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Simulating infiltration and the water balance in cropping systems with APSIM-SWIM

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Abstract

We test APSIM-SWIM's ability to simulate infiltration and interactions between the soil water balance and grain crop growth using soil hydraulic properties derived from independent, point measurements. APSIM-SWIM is a continuous soil-crop model that simulates infiltration, surface crusting, and soil condition in more detail than most other soil-crop models. Runoff, soil water, and crop growth information measured at sites in southern Queensland was used to test the model. Parameter values were derived directly from soil hydraulic properties measured using rainfall simulators, disc permeameters and ponded rings, and pressure plate apparatus. In general, APSIM-SWIM simulated infiltration, runoff, soil water and the water balance, and yield as accurately and reliably as other soil crop models, indicating the model is suitable for evaluating effects of infiltration and soil-water relations on crop growth. Increased model detail did not hinder application, instead improving parameter transferability and utility, but improved methods of characterising crusting, soil hydraulic conductivity, and macroporosity under field conditions would improve ease of application, prediction accuracy, and reliability of the model. Model utility and accuracy would benefit from improved representation of temporal variation in soil condition, including effects of tillage and consolidation on soil condition and bypass flow in cracks.

Additional keywords: infiltration, crop models, APSIM, water balance, soil structure.

Introduction

Models have been successfully used to simulate interactions between crops, soil, and the environment. Models such as EPIC (Williams *et al.* 1985) and PERFECT (Littleboy *et al.* 1989) have been used for 2 decades to evaluate erosion–productivity issues. The range of model applications now includes such diverse topics as climate change impacts on cropping options, land use evaluation, and research and development of improved cropping systems (e.g. Hammer *et al.* 1987; Probert *et al.* 1995; Thomas *et al.* 1995). Modelling studies benefit from being able to separate factors that may confound experimental studies, such as variable weather and soil types or the influence of pests and disease. Compared with experimental studies, simulations can be made quickly and easily, for longer weather sequences (100 years or longer) and for a greater range of treatments. Models are limited by uncertainty representing the physical system, functionality, complexity, and ability to derive parameter values (Grayson *et al.* 1992; Lane and Nichols 1996; Hammer 1998).

Many existing soil-crop models use simple representations of infiltration (e.g. the USDA curve number method, USDA 1972) and movement of water in the soil (e.g. the 'storage-routing' method of Knisel 1980) and do not have sufficient utility to study individual infiltration processes (Connolly 1998). Few explicitly represent surface sealing

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or crusting, a primary restriction to infiltration in subtropical climates. Models with a detailed representation of infiltration typically do not have a detailed crop model and cannot simulate effects of infiltration on crop growth (e.g. SWIM, Verburg *et al.* 1996).

The APSIM model (Agricultural Productions Systems Simulator, McCown *et al.* 1996) has incorporated SWIM (Verburg *et al.* 1996) as an alternative to the USDA curve number method, allowing evaluation of effects of soil condition, management, and the weather on infiltration and crop growth in more detail than previously possible. An additional benefit is an improved ability to derive parameter values from independent, point measurements, rather than by optimisation against measured soil water or runoff (Bristow *et al.* 1994). However, while methods for measuring infiltration and soil hydraulic properties are well established, methods for parameterising and applying detailed infiltration models in a cropping system framework are not well developed.

This paper evaluates some methods of parameterising and applying the APSIM model configured with the SWIM and SURFACE modules (termed the APSIM-SWIM model) and tests predictions of infiltration, the water balance, and crop yield.

Materials and methods

Experimental strategy

Data from existing agronomic/runoff studies at 4 sites (Fairlands, Billa Billa, Goodger, and Greenmount) in southern Queensland were used to test APSIM-SWIM's prediction of runoff, soil water, and crop growth in a cropping system context at the large plot or contour bay scale. Additional experiments were conducted at Goodger, Fairlands, and a site at Jimbour to test predictions of infiltration, runoff, evaporation, and crusting at the small or point scale under more controlled conditions.

The model was parameterised from soil hydraulic properties, surface roughness, and crusting measured at the sites.

The agronomic/runoff studies

A summary of data used from the Fairlands, Billa Billa, Goodger and Greenmount studies, a brief description of each site, and references to detailed descriptions are given in Table 1. These sites are representative of grain cropping areas in southern Queensland and northern New South Wales.

All sites had 'conventional' and 'zero-tillage' treatments. Conventional tillage involved 2–8 tillage operations over the summer fallow to control weeds and prepare a seedbed. With zero-tillage, chemicals were used to control weeds and seed was sown directly into undisturbed soil and stubble from the previous crop. At Fairlands, Billa Billa, and Greenmount various varieties of wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) were simulated. At Goodger, wheat, peanuts (*Arachis hypogaea*), soybeans (*Glycine max*), and maize (*Zea mays*) were simulated. Experimental plots across the sites varied in size from 180 m^2 to 6 ha. Crops were mostly grown with rainfall only, but some at Billa Billa had supplemental irrigation. From 0 to 75 kg/ha of NO_3-N was applied at planting.

Soil water measured gravimetrically or using neutron probes was available for varying intervals during fallow and in-crop. Surface cover was estimated visually at Fairlands and Greenmount, normally after runoff events. Surface roughness was measured using a roughness profile meter at Fairlands North and estimated visually at Wallumbilla and Greenmount. Visual estimates of roughness equated approximately to random roughness (*RR*) measured using the profile meter. At Fairlands (Wallumbilla), water levels in the outlets of contour bays were recorded using Cipolleti weirs and direct-height float recorders. At Greenmount, a 90° V-notch weir (Bay 0) and a 0.61 H flume (Bay 1) equipped with Stevens Type F float recorders were used to measure water level. Stage-height relationships converted water level to runoff rate.

Rainfall at Fairlands, Greenmount, and Billa Billa was measured using Mort and tipping bucket pluviometers with a time interval generally <5 min. Runoff predictions on days when short-time intensity data were not available was excluded from the daily runoff analysis, but included in annual totals. Rainfall was recorded with a 24-h time step at Billa Billa. Daily maximum and minimum temperatures and radiation were recorded either at the sites or nearby.

Organic carbon was measured using the Walkley and Black method (Bruce and Rayment 1982; Rayment and Higginson 1992) was multiplied by 1.3 to convert to total organic carbon.

Table 1. Characteristics of the experimental sites
Analytical data are for soil cropped for the specified period

	Fairlands	Greenmount	Billa Billa	Goodger
Location	26°00′S, 149°7′E	27°46′S, 151°55′E	28°10′S, 150°12′E	26°38′S, 151°50′E
Soil type	Brown Sodosol[A]; Sodic Gypsiustert[B]	Black Vertosol[A]; Vertisol[B]	Sodosol, Red Chromosol[A]; Typic Natrustalf[B]	Red Ferrosol[A]; Udic Haplustert[B]
Description by:	Freebairn *et al.* (1988); Connolly (2000)	Freebairn and Boughton (1981)	Radford *et al.* (1992); Thomas *et al.* (1995)	Bell *et al.* (1995)
Median annual rainfall (mm)	555	708	604	759
Period of cropping (years)	26–30	20–30	18–25	>50
Treatments/trials used	Wallumbilla Bays 2 and 3, Fairlands North Cult CT, Cult ZT, Virgin CTA	Bays 0 and 1	Fumigated cult. ZT 75N, natural rain grown and irrigated, wheat experiment CDS 0N,	Continuous crop, conventional and direct drill, no deep rip
Data available for testing	Surface roughness and cover, soil water, runoff, crop growth and yield (wheat, barley)	Surface cover, soil water, runoff, crop growth (wheat)	Soil water, crop growth and yield (wheat)	Soil water, crop growth and yield (wheat, peanuts, soybeans, and maize)
Sand 0–0.1 m (%)	59	16	57	21
Silt 0–0.1 m (%)	7	21	14	14
Clay 0–0.1 m (%)	35	63	29	65
ESP 0–0.1 m (%)	4	1	3	1
Total organic carbon 0–0.1 m (%)	1.3	2.1	1.2	2.3
Contour bay/plot area (ha)	0.09, 4.0–5.9	0.9–1.3	0.01–0.02	3.0
Contour bay/plot slope (%)	1.8	7.5	1.0	2.0

[A]Isbell 1996.
[B] Soil Survey Staff 1975.

Additional experiments

Additional experiments were made at Goodger and Fairlands, described in Table 1, and at the Jimbour site. The Jimbour experiments (Taylors and Grants) are located near Dalby Queensland (26°54′S 151°6′E) on a Black Vertosol (Isbell 1996)/Vertisol (Soil Survey Staff 1975). The sites have been cropped for >50 years and soil in the surface 0.1 m has 62% clay, 19% silt and 15% sand, ESP of 4, and 1.2% organic carbon.

The evaporation experiment at Goodger

In this experiment, 25-m^2 plots in the continuously cropped, conventional tilled treatment area at Goodger were wet to saturation, then soil moisture was recorded daily over 75 days from February to May 1997. One plot was bare and consolidated from previous rainfall, the other was in the same condition but covered with 10 000 kg/ha of wheat stubble, giving 100% surface cover. Moisture was measured at 0.1 and 0.2 m depth in each plot using an enviroscan probe (Buss 1993). Two duplicates were measured and averaged.

The rainfall simulation experiments at Goodger and Fairlands

Rainfall was applied to 1.6-m^2 plots using the field simulator described later in *Methods of characterising soil hydraulic properties*. At Goodger, rainfall was applied at 120 mm/h for 60 min. Runoff was measured at the plot outlet. Soil water content was measured during rainfall at intervals down to 0.9 m using an enviroscan probe (Buss 1993). Results from 2 duplicate plots were averaged. The soil was consolidated from previous rain, but the surface 0.1 m was lightly cultivated prior to the experiment to remove any crust. Maize stubble (10 000 kg/ha) was placed on the surface, providing 100% cover. Land slope is about 2%.

At Fairlands, rainfall was applied at 100 mm/h for 60 min and runoff measured. Results from 2–4 duplicate plots were averaged. Rough and smooth treatments were characterised. The smooth treatment had a consolidated surface and 5–10% surface cover from the previous wheat crop. The rough treatment had 5% surface cover, had previously been cultivated across slope with a tractor-drawn chisel plough, and had received 27 mm of rainfall since cultivation, but furrows still contained substantial depression storage. Land slope is 2.5–2.9%.

The crust development experiment at Jimbour

Rainfall was applied using the laboratory rainfall simulator described below in *Methods of characterising soil hydraulic properties* in 4 applications of 30 min at 100 mm/h. Each application was separated by 24 h, during which the surface dried slightly. Crust conductivity was measured during rainfall. Two duplicates were measured and averaged. Rainfall was applied to bare soil and with wheat stubble applied to the surface to approximate cover levels of 10% (400 kg/ha), 50% (2000 kg/ha), and 90–100% (4000 kg/ha).

Methods of characterising soil hydraulic properties

Soil moisture characteristic

The desorption moisture characteristic was measured using methods described in McIntyre (1974). Four replicates of undisturbed samples were collected in 0.03-m-long by 0.03-m-diameter tubes. Samples were wet up slowly for a period of up to 7 days on a bed of wet filter paper using deionised water with 0.05 kg/m^3 of copper sulfate ($CuSO_4.7H_2O$) added to prevent algal growth. Porous ceramic plates and pressure plate apparatus were used to apply suction in increments up to –1500 kPa.

Hydraulic conductivity

Soil hydraulic conductivity in the field was measured using disc permeameters and ponded rings. Disc permeameters (Perroux and White 1988) were applied using Reynolds and Elrick's (1991) method to measure hydraulic conductivity at saturation, –0.1, –0.2, –0.3, and –1.0 kPa supply potentials. Measurement times were 3–8 min at each potential. Rainwater was used (electrical conductivity <3 µS/m). Eight replicates were measured and averaged. Fine bedding sand (mean diameter <0.001 m) was used to ensure good contact between the disc permeameter and the soil. Measurements were made within a 3-m^2 area to minimise soil variation. The disc permeameters did not measure flow in pores >3 mm (supply potential –0.1 kPa), so large cracks and macropores were not characterised.

The single ponded ring, 1-depth method of Reynolds and Elrick (1990) was used. Rings were 30 cm in diameter and inserted to between 5 and 15 cm deep. Water head was maintained at a constant level using a float. Readings of water flux were made for between 500 and 1000 min. Results from 4 duplicates were averaged.

Surface crusting

The method of Freebairn *et al.* (1991) was used to measure rate of crust formation under rainfall. An oscillating boom rainfall simulator, based on the design of Bubenzer and Meyer (1965), was used to apply rainfall to small trays of soil in a laboratory. Rainfall energy from the simulator nozzles was 23 J/m^2.mm at 100 mm/h (J. Foley, pers. comm.). Rainfall application was intermittent (1 sweep every 2 s) but produced cumulative energy and drop size distributions similar to natural rainfall (R. Loch, J. Foley, pers. comm.). Rainwater (electrical conductivity <3 µS/m) was used.

Air-dry soil was placed at 20% slope under the rainfall simulator in 0.3-m^2 metal trays. The soil surface was bare or wheat stubble was added to provide surface cover. Depth of wetting did not exceed soil depth. Infiltration was calculated by logging change in tray weight. Soil matric potential below the crust was measured using ceramic pencil tensiometers (0.005 m diam. and 0.2 m long) placed approximately 0.01 m under the soil surface. Rainfall was applied at 100 mm/h for 30 min Gravimetric moisture was measured before and after rainfall. Bulk density was measured.

Conductance of the crust, G_{crust}, was calculated at any time after ponding with Darcy's law (Darcy 1856; Freebairn *et al.* 1991, Eqn 1):

$$G_{crust} = f/(H_o - H_f + L_f)*L_f \qquad (1)$$

where f is infiltration rate, H_o is matric potential due to water head above the crust surface, H_f is matric potential below the crust, and L_f is crust thickness. H_o was set at 1 mm as the surface was ponded. Actual depth of the tensiometers varied so measured matric potential was adjusted to the depth of the crust assuming potential gradient below the crust was unity. Surface crust thickness is not well defined, though experimental evidence points to a thickness of 3–10 mm (Sharma *et al.* 1981; Loch 1989). We assumed the crust was 3 mm thick.

Field infiltration

Infiltration was measured in the field using a portable rainfall simulator. The field simulator was essentially identical to the laboratory simulator, with additional framing and a runoff collection device and portable water supply. Rainfall was applied simultaneously to two 1-m-wide and 1.6-m-long plots. Runoff water was collected at the downslope edge and routed by vacuum through calibrated tipping buckets. Tip rate was logged at 1-min intervals. Water used for simulations was either rainwater or good quality dam or creek water with an electrical conductivity <3 µS/m (following Agassi *et al.* 1985; Loch 1994).

Surface roughness

Surface roughness was measured in the field with a profile meter, which consisted of a frame containing a row of metal pins, spaced at 0.03-m intervals. The frame was placed over a plot 1 m by 1 m and levelled with adjustable legs. Transects were taken at 0.1-m spacing by simultaneously lowering the pins to the soil surface and recording height of the pins. Random roughness, *RR*, was calculated using the method of Allmaras *et al.* (1966) as the product of mean pin height over the plot and standard error of logarithmic heights of the pins. Volume of depression storage was calculated using a modified algorithm from Moore and Larson (1979) and was the volume held on the plot when runoff from the whole plot reached the outlet. Plot slope was determined by averaging the slope of linear regressions fitted through surface elevations parallel to land slope.

The APSIM-SWIM model

APSIM is a software system for simulating crop and pasture production, residue decomposition, soil water and nutrient flow, runoff, and erosion using conditional rules (McCown *et al.* 1996). We used the SWIM (Verburg *et al.* 1996) with SURFACE modules in APSIM to represent infiltration and runoff and call this combination APSIM-SWIM. For some simulations the SOILWAT2 module (McCown *et al.* 1996), which uses the USDA curve number method to simulate runoff, was used instead of SWIM and SURFACE and the model in this configuration is referred to as APSIM-SOILWAT.

In APSIM-SWIM infiltration and runoff is influenced by surface crusting, permeability of subsurface soil layers, and surface detention of runoff water. SWIM represents soil water holding capacity and sub-crust permeability and SURFACE simulates crusting. Soil water holding capacity is represented with the moisture characteristic and soil hydraulic conductivity using the $K(\psi)$ relationship (e.g. Campbell 1974). Neither the moisture characteristic nor $K(\psi)$ relationship can be changed during a simulation. Crust development is simulated in SURFACE using the method of Silburn and Connolly (1995), adapted from Brakensiek and Rawls (1983) (Eqn 2):

$$G_{crust} = G_{min} + (G_{max} - G_{min})\exp(CE_s) \tag{2}$$

where G_{crust} is crust conductivity at any point in time, G_{max} is maximum or initial crust conductivity, G_{min} is final or steady state conductivity, E_s is cumulative rainfall crusting energy, moderated by effects of cover and roughness (Eqn 3), and C is a factor determining rate of decline in G_{crust} between G_{max} and G_{min} (Eqn 4):

$$E_s = \int[B(1 - RR/4)E_oR]dt \tag{3}$$

$$C = 1/E_o'\mathrm{Ln}[G_{min}/(G_{max} - G_{min})] \tag{4}$$

where E_o' is the rainfall energy for G_{crust} to decrease to 2 G_{min}, B is the fraction of the surface exposed, RR is random roughness, E_o is rainfall kinetic energy per unit depth of rainfall, and R is rainfall during the time step.

SURFACE changes *RR* with cumulative rainfall, based on the specified maximum and minimum *RR* and a decay rate. SWIM runs down the capacity of depression storage with cumulative rainfall to a minimum value at a specified rate. Tillage resets *RR* and depression storage to their maximum values.

APSIM-SWIM parameters describing hydrologic response of the catchment (runoff rate factor, *roff0*, and power, *roff1*) are typically held constant during a simulation but parameters describing crusting and depression storage are varied depending on the type and intensity of tillage.

APSIM-SWIM outputs on a daily basis, even though SWIM uses an internal time step as short as 1 min. To simulate event hydrographs with a short time step, we ran the stand-alone version of SWIM (Verburg *et al.* 1996).

The other modules used in APSIM-SWIM were: RESIDUE2, SOILN2, SOILWAT2, and the crop growth modules NWHEAT, SOYBEAN, PEANUT, and MAIZE (McCown *et al.* 1996). The crop modules simulate transpiration (SWIM simulates water extraction from soil layers), surface cover from green plants, dry matter production, and grain yield. RESIDUE2 decomposes residue over time, incorporates residue into the soil with tillage, and estimates residue cover of the soil surface. SOILN2 simulates soil organic and mineral N dynamics.

Model testing

Model accuracy and robustness was tested by comparing measured and predicted random roughness, surface cover, soil water, runoff, and crop yield. Goodness of fit was indicated using coefficient of determination calculated about the line of best fit, R^2, and the line $y = x$, *EF* (or efficiency factor) (Mayer and Butler 1993) and root mean square error expressed as a percentage of the measured mean, defined as the 'general standard deviation' in Jorgensen *et al.* (1986).

Model parameterisation methods

Parameterisation strategy

The general parameterisation strategy, summarised in Table 2, was to derive soil hydraulic properties independently of data used for testing, using rapid and portable measurement methods. Established model parameter values describing crop growth, residue, and soil N dynamics were largely used, with key parameters varied to improve the model's representation of N mineralisation, crop water and N use, and yield.

Table 2. Summary of the methods used to derive parameter values for APSIM-SWIM

APSIM-SWIM function	Method of derivation
Surface crusting	Parameters for tilled and bare soil in fallow derived from laboratory rainfall simulation, G_{min} was adjusted upward for different cover levels and during the crop
Moisture characteristic	Represented with the smoothed Brooks-Corey function (Verburg *et al.* 1996), fitted to the measured moisture characteristic
$K(\psi)$ relationship	Represented with the smoothed Brooks-Corey function; parameter values were derived from field measurements of hydraulic conductivity and the moisture characteristic
Bypass flow	Calibrated against measured infiltration for the Goodger rainfall simulator experiment
Surface roughness and depression storage	Parameter values derived from roughness measured using a profile meter before and after simulated or natural rainfall events. Also calibrated against measured runoff for the rainfall simulator experiment at Fairlands
Catchment hydrology	The parameter *roff0* optimised against the runoff hydrograph for a subset of events, *roff1* was held constant at 1.88
Crop growth	C, $N0_3$-N and pH measured on cores. Parameter values describing the organic matter pool (*fbiom*, *finert*) optimised against observations of soil mineralisation. The crop parameters *kl* and *xf* for maize, peanut, and soybean, and vernalisation sensitivity and photoperiod sensitivity for wheat were varied until observed time of anthesis, rate of water extraction, leaf area index, and yield were adequately represented. 1500 kPa moisture from the measured moisture characteristic was used for the crop parameter *ll*
Weather and rainfall intensity	Measured directly at or near the sites. Rainfall intensity was disaggregated from daily rainfall at Billa Billa using the model of Connolly *et al.* (1998)

Table 3. Summary of APSIM-SWIM parameter values used to simulate the agronomic/runoff studies

PAWC, plant available water capacity; parameters in the Brooks Corey representation of the moisture characteristic (Verburg *et al.* 1996) and $K(\theta)$ relationship are θ_s, saturated water content; ψ_e, air entry matric potential; b, a constant; K_{matrix}, saturated hydraulic conductivity of the soil matrix; K_{mpore}, saturated hydraulic conductivity of macropores

	Fairlands	Greenmount	Billa Billa	Goodger
		Surface crust		
Initial conductance, *Gmax* (1/h)	10	15	10	15
Minimal conductance, *Gmin* (1/h)	1.01 (tilled) 1.2 (in-crop)	0.004 (tilled) 0.65 (in-crop) 0.60 (zero-till)	0.01 (tilled) 1.2 (zero-till)	0.0128 (tilled) 1.2 (zero-till)
Crust decay rate (derived from Eo') (m^2/J)	0.0036	0.0036	0.009	0.004
		Surface roughness and hydrology		
Maximum random roughness, *RRmax* (mm)	5–30	10–40	10–30	15–30
Minimum random roughness, *RRmin* (mm)	5	5	5	5
Random roughness decay rate (m^2/J)	0.005	0.015	0.005	0.005
Maximum depression storage, *hm1* (mm)	0.5	0.5	0.5	0.5
Minimum depression storage, *hm0* (mm)	0.001	0.02	0.001	0.001
Depression storage decay rate (J/m^2)	500	100	500	500
Runoff rate factor, *roff0* [(mm/h)/($mm^{\text{runoff rate power}}$)]	0.1–0.2	0.4–1.3	1.5	1.5
Runoff rate power, *roff1*	1.88	1.88	1.88	1.88
		Wheat phenology		
Vernalisation sensitivity	1.0	1.0–3.0	1.0–2.0	1.5
Photoperiod sensitivity	2.5–3.0	2.5–3.5	2.5	3.0
		0–0.1 m deep		
θ_s (v/v)	0.430	0.700	0.500	0.525
ψ_e (cm)	50	20	50	5
B	3	9	3	7
K_{matrix} (mm/h)	2	3	1.2	5
K_{mpore} (mm/h)	3	1	1.0	450
kl	–	–	–	0.08
xf	–	–	–	1.0
		0.1–0.3 m deep		
θ_s (v/v)	0.430	0.570	0.419	0.514
ψ_e (cm)	40	10	20	10
B	8	11	9	11
K_{matrix} (mm/h)	0.2	0.5	0.4	5
K_{mpore} (mm/h)	0.5	0.5	0.5	100
kl	–	–	–	0.08
xf	–	–	–	0.5 (peanut, soybean) 1.0 (maize)
		0.3–0.6 m deep		
θ_s (v/v)	0.440	0.560	0.404	0.500
ψ_e (cm)	30	50	20	10
b	11	11	8	12
K_{matrix} (mm/h)	0.3	0.5	0.1	2
K_{mpore} (mm/h)	0.5	1.0	0.1	10
kl	–	–	–	0.08
xf	–	–	–	0.3 (peanut, soybean) 1.0 (maize)

continued next page

Table 3. (continued)

	Fairlands	Greenmount	Billa Billa	Goodger
	0.6–0.9 m deep			
θ_s (v/v)	0.420	0.532	0.383	0.481
ψ_e (cm)	10	100	20	40
b	13	8	12	15
K_{matrix} (mm/h)	0.4	0.5	0.1	1
K_{mpore} (mm/h)	0.5	1.0	0.1	60
kl	–	–	–	0.05
xf	–	–	–	0.1 (peanut, soybean) 1.0 (maize)
	0.9–1.2 m deep			
θ_s (v/v)	0.405	0.520	0.365	0.455
ψ_e (cm)	10	300	20	40
b	13	8	12	15
K_{matrix} (mm/h)	0.4	0.5	0.01	1
K_{mpore} (mm/h)	0.5	0.0	0.1	40
kl	–	–	–	0.03
xf	–	–	–	0.1 (peanut, soybean) 1.0 (maize)
	1.2–1.5 m deep			
θ_s (v/v)	0.390	0.520	0.358	0.430
ψ_e (cm)	20	300	20	60
b	14	8	12	18
K_{matrix} (mm/h)	0.4	0.5	0.01	1
K_{mpore} (mm/h)	0.5	0.0	0.1	40
kl	–	–	–	0.01
xf	–	–	–	0.1 (peanut, soybean) 1.0 (maize)

Parameter values derived for the 4 agronomic/runoff studies are summarised in Table 3. The model was generally set to simulate the entire experimental period without resetting model variables. Soil water was reset on occasions during the simulation when error arose because of conditions not represented by the model, such as a result of weed growth or pests or disease.

Certain parameter values were calibrated against measured infiltration or runoff if there were no independent data available that could be used for parameterisation. Parameter values describing depression storage for the rainfall simulator experiment at Fairlands, bypass flow for the rainfall simulator experiment at Goodger, and flow hydraulics for a subset of runoff events from the contour bay experiments at Fairlands and Greenmount were calibrated.

Surface crusting

Parameters describing surface crusting were readily measured in the laboratory on disturbed soils (Fig. 1). In the field, though, crust conductivity is influenced by cover, wetting and drying cycles, crop activity, and micro-topography effects (Falayi and Bouma 1975; Roth and Helming 1992) which are not easily mimicked in the laboratory. We attempted to replicate affects of cumulative rainfall and cover on crust permeability at Jimbour (Fig. 2). On bare soil, crust conductance continued to decline until cumulative rainfall energy reached about 4000 J/m^2 (210 mm of rain). Steady state conductance in Eqn 2, G_{min}, increased as cover increased. G_{max} and the crust decay rate (proportional to Eo') were held constant as cover increased, and the model accurately reproduced the reduction in crusting energy and rate of crust formation. Accordingly, we derived the parameters in Eqn 2–4 from laboratory simulations on disturbed soil for varying cover levels and adjusted G_{min} to account for crop activity and other factors affecting crust formation in the field.

Moisture characteristic

The smoothed Brooks-Corey function (Hutson and Cass 1987) was used in APSIM-SWIM to represent the moisture characteristic. Figure 3 shows a typical representation of the moisture characteristic measured

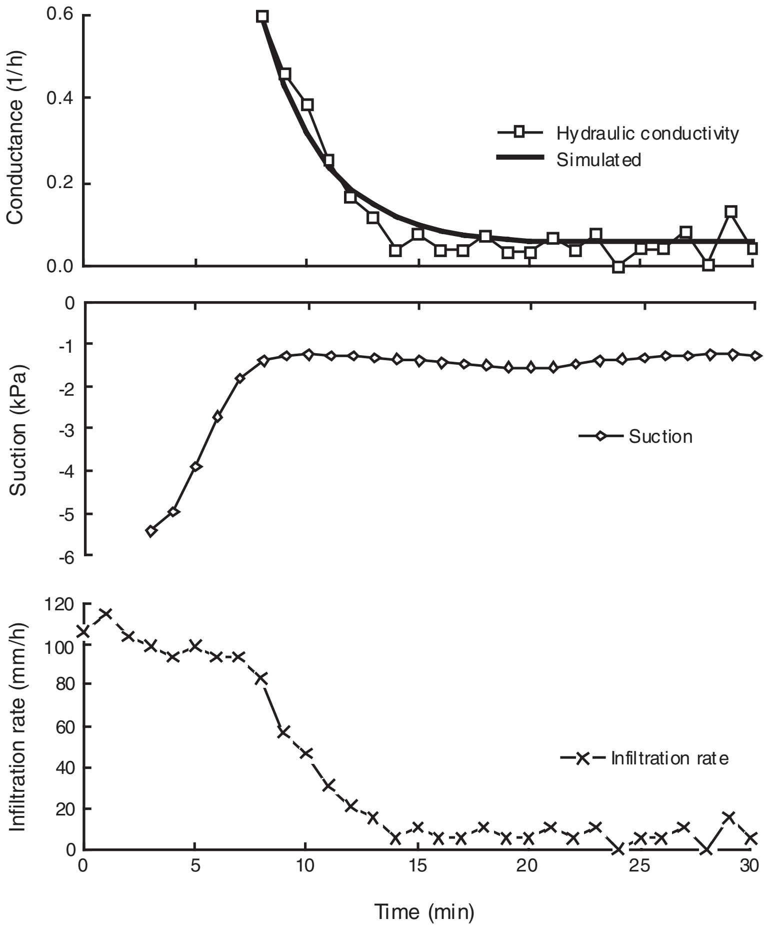

Fig. 1. Crust development at Jimbour, as measured using the method of Freebairn *et al.* (1991). Conductance was simulated with Eqn 1 using G_{max} = 10/h, G_{min} = 0.055/h, crust decay rate = 0.024 m^2/J.

at Fairlands. Average soil condition was represented because there is no capability in APSIM-SWIM to vary the moisture characteristic with consolidation or tillage disturbance.

K(ψ) *relationship*

Theoretically, the *K*(ψ) relationship can be derived from data collected using disc permeameters (e.g. Mead and Chan 1992; Lorimer and Douglas 1995; Verburg *et al.*1996; Bell *et al.* 1997), but in this study the disc permeameters overestimated *K* for all but the Red Ferrosol (Goodger). On the Vertosols, Sodosols, and Chromosols, *K* derived from ponded ring data was generally 2 orders of magnitude lower than disc permeameter *K* (e.g. Fig. 4). In addition, when *K*(ψ) derived from disc permeameter data was input to APSIM-SWIM, internal drainage was over-predicted and runoff under-predicted. For example, simulation error as a result of using *K*(ψ) relationships derived from disc permeameters was evident for a runoff event observed on 3 April 1988 for Bay 0 at Greenmount. Runoff was caused by restricted permeability of sub-surface soil because the soil was saturated from prior rainfall and there was no surface crust because of dense pasture cover. No runoff was predicted using the disc permeameter derived *K*(ψ), but when *K*(ψ) derived from ponded ring data was used the runoff hydrograph was accurately simulated.

On the Red Ferrosol (Goodger), *K* measured using disc permeameters matched ponded ring *K* values (Fig. 4). Variation in *K* close to saturation was probably a result of macroporosity changing with degree of

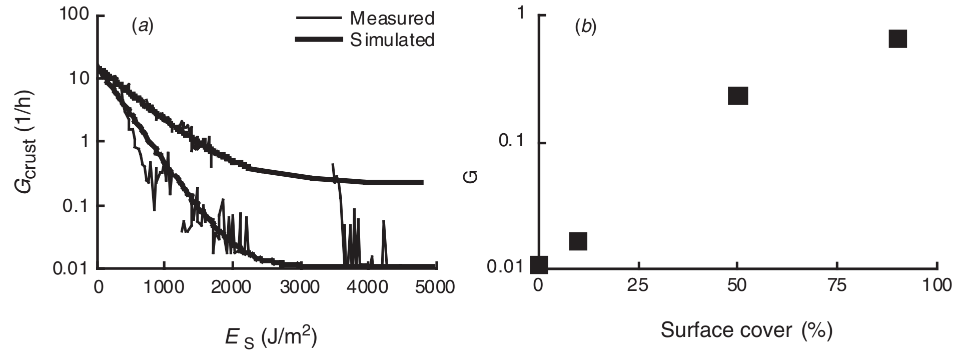

Fig. 2. Change in (*a*) crust conductance, G_{crust}, with cumulative rainfall crusting energy, E_s, for 0 and 50% cover, and (*b*) effect of surface cover on minimum crust conductance, G_{min}, for the black Vertosol at Jimbour.

consolidation, water content, and management prior to measurement. Model-derived predictions of infiltration and internal redistribution of soil water were accurate using disc permeameter $K(\psi)$ (see *Model accuracy and robustness*).

The discrepancy between disc permeameter and ponded ring data on non-Ferrosols is most likely due to lateral flow from the disc permeameter not being adequately accounted for in the analysis method, and was probably exacerbated by short time of measurement (<10 min at each suction). Such a short time of measurement and the application of water at negative head may not allow swelling or slaking to the extent as under natural wetting cycles. Depth of wetting is also likely to be small with disc permeameters, so flow tortuosity and macropore discontinuity over a larger depth may not be adequately characterised.

Catchment hydrology, surface conditions, and bypass flow

SWIM's parameters describing routing of runoff water were catchment-specific, affected by catchment area, slope, channel configuration, and surface roughness and cover. Accordingly, parameters were derived by optimisation against a subset of measured runoff hydrographs. Runoff rate constant (*roff0*) varied from 300 for 1-m^2 rainfall simulator plots to 1 for 4-ha contour bays. Runoff rate power (*roff1*) was held constant at 1.88. Temporary and permanent detention of runoff water in surface depressions, random roughness, and change with cumulative rainfall could be measured on small plots using the profile meter.

Surface cover was simulated by the modules responsible for crop growth and residue decomposition. Default parameter values were used.

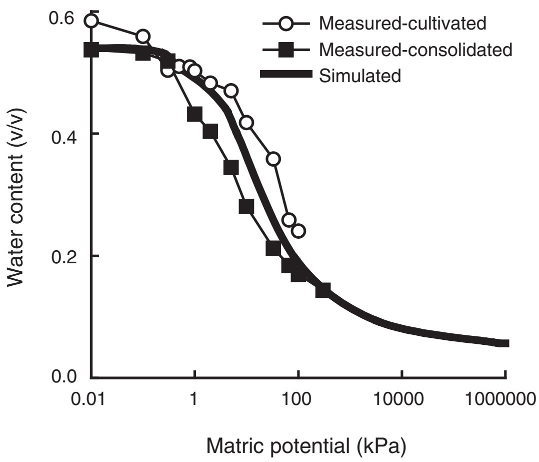

Fig. 3. Typical representation of the soil moisture characteristic using the smoothed Brooks-Corey function. The measured data are for the 0–0.1 m layer at Fairlands.

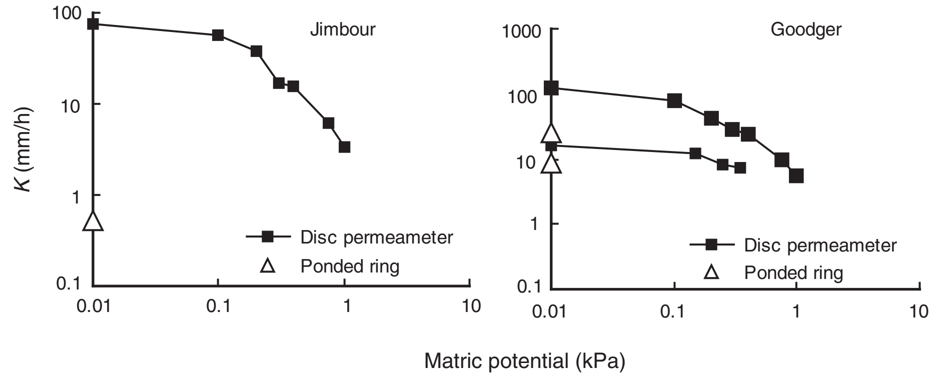

Fig. 4. Hydraulic conductivity, *K*, calculated from disc permeameter and ponded ring data at Jimbour and Goodger, 0.1–0.15 m deep.

Bypass flow was simulated only at Goodger because there were insufficient data for the other sites to indicate its importance or to parameterise the model.

Soil chemical condition, crop agronomy, and weather

Measured organic carbon, $N0_3$, and pH were input. Parameter values describing the organic matter pool were optimised until observations of soil mineralisation were correctly simulated. Parameters describing crop growth were varied until measured time of anthesis, soil water extraction by roots, leaf area index, and yield were adequately represented. Tillage, planting and other agronomic operations were entered directly in APSIM's control file.

Weather was measured at all sites and rainfall intensity at all but Billa Billa. Rainfall intensity was disaggregated from daily rainfall at Billa Billa using the model of Connolly *et al.* (1998).

Results of the evaluation of model accuracy and robustness

Infiltration and event runoff hydrographs

With accurate specification of initial conditions, SWIM accurately represented infiltration and runoff from individual rainfall and rainfall simulator events. Figure 5 shows predicted runoff from high intensity rainfall on smooth (consolidated) and rough (tilled) rainfall simulator plots at Fairlands. The model accurately simulated infiltration controls, mostly surface crusting and the impact of surface detention on runoff, once parameter values describing depression storage were optimised. Infiltration and movement of water in the soil profile for simulator plots at Goodger were reasonably well represented once bypass flow parameters were optimised (Fig. 6).

Runoff hydrographs from contour bay catchments at Greenmount and Fairlands were accurately represented when the catchment hydrology parameter, *roff0*, was derived from a subset of runoff hydrographs and antecedent conditions were specified. Figure 7 shows SWIM's prediction of runoff from a relatively complex rainfall event at Greenmount using specified catchment hydrology and antecedent conditions. The simulated runoff hydrograph leads the measured hydrograph slightly, but peak runoff rate and total volume were accurately predicted, both for this and a range of events at Fairlands and Greenmount (Fig. 8, Table 4).

Surface conditions

Temporal variation in measured surface cover and roughness was difficult to simulate accurately, but mostly because of effects of processes not represented by the model.

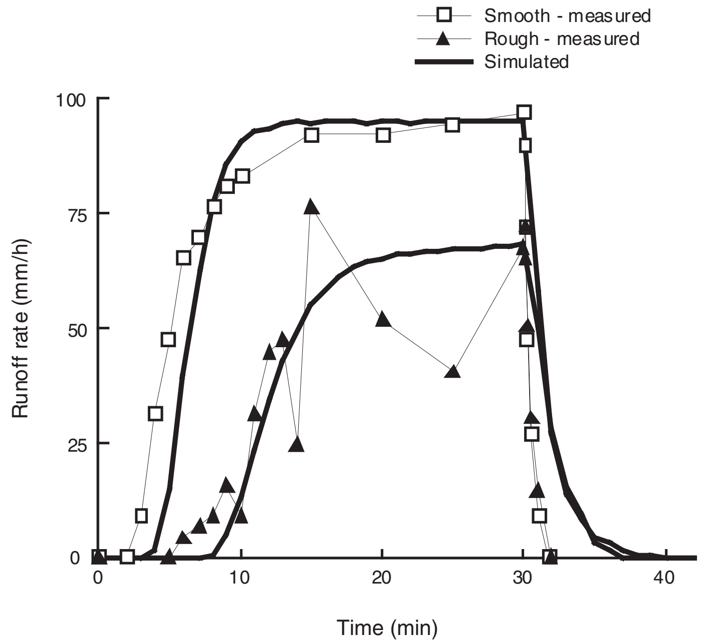

Fig. 5. Measured and predicted runoff from 1-m^2 rainfall simulator plots at Fairlands, simulated using the standalone SWIM model with parameters describing depression storage optimised. Parameter values varied from Table 3 included for the smooth treatment: *hm1* = 0.1 mm, *hm0* = 0.1 mm, depression storage decay rate = 500 J/m^2, *roff0* = 100 (mm/h)/(mm$^{\text{runoff rate power}}$); for the rough treatment: *hm1* = 2.0 mm, *hm0* = 0.1 mm, depression storage decay rate = 500 J/m^2, *roff0* = 25 (mm/h)/(mm$^{\text{runoff rate power}}$).

Figure 9 shows typical seasonal variability in cover and roughness. Factors not considered by the model, such as weed growth or crop failure because of pests or disease, greatly influenced the model's predictions of cover and errors tended to persist for some time (Fig. 10, Table 4). These confounding factors aside, the model tracked temporal variation in cover.

There was only a small dataset to test the model's prediction of roughness but predictions reliably reproduced the measured data (Fig. 10, Table 4).

Roughness was more reliably simulated than cover partly because processes affecting roughness were more closely defined in the model and were parameterised using local rainfall simulator data. Surface cover was predicted with a combination of the crop and RESIDUE2 modules using default parameter values, and cover was not reset when crop predictions were in error (e.g. after a crop failure or weed growth). Roughness was effectively reset with tillage meaning errors tended not to persist for as long as with cover.

Daily and annual runoff

Daily runoff predictions were variable (Fig. 11, Table 4), probably due to errors in predicting cover and roughness leading to an accumulated error in antecedent crust conductivity. There were no field measurements of crust conductivity to test this, but when the events in Fig. 8 were simulated using the continuous model, correlation between

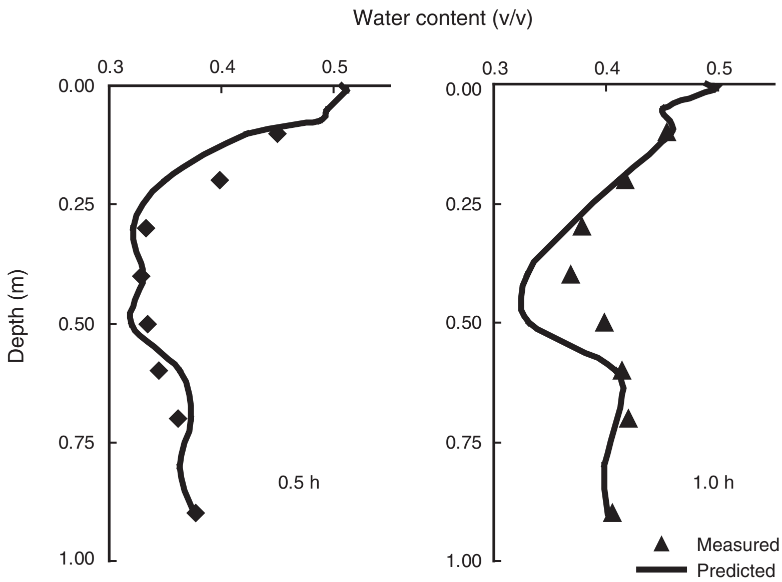

Fig. 6. Measured and predicted soil water during the rainfall simulator experiment at Goodger using SWIM with bypass flow parameter values optimised. Parameter values varied from Table 3 included: depth of bypass flow, *ibP* = 0.6 m, conductance, *gbP* = 0.035/h, storage, *sbP* = 1.1 cm of water/cm of positive ψ.

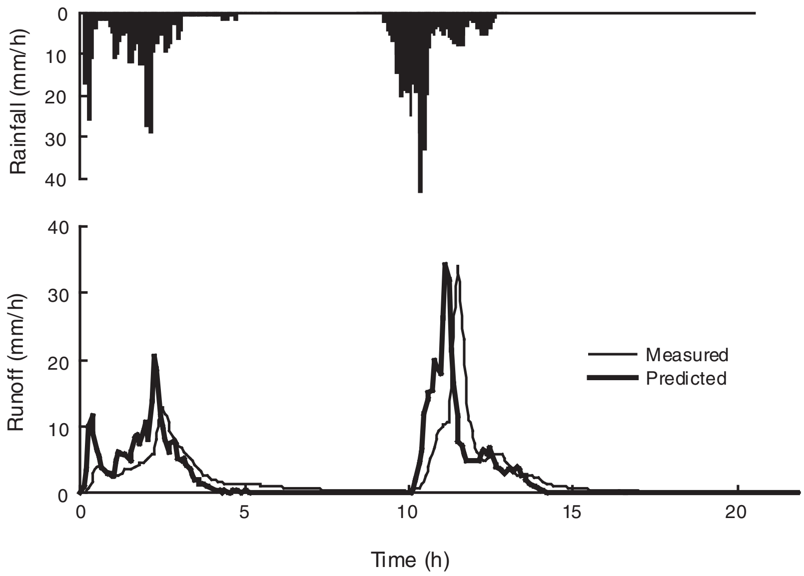

Fig. 7. Measured and predicted runoff from an event on 2 May 1983, Bay 1 at Greenmount, simulated using SWIM with specified antecedent conditions. The soil surface was bare, smooth and wet with a strong pre-existing crust. Parameter values varied from Table 3 included: G_{max} = 0.004 1/h, G_{min} = 0.004 1/h, *hm1* = 0.2 mm, *hm0* = 0.01 mm, *roff0* = 1.3 (mm/h)/(mm$^{\text{runoff rate power}}$).

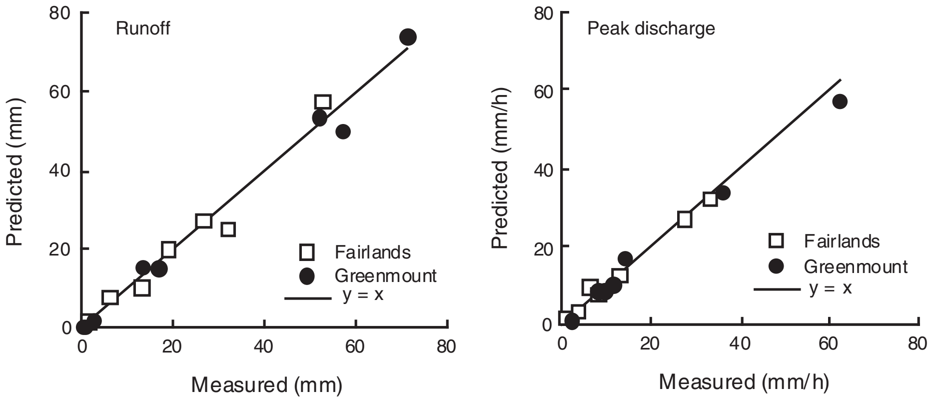

Fig. 8. Measured versus predicted runoff and peak discharge for a subset of runoff events from contour bays at Fairlands and Greenmount, simulated using SWIM with specified antecedent conditions. Goodness of fit statistics are given in Table 4.

measured and predicted runoff decreased markedly, indicating the importance of accurate specification of antecedent conditions (Table 4).

There were no data to indicate the impact on runoff and the water balance of cracking, disturbance, and consolidation of the tilled layer, or temporal variation in soil hydraulic condition (other than the surface crust); these processes are not simulated in APSIM-SWIM. It would seem likely, though, that these processes may be important for some soils and simulation applications, and improved model capability in this area would be of benefit.

Annual runoff was simulated more accurately than daily, indicating that longer term simulations can be undertaken with a reasonable degree of confidence. Increased accuracy at this increased level of aggregation was probably due to compensating errors, typical of soil-crop models (Lawrence 1990; Silburn and Freebairn 1992; Littleboy *et al.* 1992).

Table 4. Summary of goodness of fit statistics

	Slope	Intercept	R^2	EF	General standard deviation
Event runoff, SWIM, antecedent conditions specified (mm)	1.0 ± 0.04	–0.6 ± 1.3	0.98	0.98	13
Event runoff, SWIM, antecedent conditions predicted (mm)	0.6 ± 0.16	–2.3 ± 5.0	0.56	0.18	84
Event peak discharge, SWIM, antecedent conditions specified (mm/h)	0.9 ± 0.03	0.7 ± 0.6	0.99	0.98	12
Surface cover, APSIM-SWIM (%)	0.8 ± 0.05	2.6 ± 2.2	0.58	0.55	59
Random roughness, APSIM-SWIM (mm)	0.73 ± 0.26	1.59 ± 2.87	0.50	0.35	34
Daily runoff, APSIM-SWIM (mm)	0.59 ± 0.04	2.75 ± 0.54	0.50	0.25	140
Daily runoff, APSIM-SOILWAT (mm)	0.36 ± 0.09	3.12 ± 1.50	0.22	–0.44	137
Annual runoff, APSIM-SWIM (mm)	1.20 ± 0.10	–17.2 ± 7.0	0.83	0.65	53
Annual runoff, APSIM-SOILWAT (mm)	1.22 ± 0.13	–14.8 ± 8.6	0.83	0.64	52
Soil water, 0–0.1 m, APSIM-SWIM (v/v)	0.65 ± 0.03	0.06 ± 0.04	0.75	0.52	31
Total soil water, APSIM-SWIM (mm)	0.74 ± 0.03	110 ± 15	0.85	0.71	10
Yield, APSIM-SWIM (t/ha)	0.91 ± 0.06	0.06 ± 0.13	0.88	0.87	40

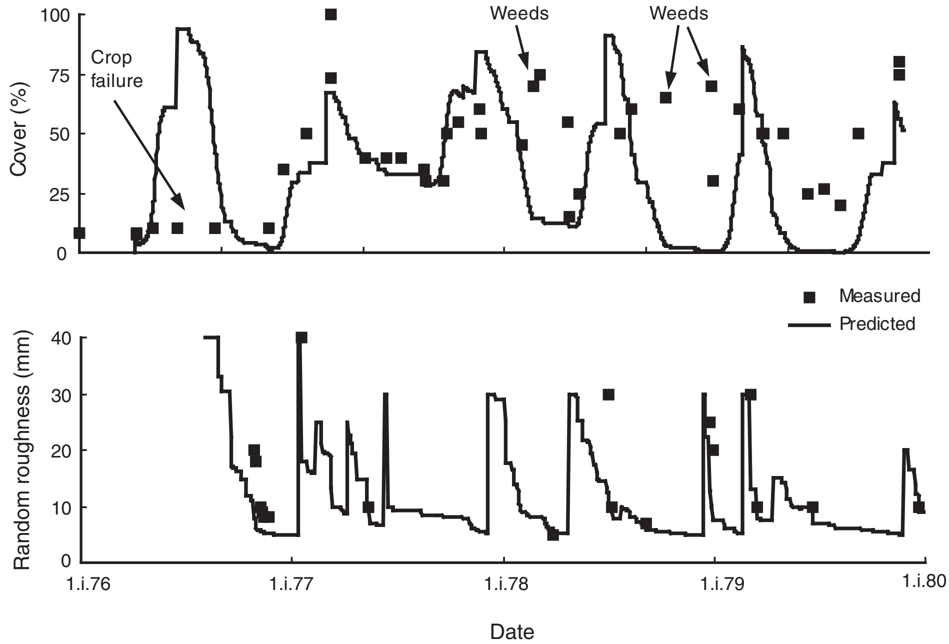

Fig. 9. Typical temporal variation in surface cover (Fairlands) and visually observed roughness (Greenmount) and APSIM-SWIM predictions.

The water balance

APSIM-SWIM generally tracked soil water with a high degree of precision (Fig. 12, Table 4), indicating partitioning between the runoff, drainage/evaporation, and transpiration components of the water balance were well represented. In the 0–0.1 m layer at Greenmount, APSIM-SWIM tended to underestimate soil water content when the soil was wet and overestimate when dry (Fig. 13). This may have been error associated with shrinking/swelling, which was not represented in the model. Deeper layers and soil water

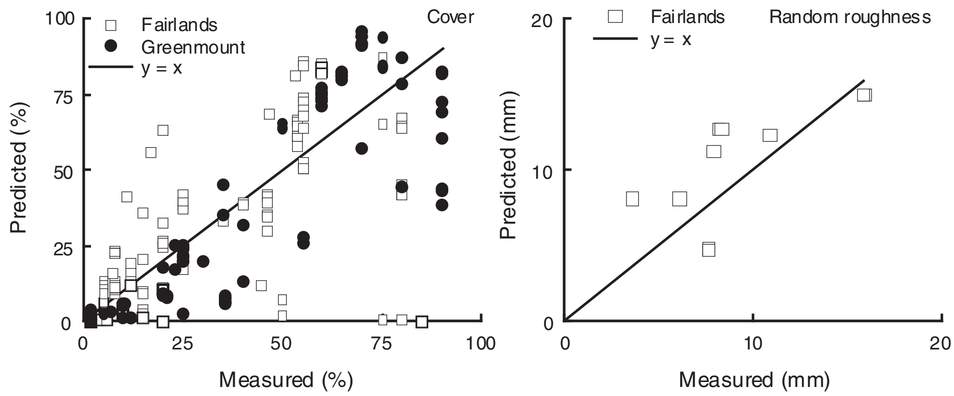

Fig. 10. Measured versus predicted surface cover and random roughness for Fairlands and Greenmount, simulated using APSIM-SWIM with predicted antecedent conditions. Goodness of fit statistics are given in Table 4.

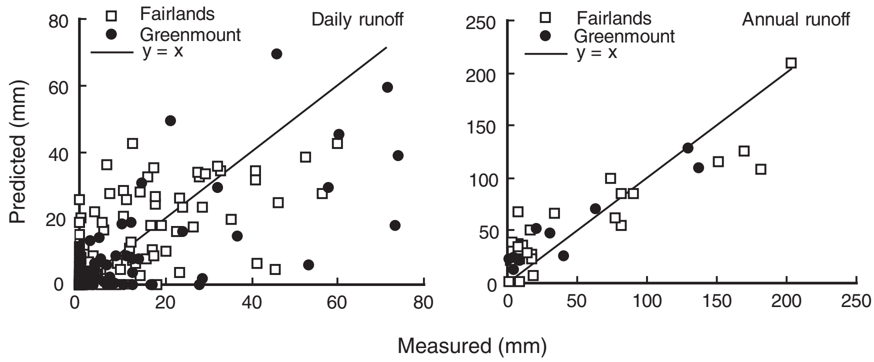

Fig. 11. Measured versus predicted daily and annual runoff, simulated using APSIM-SWIM with predicted antecedent conditions. Goodness of fit statistics are given in Table 4.

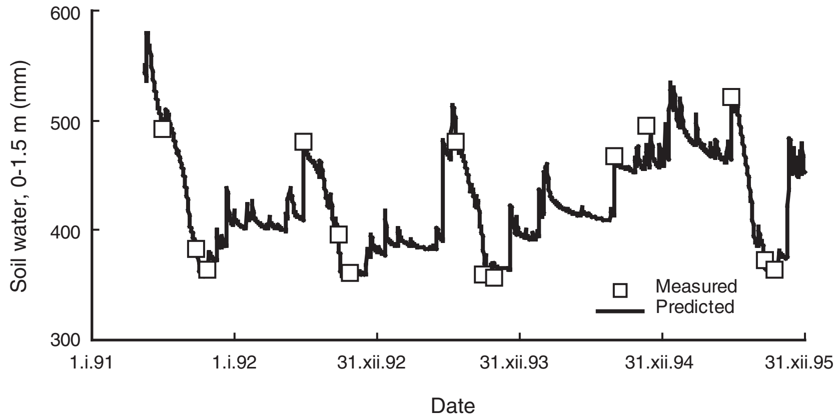

Fig. 12. Typical prediction of soil water with APSIM-SWIM (Billa Billa, summed over the soil profile, 0–1.5 m deep).

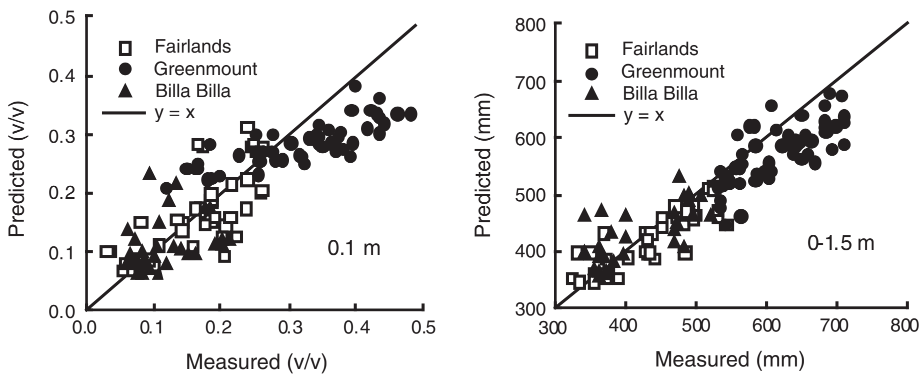

Fig. 13. Measured versus predicted soil water for the 0–0.1 m layer and summed over the soil profile (0–1.5 m), simulated using APSIM-SWIM with predicted antecedent conditions. Data were not available for the 0.1 m deep layer at Goodger. Goodness of fit statistics are given in Table 4.

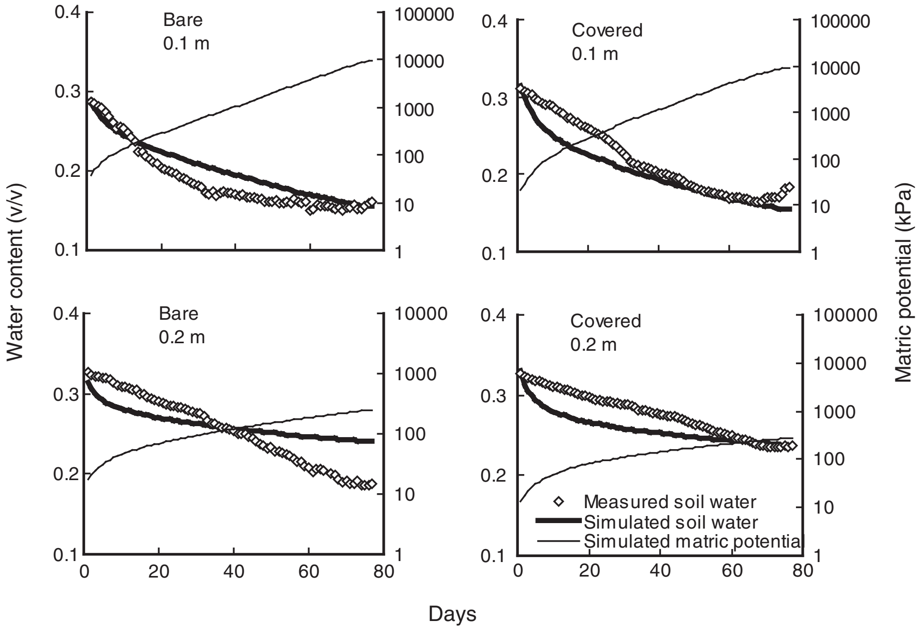

Fig. 14. Measured and predicted soil water and predicted matric potential at 0.1 and 0.2 m deep for bare and covered plots in the Goodger evaporation experiment, simulated using APSIM-SWIM.

summed over the soil profile, though, were simulated reliably. Soil water in all layers of the other soils was generally well represented.

The rate and magnitude of drying for bare and covered soil in the evaporation experiment at Goodger was reasonably well represented, especially considering soil hydraulic condition was not characterised at the time of measurement (Fig. 14). Water content after 70 days of drying was generally accurate, though the rate of drying early in the experiment tended to be a little fast. Soil water at 0.2 m was overestimated on the bare

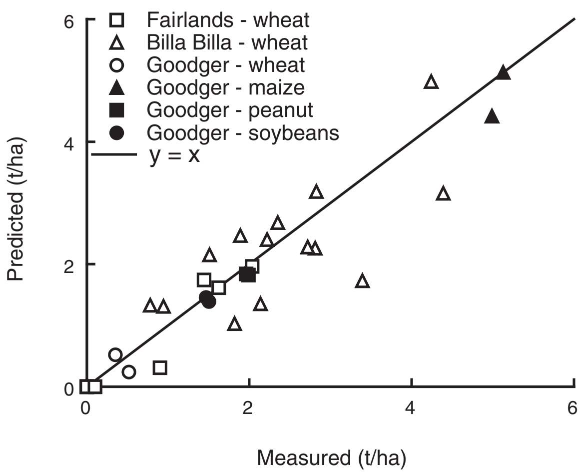

Fig. 15. Measured versus predicted crop yield, simulated using APSIM-SWIM. Goodness of fit statistics are given in Table 4.

treatment toward the end of the simulation, indicating evaporative demand at that depth was underestimated. These errors were most likely caused by inadequate parameterisation rather than any intrinsic limitation of the model.

Crop yield

Yield was well represented by the model, with predictions sensitive to water and nitrogen stresses over the range of measured data (Fig. 15). Most predictions were for wheat, but peanuts, soybeans, and maize were also reliably simulated at Goodger.

Discussion

Model accuracy and robustness

APSIM-SWIM's accuracy was broadly comparable with soil-crop models that use the USDA curve number method of simulating runoff, including APSIM-SOILWAT. Applications to the same or similar catchments simulated here typically predicted profile soil water with an R^2 about the line of best fit of 0.7–0.8, daily runoff 0.5–0.8, annual runoff 0.8–0.95, and yield 0.3–0.8 (Lawrence 1990; Littleboy *et al.* 1992; Silburn and Freebairn 1992; Probert *et al.* 1995). These applications used parameter values optimised against measured runoff and soil water. Our predictions of daily and annual runoff using the APSIM-SOILWAT configuration (which uses the USDA curve number method) with optimised parameter values, instead of APSIM-SWIM, produced poorer predictions of daily runoff and comparable annual predictions (Table 4).

That a comparable level of accuracy was achieved with APSIM-SWIM using parameter values derived from independently measured soil properties, rather than by optimisation against measured runoff or soil water, and using an increased level of detail is an indication of the robustness of the model and application methodology. Predictions were reliable even though some processes were not well represented and despite limitations in methods used to derive parameter values. This gives confidence in application of the model when parameterisation data sets are not comprehensive.

Model utility

The real benefit of APSIM-SWIM compared with other models is not necessarily improved accuracy, but improved utility, due to increased detail with which the physical system is represented and improved parameterisation methodology. Increased detail improves the ability of the model to simulate processes related to infiltration in cropping systems, reduces uncertainty in simulation outputs, and can improve the reliability and robustness of simulation outputs. Parameterisation from independent, point measurements (e.g. using rainfall simulators, pressure plate apparatus and ponded rings) can speed up parameterisation and enhance our ability to characterise processes related to infiltration and redistribution of water in the soil profile.

Increased model utility is important if issues relating to infiltration and soil condition are to be studied effectively using soil-crop models. Connolly *et al.* (2001), for example, demonstrate the benefits of enhanced model utility using APSIM-SWIM to separate effects on runoff of surface crusting from compacted sub-surface soil. This evaluation would not be possible using a USDA curve number approach because this method does not distinguish between crust or sub-surface limitations to infiltration. APSIM-SWIM effectively contains the utility of the standalone version of SWIM, including the ability to accurately simulate the runoff hydrograph, depression storage of runoff water, and macroporosity and by-pass flow.

Parameter transportability in APSIM-SWIM is improved compared with many existing models because components of the soil-crop system are represented explicitly and can be parameterised independently. Parameters describing infiltration, for example, are derived using a separate set of data to parameters describing runoff routing through the catchment. The infiltration parameters could then be used unchanged at another catchment with the same soil but different hydrologic characteristics.

Application issues

Representation of the soil is considerably more detailed in APSIM-SWIM than in models that use the USDA curve number approach and requires specification of a greater number of parameters. Unless the extra detail or flexibility that SWIM provides is specifically required, the simpler USDA curve number approach is probably more appropriate. APSIM-SWIM is an addition to the soil/crop modeller's toolkit, not a replacement.

An important data requirement of APSIM-SWIM, if crusting is to be represented, is rainfall intensity. Measured records of daily temperature, radiation, and rainfall are widely available in Australia and infilling and extrapolation models have extended the number and duration of weather records (e.g. SILO, Queensland Department of Natural Resources 2000). Rainfall intensity records, though, are short, typically <20 years, and only available at a few locations. For long simulations, rainfall intensity information needs to be generated from daily records; rainfall disaggregation models are available that can be used satisfactorily with APSIM-SWIM (e.g. Connolly *et al.* 1998, 2001).

Improved methodologies for characterising crust dynamics and soil hydraulic conductivity and macroporosity in the field are required if APSIM-SWIM, or models of this type, are to become broadly useful for evaluating effects of soil hydraulic condition on the water balance and crop growth. The parameterisation and application methodology tested in this paper only allowed application of APSIM-SWIM to a limited range of scenarios. Crust conductivity was measured in the laboratory using disturbed soil for a restricted range of rainfall and cover conditions. A capability to measure crust interactions *in situ* and for a greater range of rainfall, cover, crop growth, and management conditions is needed. The disc permeameter method used over-predicted K on certain soils. A method is needed which combines the ease of application and functionality of disc permeameters with the absolute accuracy of ponded rings and addresses the apparent error in K derived using disc permeameters. Rapid, *in situ* assessment of soil condition is important where a number of soil/treatment/depth combinations need to be characterised. The ability to characterise macroporosity, consolidation, and shrinking/swelling is also important in situations where bypass flow or temporal change in soil hydraulic condition is important.

Conclusions

APSIM-SWIM, parameterised using independently measured soil properties, was capable of simulating infiltration, runoff, the water balance and crop yield for grain cropping systems in southern Queensland with a similar degree of accuracy to established soil-crop models. The main benefits of APSIM-SWIM, compared with existing soil-crop models, are increased detail with which infiltration and soil processes can be simulated, improved parameterisation from independent point measurements, and improved parameter transferability. Accuracy and utility of the model could be improved if more attention is given to simulating dynamic soil surface conditions, particularly cover and possibly cracking and disturbance and consolidation of the tilled layer, and temporal change in soil hydraulic condition. Developing methods that allow characterisation of crust dynamics under field conditions and improving *in situ* measurement of soil hydraulic conductivity and macroporosity would improve our ability to parameterise and apply the model.

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