Application of ALSIS to the Hydrological Modelling of New Zealand's Mahurangi Catchment; Comparisons of Temporal Distribution of Soil Moisture

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Abstract: In this study we apply the ALSIS (Atmosphere Land Surface Interaction Scheme) model to a site within the Mahurangi catchment of northern New Zealand. We test the model via comparisons with detailed measurements of soil moisture collected during 1998 and 1999. ALSIS is a surface hydrology model for the prediction of evapotranspiration, surface and subsurface runoff and deep soil drainage. Emphasis here is placed on simulating soil moisture. ALSIS solves both the Richards' equation and the temperature diffusion equation for multiple soil layers. Soil and vegetation parameters required by ALSIS were largely obtained through standard national sources, while intensive field measurements provided a comprehensive set of meteorological forcing data. Detailed testing of ALSIS is carried out at point locations where good temporal records of soil moisture exist. Model output was controlled by: our knowledge of soil properties and their variation within the area; similar knowledge with respect to vegetation; the accuracy of the meteorological forcing data; and the set-up of the model itself. Comparisons are made of modelled and observed temporal statistics, and direct comparisons of temporal patterns. Problems with model parameterisation are identified and suggestions for improvements are described.

Keywords: Surface hydrology; Soil moisture; MARVEX

1. INTRODUCTION

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. The spatial distribution of soil moisture in the landscape is also of importance to hydrologists, as it assists in predicting the extent and position of runoff-producing areas and thereby allows prediction of solute transport and erosion processes.

In this study we apply the ALSIS (Atmosphere Land Surface Interaction Scheme) model to point locations within the Mahurangi catchment of northern New Zealand. We test the model via comparisons with temporal records of soil moisture collected during 1998 and 1999. As well as field measurements of soil moisture, detailed meteorological measurements were also collected at various sites within the catchment. This work forms one part of a comprehensive field hydrology study known as MARVEX (MAhurangi River Variability EXperiment) [Woods et al 2001].

The aims of the work reported here are to simulate the temporal behaviour of soil moisture via the ALSIS model using our best estimates of parameter values based on field surveys for points within the Mahurangi catchment with particular topographic, soils and vegetative properties. We may then infer the accuracy of representation and the relative dominance of lateral soil moisture re-distribution processes. This will enable an assessment of the potential for ALSIS to be used in simulating the spatial distribution of soil moisture. Ultimately field data and ALSIS output will be examined to identify differences in behaviour over many locations in the Mahurangi River catchment. A total of 18 continuously logging measurement sites are available for comparison. Application of ALSIS to other field sites will determine the extent to which parameter values vary, and if so, whether these variations can be attributed to differences in landscape position and published soil or vegetation type. This will enable methods to be developed that allow the extrapolation of information collected at a point to be interpreted at larger scales. It will also help determine whether "effective parameter" values for models like ALSIS can be defined apriori for application at the hillslope or catchment scales.

2. MODELLING SOIL MOISTURE

ALSIS is a "land surface scheme" and solves the one-dimensional conservation equations for temperature and soil moisture. As stated in Shao et al [1997]: "a land surface scheme is composed of three major components: bare soil transfer processes, vegetation canopy transfer processes, and soil thermal and hydrological processes" (p.197).

2.1 ALSIS

ALSIS has previously been applied to large scale spatial modelling [Shao et al, 1997] as well as point scale [Irannejad and Shao, 1998]. A full description of the ALSIS model is presented in Irranejad and Shao [1998]. In that paper, model output is discussed as being most sensitive to parameters describing soil properties; especially "macroscopic capillary length scale", λ_s, and the Broadbridge and White *C* parameter. For this study the model represents the soil in ten layers of varying thickness, with water free to move between the layers and in and out of the profile according to evaporation and infiltration theory.

2.2 Treatment of Soil Moisture

In ALSIS the one-dimensional (vertical) Richards' equation is used to describe the evolution of soil moisture in response to precipitation and evapotranspiration. Recent versions of ALSIS have allowed for choice in the treatment of soil moisture such that soil hydraulic behaviour may be described either by Broadbridge and White [1988], by Brooks and Corey [1964], or by van Genuchten [1980]. In this study the non-linear relationships between soil hydraulic conductivity, matric potential and soil moisture are based on the Broadbridge and White soil model [Shao et al, 1997].

3. CARRAN'S FIELD SITE, MAHURANGI RIVER CATCHMENT, NEW ZEALAND

The Mahurangi catchment is approximately 60km north of Auckland, New Zealand. The catchment is 46km^2 in area, with steeply sloping hills leading to undulating floodplains. The Carran's field site is one of four subcatchments in which there are soil moisture monitoring locations; others being: Satellite Station, Clayden's, and Marine Road.

Carran's is on a convergent hillslope section comprising gradients of 1:8 over an area of approximately 4.8 hectares. Soils at Carran's are clay loams, no more than a metre deep. Sheep and cattle graze the site, which is planted in pasture. Elevations range from 55m to 85m above sea level. Average annual precipitation in the Mahurangi catchment is approximately 1600mm/yr, and corresponding potential evapotranspiration is around 1300mm/yr.

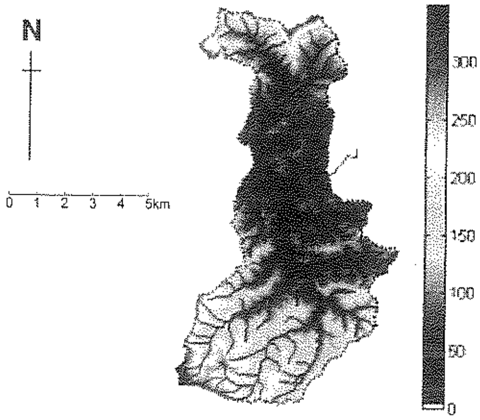

Figure 1. Elevation (m) and drainage network of the Mahurangi River catchment, New Zealand.

Time series of soil moisture were collected via permanently installed CS615 water content reflectometers, which were logged at 30 minute intervals over two years. Placement of the CS615 devices was designed to capture small-scale variability as well as vegetation and topographic influences and controls on soil moisture content. Three CS615 devices are installed along one length of hillslope; one at the top (upper), one near the middle (mid), and one close to the bottom of the hillslope (lower). Two sensors were fitted to each measurement site; one installed at 30cm depth, the other installed a depth of 30-60cm in the B-horizon.

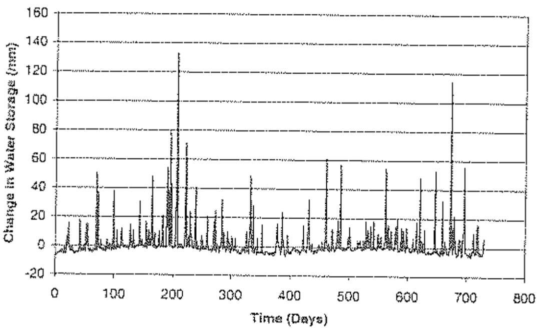

Figure 2. Change in daily water balance at Carran's, (+ precipitation; – evapotranspiration).

Table 1. Hydraulic properties of the soil at Carran's, "Warkworth clay and sandy clay loam" (WA) soil, required as input to ALSIS.

	Description	Units	Initial Estimate		Source	Improved	
			shallow	deep		shallow	deep
K_s	Saturated hydraulic conductivity	ms^{-1}	1.11×10^{-7}	5.61×10^{-8}	NZ soil inventory*	1.11×10^{-6}	5.61×10^{-7}
θ_s	Saturated volumetric water content	m^3m^{-3}	0.60	0.60	Field measurements; Aug 1998	0.60	0.60
θ_r	Air dry volumetric water content	m^3m^{-3}	0.191	0.291	Field measurements; Feb 1999	0.191	0.291
λ_s	Macroscopic capillary length scale	m	0.300	0.555	Literature** and Australian values	0.100	0.300
C	Soil hydraulic characteristic p'meter	-	1.30	1.30	Literature** and Australian values	1.05	1.05

* NZ Soils Bureau [1968]. **Smettem [1999]. White [1988].

Table 2. Vegetation properties for ALSIS.

	Description	Units	Pasture	Source
LAI	Leaf area index	-	1-2 seasonal	Literature* and comparison with Australian values
f_v	Fraction of vegetation cover	-	1.0	Field observation.
h_v	Height of vegetation	m	0.2	Estimated from field experience and literature

* Hillel [1998].

Neutron moisture meter access tubes for moisture measurement throughout the soil profile were collocated with CS615 loggers installed on representative hillslopes [Woods et al 2000]. Access tubes allow measurement of the soil moisture profile with a Neutron Moisture Meter (NMM), commonly to a depth of 1.5m. Soil moisture profiles were measured on 14 occasions during 1998-99.

Meteorological, soil, and vegetation data are all available for the Mahurangi catchment for the period 1998-99. Time series were either directly measured or calculated from field data for each of: solar radiation, longwave radiation, rainfall, wind speed, temperature, air pressure and humidity [Smith, 1990]. Each field site had rainfall independently gauged for the period. Temperature series were determined for each field site based on a meteorological station at Satellite Station and elevation lapse rates. Other meteorological data were common across all sites.

4. REPRESENTATION AND SIMULATION OF CARRAN'S FIELD SITE

In this study we apply ALSIS at point locations and compare model output with measured time series of soil moisture, and with measurements of soil moisture through the profile.

As well as the number and depth of soil layers, other soil and vegetation properties are required to run ALSIS (Table 1, 2).

Values describing threshold levels of moisture content were sourced from field measurements. These measured values of air-dry moisture content and moisture content at saturation have proved acceptable in the modelling of time series for all sites.

4.1 Uncalibrated Model Simulation of Soil Moisture

Simulations of the temporal soil moisture record measured at Carran's were made using ALSIS. At each of Upper, Mid and Lower, both a shallow (0-30cm) and deep (30-60cm) soil moisture record were obtained for direct comparison.

Model users will generally not have the information to calibrate a model such as ALSIS prior to application and for typical large-scale applications detailed hydrologic response data are not available. From a practical viewpoint, we therefore initially ran the model uncalibrated; using the best set of parameter values available from published data.

Simulation of soil moisture in the root zone using literature-based values for soil and vegetation parameters is poor (Figure 3). In particular, dry-downs are unrealistically slow and the seasonal signal is damped.

ALSIS is most sensitive to soil parameter values. Values of saturated hydraulic conductivity, K_s, the macroscopic capillary length scale, λ_s, and the soil hydraulic function shape parameter, C, were modified to improve the simulation of soil moisture (Table 1). K_s was increased by one order of magnitude.

λ_s significantly influences moisture content, especially through the profile, yet was not measured in the field. The original values were obtained by using the value for the most similar Australian soil. Similarity was based on the clay content. Adjusted values are also consistent with the range of λ_s cited in the literature. Different values of macroscopic capillary length scale for shallow and deep layers of the profile are appropriate.

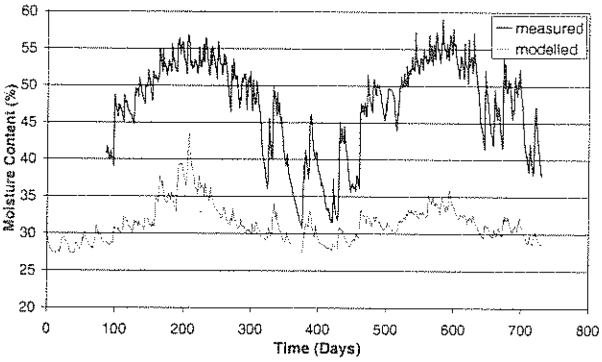

Figure 3. Measured and simulated soil moisture; Carran's Upper CS615 and original parameter set, shallow probe.

A value of $C = 1.3$ was originally selected based on that used to model Australian soils of high clay content; however values of C for clayey soils in the literature are quite variable. $C = 1.05$ was found to better suit both the surface and deeper soils and is consistent with the range found in the literature.

Results of simulations with these parameter changes are now discussed for the shallow continuous measurements, then for the deeper continuous measurements and finally for the profile simulations. The shallow simulation results are compared for the three sites at Carran's, then simulation of long and short-time-scale fluctuations are considered separately.

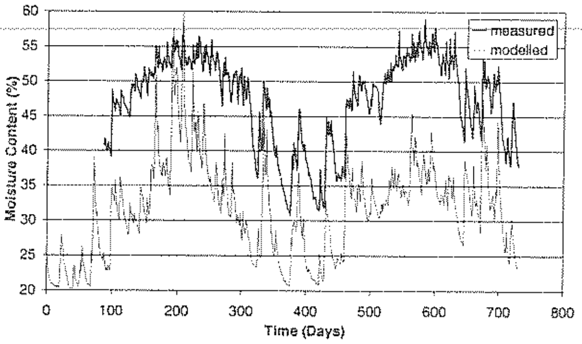

Figure 4. Measured and simulated soil moisture; Carran's Upper CS615 and improved parameter set, shallow probe.

Figure 4 shows that the model output compares favourably with measurements of soil moisture, except for the model being consistently ~15% V/V too dry. Upper, mid and lower –slope CS615 devices measured a similar temporal pattern of soil moisture, both in range and seasonal trend. Comparing model output with each of these three series suggests that the simulations are of similar quality for any of the CS615 time series, though Upper CS615 is best represented (Figure 5). This point application of ALSIS may be expected to best represent the site at which there is the least likelihood of lateral flow; the Upper site.

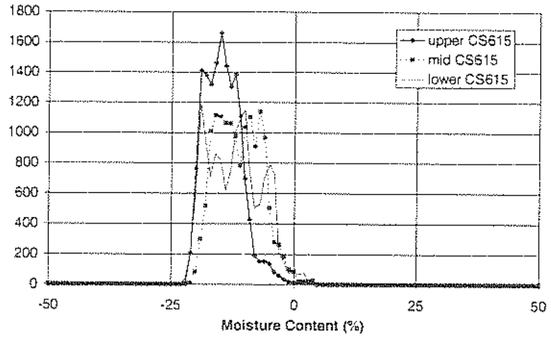

Figure 5. Frequency plot of (Measured – Modelled) soil moisture hourly series; Carran's, shallow soil.

The simulation results can be examined in more detail by considering short and long time-scales. Smoothed yearly patterns highlight how successfully the seasonal pattern is simulated by ALSIS (Figure 6). Mean series are further smoothed via a 2-harmonic Fourier transform function. ALSIS makes a consistent underestimate of soil moisture by ~15% V/V. The otherwise good simulation suggests that problems lie in the model of soil hydraulic properties used.

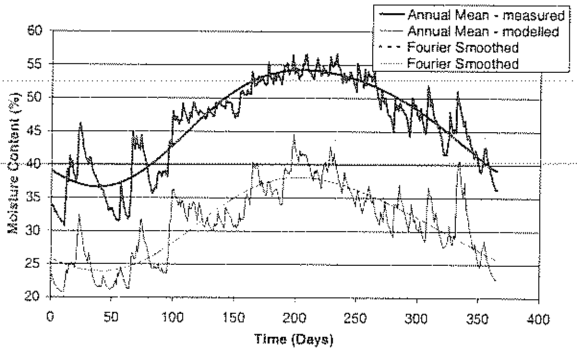

Figure 6. Annual mean and Fourier-smoothed series, Carran's Upper CS615, shallow probe.

Seasonality was then removed from the raw series, and small time scale fluctuations compared (Figure 7). Recession behaviour is well represented by ALSIS, particularly during summer. This suggests that evapotranspiration fluxes are accurately modelled at all time scales. Response to storm events, ongoing drainage and evapotranspiration are all modelled accurately at small time scales.

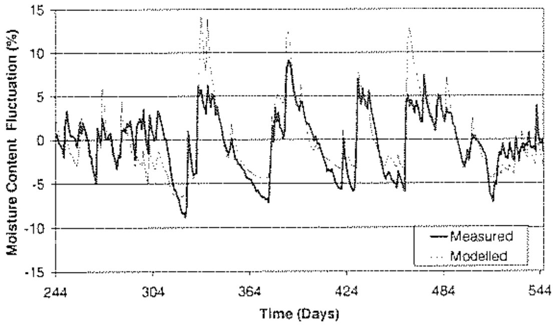

Figure 7. Residual of original soil moisture time series (Figure 4) and Fourier-Smoothed series (Figure 6); Carran's Upper.

In summary, at pasture sites ALSIS represents the short time scale variability in near-surface soil moisture well, with accurate rates of change at the daily to weekly scale. Seasonal fluctuations are also modelled accurately. However the model consistently underestimates soil moisture. This error can not be accounted for by uncertainty in the data.

Soil moisture in the deeper profile is not well modelled, particularly during the first winter (Figure 8). Fluctuations in soil moisture content of the deeper profile occur over longer time scales due to a lag effect. Simulation of changes in deeper profile soil moisture through time is, in most cases poor.

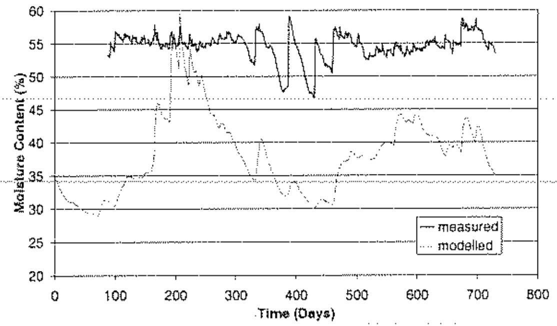

Figure 8. Measured and simulated soil moisture; Carran's Upper CS615 and improved parameter set, deep probe.

Profile measurements of soil moisture at points within Carran's show an increase in moisture content with depth, and a transition in soil properties at a depth of around 50cm (Figure 9). Soil properties are modelled to change from those of shallow soil to those of deep soil at 50cm depth (Table 1). Using improved soil parameter values, ALSIS produces realistic depth profiles of soil moisture (Figure 9), albeit with the offset problem noted above and a deeper simulated transition.

4.2 Limitations and Consequences

Model simulations only partially represent temporal trends in measured soil moisture. The overall water balance of ALSIS showed that from an input of 3235mm of rainfall over 2 years, 2139mm was lost to evapotranspiration, 612mm became runoff, and the remainder, 484mm, disappeared out of the bottom of the profile as deep seepage.

Overall modelling of the first winter period is poor, particularly in the deep profile, as ALSIS failed to deal adequately with the extreme rainfall event in July 1998. This may be due to the model underestimating antecedent soil moisture and thus overestimating the saturation deficit available to store infiltrated water.

Simulations of soil moisture in the Mahurangi could be refined by further adjusting parameter values. We have seen that ALSIS output is very sensitive to the choice of K_s, λ_s, and C. When we applied ALSIS uncalibrated, we modelled soil moisture incorrectly. We found that literature-based values of K_s, λ_s, and C were incorrect; K_s being one order of magnitude too small, and both λ_s and C affecting soil moisture in the profile. Adjusting soil parameters within believable ranges produced a very different representation of soil moisture in the Mahurangi. However it was not possible to overcome the consistent underestimation of soil moisture. We suspect that this may be due to limitations in the soil hydraulic model used.

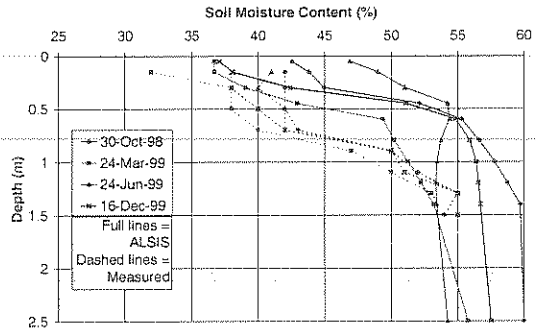

Figure 9. Soil moisture in the profile; measured and modelled; Carran's Upper NMM access point.

Temporal patterns produced may be improved by varying parameter values within the model. Some variations may be justified in that they better represent reality, while others may be justified only by way of allowing for processes that the model does not describe.

Alternatively, by using a measured time series to calibrate against, model users may infer some soil properties of their site. Parameter values corresponding to particular soil types may be input to ALSIS, and output then compared with measurements to ascertain which soil parameters best match field data.

5. CONCLUSIONS

Our ultimate aim is to develop methods for the estimation of soil moisture response from the point to hillslope to catchment scales.

The ALSIS model was used to model soil moisture in the Carran's subcatchment of the Mahurangi River catchment of northern New Zealand. Model input was sourced either from field measurements or from literature, such that all parameters were given a realistic value.

Model output consisted of soil moisture at ten layers through the profile, and this was compared to hourly time series and other profile measurements. Of the values initially selected to represent the Mahurangi, model output was most sensitive to incorrect values of K_s, λ_s, and C. By altering values of these parameters within realistic ranges, a satisfactory simulation of soil moisture fluctuations is possible.

Implications are that uncalibrated, untested application of ALSIS should only be carried out where soil hydraulic properties are accurately known. Realistic spatial representation by ALSIS requires detailed knowledge of soil properties over large areas.

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