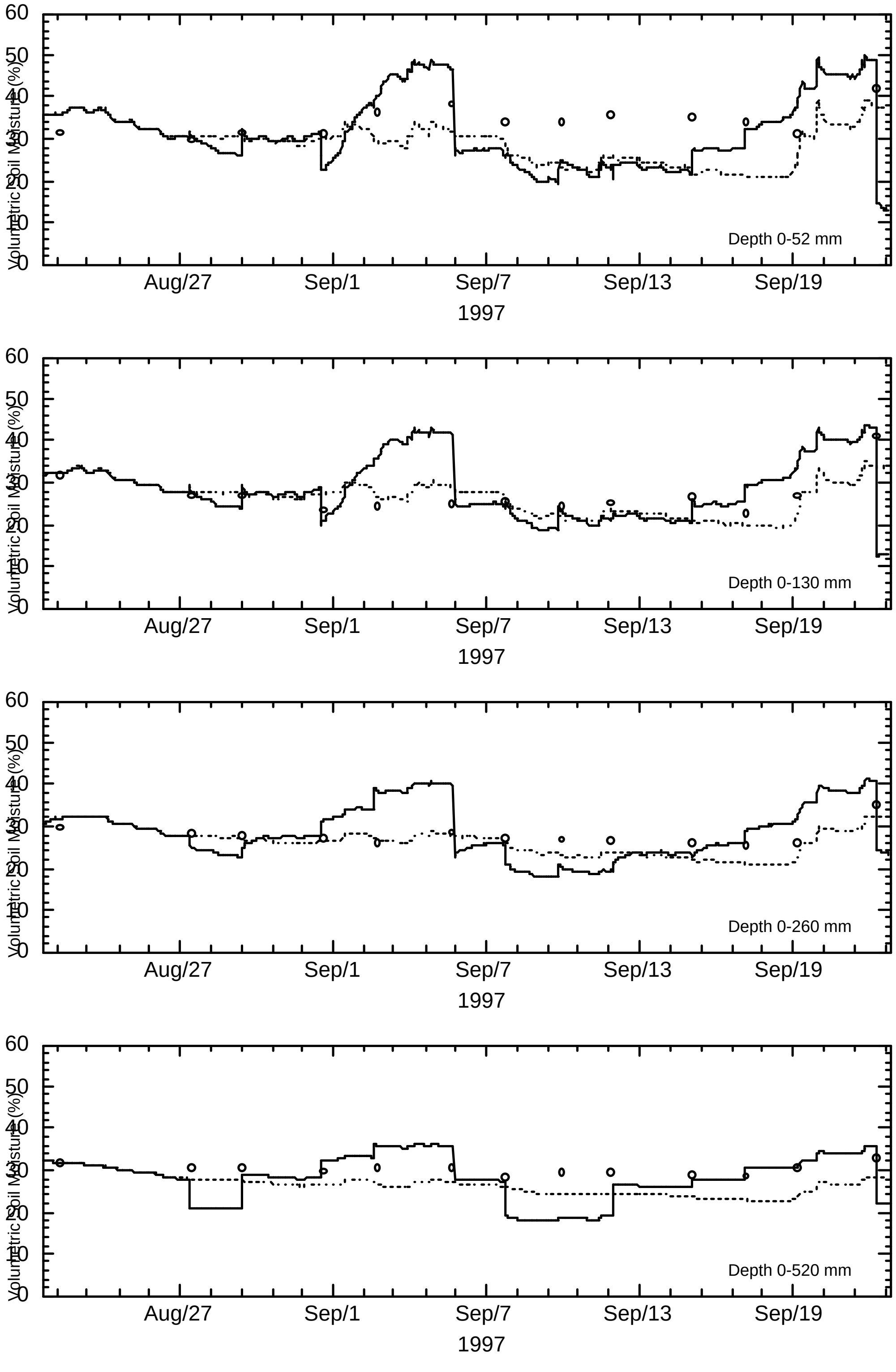

Figure 11.6: Evaluation of soil moisture profile estimation at soil moisture profile number 7. Connector TDR observations (open circles) are compared against the estimated soil moisture profile (solid line) with modified TDAS near-surface soil moisture observations and open loop simulation results (dashed line) for simulations initiated with the observed soil moisture content.

Table 11.6: Comparison of rms errors (%v/v) of soil horizons at soil moisture profile monitoring sites during estimation of the soil moisture profile using the observed initial soil moisture profile and modified TDAS near-surface soil moisture observations.

Moisture Profile	**Soil Horizons**			
	A1	**A1-A2**	**A1-B1**	**A1-B2**
1	10.0	7.4	6.9	6.9
2	17.5	11.1	6.8	5.7
3	7.4	4.1	5.7	6.8
4	8.1	11.0	6.6	3.4
5	6.4	9.3	5.8	5.7
6	6.8	8.5	7.8	9.1
7	9.2	7.0	6.2	6.4
8	5.3	6.7	5.2	6.6
9	7.3	7.7	7.3	8.9
10	10.7	8.8	6.5	5.9
11	4.0	4.4	8.5	3.6
12	7.6	5.4	4.1	3.3
13	11.2	5.1	4.5	5.7
All Profiles	9.1	7.7	6.4	6.3

the near-surface soil moisture content, and an observation error that is spatially uniform. Such a scheme may alleviate the adverse effects of lateral correlations on model updates when near-surface soil moisture observations and model predictions are already close.

Table 11.6 presents the rms error of soil moisture profile estimation for all soil moisture profiles monitored, for updating with the modified TDAS near-surface soil moisture observations. When compared with Table 11.5, these results show a general improvement in rms errors for all soil moisture profiles monitored, with an overall decrease in rms for all soil moisture profiles of approximately 1% v/v. This highlights the need for adequate spatial resolution in the near-surface soil moisture observations in order to estimate the soil moisture profile accurately.

When comparing rms errors from the profile soil moisture estimation with modified near-surface soil moisture observations (Table 11.6) against rms errors from the open loop simulation (Table 11.4), it may be seen that results from soil moisture profile estimation for soil moisture profiles 1 to 10 were only marginally worse than the open loop simulation, while profiles 11 to 13 were actually improved. This would suggest that the soil moisture profile estimation algorithm may slightly degrade soil moisture profile estimates when soil moisture profile forecasts are already good, as a result of noise in the near-surface soil moisture observations. However, when soil moisture profile forecasts are poor, there should be an improvement in the soil moisture profile estimation.

Table 11.7: Comparison of rms errors (%v/v) of soil horizons at soil moisture profile monitoring sites for the open loop simulation with a poor initial guess of soil moisture.

Moisture Profile	**Soil Horizons**			
	A1	**A1-A2**	**A1-B1**	**A1-B2**
1	24.6	18.0	14.4	15.1
2	5.3	5.6	8.2	8.8
3	15.1	8.2	10.9	11.3
4	8.6	5.4	3.7	5.0
5	14.9	8.0	8.8	8.7
6	11.4	5.5	6.3	4.7
7	24.5	16.3	15.6	14.6
8	29.0	24.9	19.3	16.8
9	28.4	26.2	22.8	19.8
10	21.6	15.7	15.7	13.9
11	21.7	16.9	9.9	16.8
12	25.6	18.9	18.6	13.7
13	22.6	14.9	16.9	14.7
All Profiles	20.8	15.8	14.2	13.4

11.3.2 INITIALISATION USING A POOR GUESS

The foregoing results have shown how the soil moisture profile estimation algorithm performed when the forecasting model was initialised with a precise estimate of the initial soil moisture profile. Such an accurate estimate of the initial conditions is somewhat unrealistic. Hence, a simulation has been performed for a poor initial guess of the initial soil moisture, but still using the modified near-surface soil moisture observations. The poor initial guess used was 12% v/v, 15% v/v, 18% v/v and 20% v/v for the A1, A2, B1 and B2 soil horizons respectively, uniform across the catchment. The results from this simulation are given in Figure 11.7 for soil moisture profile number 7, where an obvious improvement can be seen in the estimated soil moisture profile compared to the open loop simulation. This highlights the obvious benefit that may be obtained from assimilating near-surface soil moisture observations into the forecasting model.

The rms errors for simulated soil moisture with the poor initial guess are given in Table 11.7 for the open loop simulation and Table 11.8 for the soil moisture profile estimation. The rms errors show definitively a significant improvement in modelling soil moisture profiles when near-surface soil moisture observations are assimilated into the forecasting model, with rms errors of soil

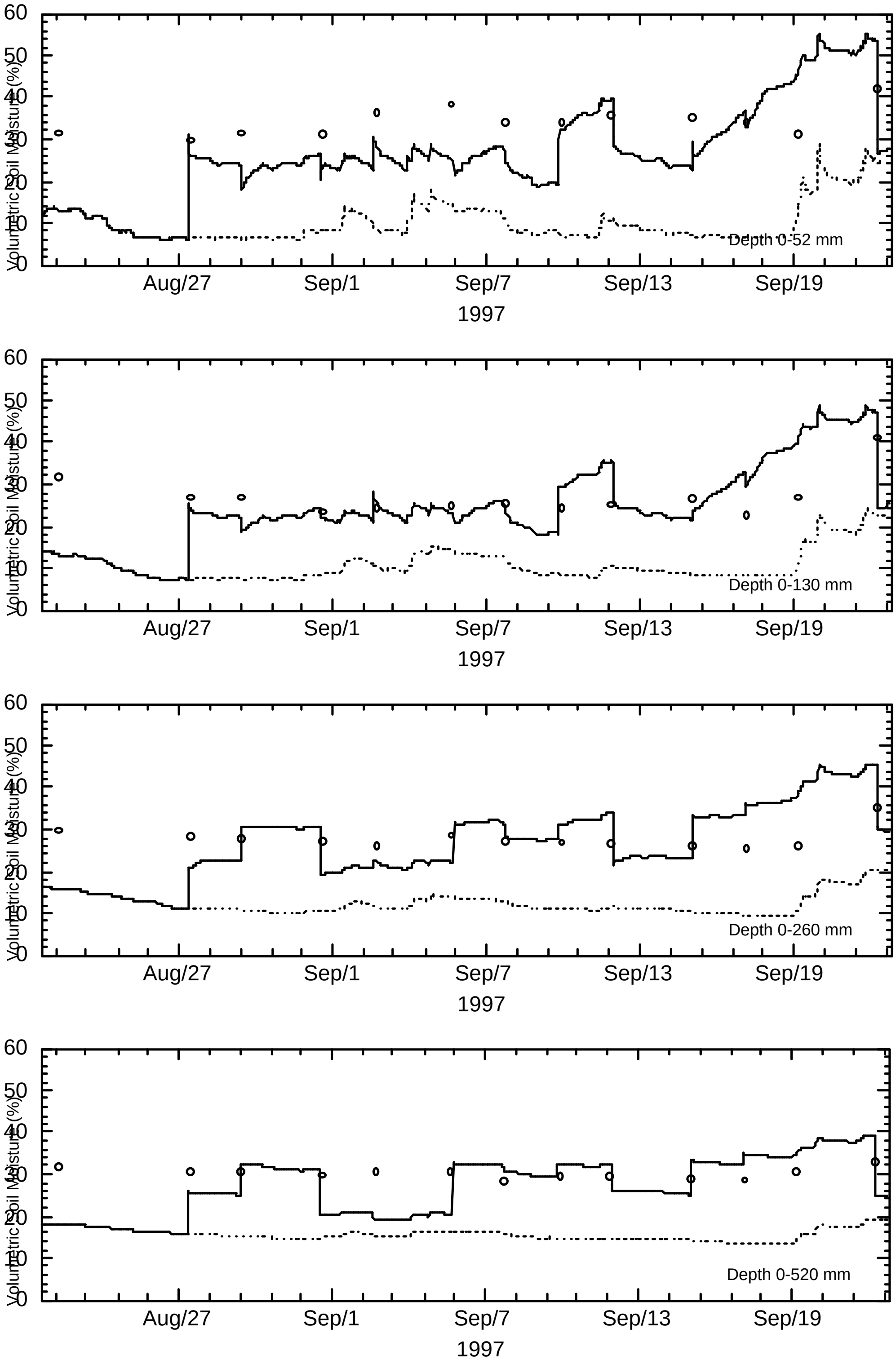

Figure 11.7: Evaluation of soil moisture profile estimation at soil moisture profile number 7. Connector TDR observations (open circles) are compared against the estimated soil moisture profile (solid line) from updating with modified TDAS near-surface soil moisture observations and open loop simulation results (dashed line), for simulations initiated with a poor initial guess of soil moisture content.

Table 11.8: Comparison of rms errors (%v/v) of soil horizons at soil moisture profile monitoring sites during soil moisture profile estimation using a poor initial guess of the soil moisture profile and the modified TDAS near-surface soil moisture observations.

Moisture Profile	***Soil Horizons***			
	A1	***A1-A2***	***A1-B1***	***A1-B2***
1	10.2	8.4	7.3	5.6
2	17.2	10.9	6.8	5.7
3	6.9	6.4	4.7	5.4
4	9.4	11.6	7.9	5.4
5	5.1	8.2	4.7	5.7
6	5.7	5.6	5.1	4.8
7	10.3	5.8	5.8	5.7
8	5.0	7.1	5.7	7.2
9	8.2	8.8	9.3	10.8
10	8.4	9.0	6.4	4.9
11	7.0	6.5	10.1	6.0
12	10.7	6.5	5.7	3.9
13	10.4	3.5	5.1	7.0
All Profiles	9.3	7.9	6.7	6.2

moisture profile estimation for the poor initial guess being approximately the same as for the soil moisture profile estimation with the accurate initialisation (Table 11.6). Thus, this would suggest that initialisation of the model is not an important aspect of the soil moisture profile estimation algorithm when using the Kalman-filter assimilation scheme.

Moreover, it was shown in section 11.3.1.2 that when the forecasting model was initialised with an accurate estimate of the soil moisture profile, soil moisture profile estimation using the soil moisture profile estimation algorithm was only slightly degraded from the open loop simulation. The conclusion that may be drawn from this is that the profile estimation algorithm yields an improved estimate of the soil moisture profile when simulation results are poor, while only slightly degrading the soil moisture profile estimation when simulation results are good. This slight degradation was a result of both noise in the near-surface observations and difficulties associated with relating point measurements to spatially averaged model estimates. Hence, this has illustrated the advantage of assimilating near-surface soil moisture observations into a hydrologic model, so that improved estimates of the spatial distribution and temporal variation of soil moisture profiles is achieved.

Table 11.9: Comparison of rms errors (%v/v) of soil horizons at soil moisture profile monitoring sites during soil moisture profile estimation using a poor initial guess of soil moisture content and only the first set of modified TDAS near-surface soil moisture observations.

Moisture Profile	***Soil Horizons***			
	A1	***A1-A2***	***A1-B1***	***A1-B2***
1	11.1	6.1	4.8	7.2
2	15.0	8.2	3.8	2.0
3	5.3	7.7	4.1	1.9
4	9.9	12.5	9.5	5.9
5	3.9	4.8	4.3	8.4
6	7.9	3.7	4.5	4.2
7	14.0	6.9	5.6	6.3
8	9.4	10.6	7.7	8.2
9	6.5	6.9	6.8	11.8
10	6.6	6.8	5.8	2.1
11	5.4	6.9	11.2	2.1
12	12.7	6.9	6.5	3.8
13	6.9	4.2	3.6	6.3
All Profiles	9.4	7.5	6.4	6.1

11.3.3 A SINGLE UPDATE OF THE SOIL MOISTURE PROFILE

To evaluate the effect of update frequency on soil moisture profile estimation, the simulation with a poor guess of initial soil moisture was run with only the first set of TDAS near-surface soil moisture observations made available for updating of the forecasting model ABDOMEN3D. The results from this simulation are given in Figure 11.8 for soil moisture profile number 7, where there was an obvious improvement in the soil moisture profile estimation when compared with the open loop simulation. Furthermore, simulation results are comparable to the results from assimilation of all sets of near-surface observations.

This is most evident in Table 11.9, where it can be seen that rms errors are equivalent to those in Table 11.8 for all soil moisture profiles. This implies that the updating interval is relatively unimportant for correct estimation of the soil moisture profile when there is a good calibration of the model, with poor simulation of soil moisture profiles being only a result of a poor initialisation of the forecasting model. When the model is poorly calibrated or there are substantial errors in the forcing data, then correct estimation of the soil moisture profile will be more dependent on the updating interval.

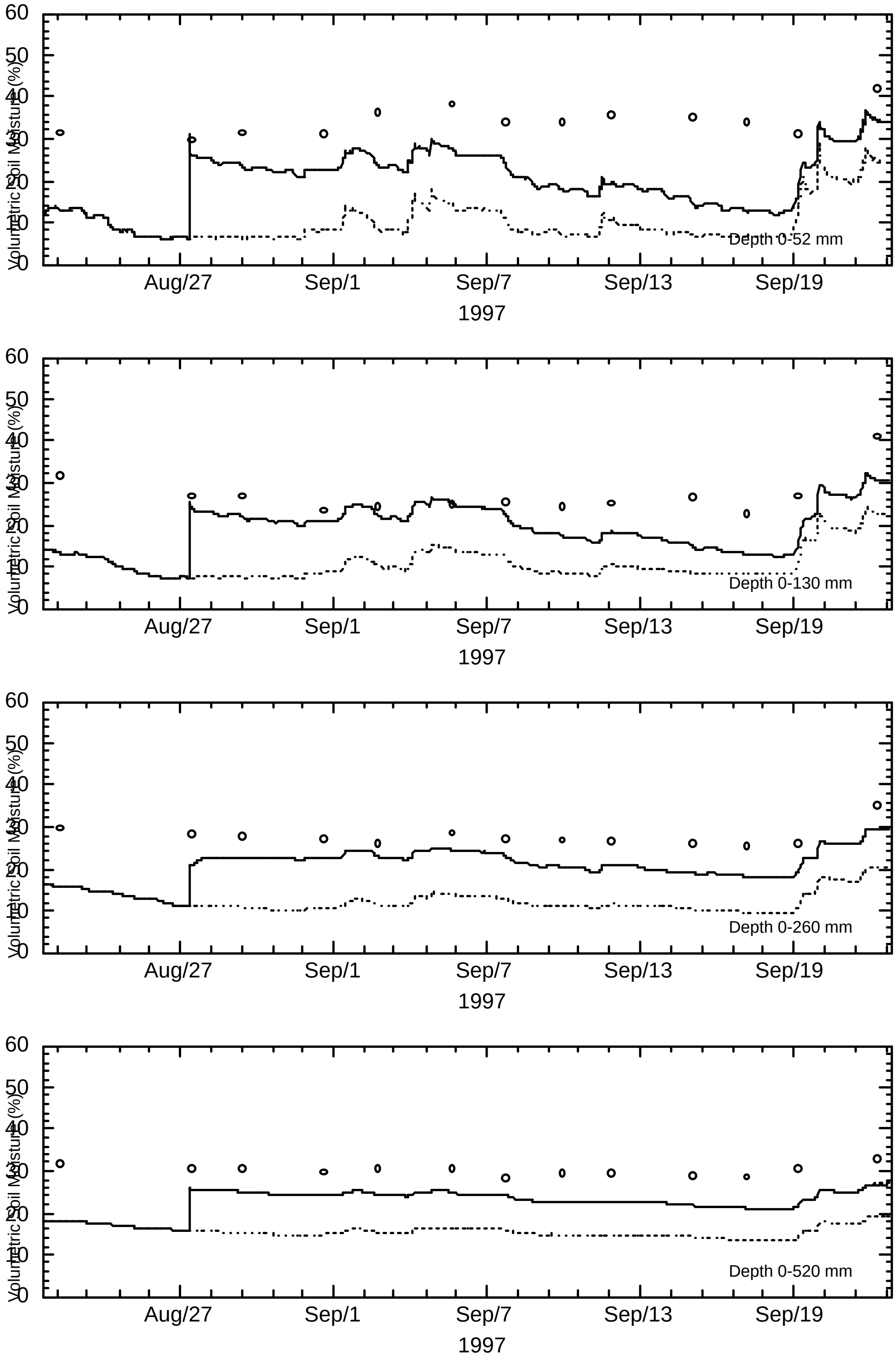

Figure 11.8: Evaluation of soil moisture profile estimation at soil moisture profile number 7. Connector TDR observations (open circles) are compared against the estimated soil moisture profile (solid line) for updating with only the first set of modified TDAS near-surface soil moisture observations and open loop simulation results (dashed line) for simulations initiated with a poor initial guess of the soil moisture content.

11.4 CHAPTER SUMMARY

This chapter has shown that apart from the main drainage lines and steeper portions of the catchment, lateral redistribution of soil moisture content did not play a dominant role in the Nerrigundah catchment, with satisfactory modelling of soil moisture profiles using the one-dimensional model ABDOMEN1D. Moreover, by calibrating the three-dimensional soil moisture profile forecasting model ABDOMEN3D to the dry summer period of 1997/98, the model was able to correctly predict the soil moisture profile without the addition of the root water uptake term. However, by calibrating to extreme drying events without the root water uptake term, soil parameters no longer had the physical meaning intended.

Application of the Modified Kalman-filter to the estimation of spatially distributed time varying field measured soil moisture has shown satisfactory results. Moreover, the utility of near-surface soil moisture observations, for updating of hydrologic models to provide improved estimates of the soil moisture profiles has been illustrated

Forecasting model updates at some update times were found to produce a degraded comparison of model predictions and soil moisture profile measurements. It was suggested that this was likely to be a result of lateral correlations imposing an update, as a result of model predictions for adjacent grid elements having a poor comparison with the near-surface soil moisture observations. Furthermore, simulation results have suggested that when near-surface soil moisture observations are of low quality, and this is not reflected by the observation variances, the soil moisture profile estimation may be poor. Hence, updates for these times may be improved by using a non-constant system state variance and a spatially uniform observation error. This study has also highlighted the difficulty of relating point measurements to the spatially averaged estimates from a soil moisture model.

Application of the Modified Kalman-filter assimilation scheme to the Nerrigundah catchment has indicated that estimation of the soil moisture profile may be degraded slightly (average rms error increase of 1% v/v for the total soil moisture storage) if simulation and observation values are already close, as a result of noise in the near-surface soil moisture observations. However, when simulation of the soil moisture profile is poor, assimilation of near-surface soil moisture into the forecasting model will make a significant improvement in the soil moisture profile estimation. This means that assimilation of near-surface soil moisture into the forecasting model will provide an improved estimate of the soil moisture profile on average for all simulation times.

This study has also shown that when using the Kalman-filter assimilation scheme, initialisation of the forecasting model states was not important for adequate estimation of the spatial distribution of soil moisture profiles (average rms error less than 5% v/v). Moreover, it has been shown that the updating interval is relatively unimportant for correct estimation of the soil moisture profile when the forecasting model has a good calibration and forcing data has a high level of accuracy. When model calibration is poor and/or there are significant errors in the forecasting model forcing data, the adequacy of soil moisture profile estimation from low temporal resolution near-surface soil moisture measurements will be a function of the time scale over which the dynamics of the forecasting model, cause a departure from the true soil moisture profile.