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# Cover-runoff equations to improve simulation of runoff in pasture growth models

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*Abstract*

An Australian native pasture growth–water balance model (GRASP) was modified to include the USDA curve number runoff method from PERFECT, with the aim of providing a more general model than the regionally derived Scanlan runoff approach used previously and to improve runoff and water balance prediction. The modified model was calibrated against measured runoff and soil water data for a range of pasture treatments in Central Queensland. Optimised curve numbers were related to cover; curve number reduced from 97 for bare conditions to a minimum of 57 for 53% cover, with no difference between soils (mudstone or sandstone derived, or eroded phases) or types of cover (grass biomass and litter, or tree litter). In the modified model this equation provides feedback of effects of grazing management and tree density on cover to the water balance.

Runoff prediction using the Scanlan runoff sub-model (derived for soils in the Burdekin catchment) was satisfactory ($r^2_{1:1} = 0.70$), indicating that soils at the Central Queensland site had similar runoff responses to those in the Burdekin. Addition of the curve number sub-model improved runoff prediction ($r^2_{1:1} = 0.87$). Adjusting curve number each day according to cover improved runoff predictions for low cover situations where cover varied through time, which is important in degraded pastures. Total soil water prediction was very good using the Scanlan runoff sub-model ($r^2_{1:1} = 0.88$) and slightly improved using the modified model ($r^2_{1:1} = 0.91$). Soil water in the surface layer was predicted well, giving confidence in prediction of soil evaporation.

This study provides important new runoff parameter values for modelling water balance and degradation of hard setting soils under pasture. The parameters derived from this study can be used with historical climate data to provide a long-term assessment of effects of grazing management on runoff on such soils.

*Additional keywords:* water balance, hard setting soils, parameter derivation, curve number.

## Introduction

Sustainability of production from grazing lands of northern Australia is a major concern for graziers and resource managers (Tothill and Gillies 1992). Increased runoff and soil loss resulting from low surface cover has been identified as one of the major processes leading to land degradation in the semi-arid tropics (Williams and Chartres 1991; McIvor *et al.* 1995; Scanlan *et al.* 1996). Simulation of the interaction of grazing management and degradation processes is one approach used to assess more sustainable management practices (McKeon *et al.* 1990; Scanlan and McIvor 1993; Johnston *et al.* 1996). To this end, a pasture simulation model, GRASP, was developed to simulate pasture growth and animal production for native pastures in Queensland (McKeon *et al.* 1982; Rickert and

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McKeon 1982; McKeon and Rickert 1984; McKeon *et al*. 1990; Day *et al*. 1993; Day *et al*. 1997; Littleboy and McKeon 1997).

The empirical run-off model used in GRASP was derived from runoff studies in the Burdekin catchment (Scanlan *et al*. 1996) and provides reasonable predictions of soil water and plant growth across a wide range of locations, pasture communities, and management practices in northern Australia (Day *et al*. 1997). Where runoff is a relatively small component of the water balance, for example with well-managed pastures on well-structured soils in the semi-arid tropics (Lawrence and Cowie 1992), accurate simulation of soil water is possible without correct simulation of runoff (Rose *et al*. 1972; Rickert and McKeon 1982).

In degraded central Queensland pastures, however, Silburn *et al*. (1992) found that runoff is a large component of the water balance, with up to 50% of rainfall lost as runoff. Similarly, Miles (1993) found runoff losses exceeded 40% of annual average rainfall in semi-arid woodlands when cover is maintained at or below 20%. Runoff losses can also be a large proportion of rainfall in monsoon tallgrass (Ive *et al*. 1976), tussock grasslands (Clewett 1985), and tropical tallgrass and acacia shrublands (Pressland and Lehane 1982). More accurate runoff models are required in these situations with markedly increased runoff at low surface cover (e.g. after heavy grazing and drought) and to model runoff-driven processes such as soil loss. Such a model needs to predict the changes in runoff response that occur as cover changes. Runoff typically decreases with greater cover (Silburn *et al*. 1992; Miles 1993; McIvor *et al*. 1995; Scanlan *et al*. 1996). The Scanlan runoff sub-model in GRASP adequately predicts runoff from Burdekin soils (red and yellow texture contrast soils) on which it was developed, and predicts effects of cover on runoff, but does not have an input parameter which can be adjusted to represent other soils. It also contains a rainfall intensity function that would need to be derived for other regions. As GRASP is being applied systematically throughout Australia (Timmers *et al*. 1999; Ash *et al*. 2000; Carter *et al*. 2000; McKeon *et al*. 2000; Hall *et al*. 2001), a reasonably general runoff model, and parameter values for a wide range of soil types, are needed.

This paper describes further development of runoff sub-models for use in native pasture simulation models, in this case using GRASP. To improve runoff prediction and provide a more general model, the USDA curve number runoff model from PERFECT (Littleboy *et al*. 1989) was incorporated into GRASP. The modified model was calibrated against measured runoff and soil water data from pasture woodland on hardsetting soils in Central Queensland. Runoff parameters derived from calibration were related to cover. The derived cover-runoff equation was used to build a dynamic sub-model within GRASP, providing a feedback between cover and the water balance.

Three scenarios from modelling against the measured data are presented, namely:

1. Scanlan runoff sub-model with no parameter calibration (Scanlan);
2. Curve number model calibrated to runoff and soil water (referred to as CN-calibration);
3. Curve number model (with parameters for 2 above) with a dynamic effect of cover on runoff (CN-dynamic).

Model predictions from these 3 scenarios were compared with measured runoff and soil water data. Sensitivity analysis of model parameters was also carried out. The modified version of GRASP, and parameters from this study, are used to explore runoff and other water balance components of various pasture treatments over longer timescales elsewhere (see, for example, Yee Yet and Silburn 2003).

## Materials and methods

### *Description of the experimental site*

Data were collected from runoff plots located on a cattle grazing property, ‘Springvale’ (24°41′S, 147°18′E), 75 km west of Emerald, Queensland, in the Nogoa River catchment. The site is described in detail in Ciesiolka (1987), Yee Yet (1994), and Connolly *et al*. (1997*a*).

#### *General description*

Climate is subtropical to tropical, subhumid to semiarid. Mean annual rainfall over the 7-year study period (October 1987 to March 1994) was 607 mm, compared with 648 mm for a 100-year period at Emerald. Rainfall is highly variable with a coefficient of variation of annual rainfall of 35%. About three-quarters of rain falls in the 6 warmer months. Main grasses are *Bothriochloa ewartiana* (desert blue grass), *Heteropogon contortus* (black spear grass), and *Themeda triandra* Forssk (kangaroo grass). Silver-leaf ironbark trees *(Eucalyptus melanophloia)* are scattered throughout the area with tree populations of up to 400 trees/ha (Ciesiolka 1987). Land slope varies from 1% in the lower slope areas to 20% on the hills and ridges (Connolly *et al.* 1997*a*).

The soils are derived from either mudstone or sandstone (Ciesiolka 1987). Main soil types on mudstone are moderately deep, texture contrast soils (Sodosols), or very shallow to shallow, poorly formed or eroded soils (Leptic Rudosols). Main soils on sandstone are shallow to moderately deep, texture contrast (Chromosols) or gradational soils (Kandosols), some elements of moderately deep sands (Orthic Tenosols), and very shallow to shallow, often stony soils (Rudosols) on steeper slopes. Surface texture is generally sandy clay loam on mudstone-derived soils and sandy loam on sandstone-derived soils, overlying clay subsoils except on Rudosols. All surface soils are hard setting.

Hydrologic experiments commenced in 1979 with monitoring of a 9.6-ha catchment (Ciesiolka 1987). The catchment was fenced and de-stocked in 1981. In 1986, 16 runoff plots were installed within the catchment (ungrazed) and 4 plots outside (grazed by cattle), incorporating a range of pasture cover (from bare to 70%) and tree basal area (from 1 to 11 $m^2$/ha) on the two main soils, and on severely eroded mudstone areas (Silburn *et al*. 1992). Data from 10 of these runoff plots were used, as described below.

#### *Specific site descriptions and measurements*

Ten pasture conditions were investigated, including high cover ungrazed, under trees, medium cover, grazed, eroded and bare scalded treatments, with a range of cover conditions on the mudstone and sandstone derived soils (Table 1). All plots have some influence of trees, although only the 3 plots with higher tree basal areas had significant numbers of trees growing, and contributing litter, on the plots. Each site involved a runoff plot and adjacent areas where soil water and pasture biomass were measured. Runoff was measured from October 1988 to March 1994 using runoff tipping buckets connected to counters, and in some cases, data-loggers. Since counter readings were available for all plots and were recorded about 6 times each year, the runoff data used are accumulated values for each service period. Daily rainfall was measured using 3 pluviometers located in the catchment. *In-situ* soil water was measured by gravimetric sampling in 10-cm increments adjacent to the plots about twice each year. Percent cover provided by standing dry matter, litter, and total cover were measured on each plot periodically. Dry weights and cover of standing biomass and litter were measured in quadrats, adjacent to all plots early in the study, and periodically at the high cover plot (Tr 8) and plots under trees. Model predictions were compared with these measured runoff (accumulated for each service period), soil moisture, biomass, and cover (on-plot) data. The quadrat cover and biomass data, and other measurements specifically designed for the purpose, were used to determine model parameters, as described in the next section.

### *Description of the GRASP model*

GRASP is a deterministic, point-based, native pasture model developed by scientists working in semi-arid and tropical grasslands to simulate ecological and management aspects of grass production and to predict soil water, pasture growth, and animal intake. The two main components of GRASP are the water balance and pasture growth sub-models. A comprehensive description of GRASP is provided in Littleboy and McKeon (1997). A brief description of the water balance and pasture growth processes follows.

**Table 1. Description of experimental plots**

| Plot | Cover[A] (%) | Basal area Tree (m²/ha) | Basal area Grass (m²/ha) | Plot area (m²) | Slope (%) | Soil depth (mm) | PAWC[B] (mm) | Geology | Australian Soil Classification[C] | Pasture and soil surface conditions |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | *Ungrazed* | | | |
| 8 | 71 | 3.3 | 4.0 | 43.4 | 4.0 | 500 | 116.5 | Mudstone | Sodosol | High grass cover, near exclosure |
| C | 16 | 5.0 | 0.1 | 73.9 | 5.2 | 400 | 74.4 | Mudstone/sandstone | Sodosol | Mostly bare, scalded, and hard-set |
| 2 | 9 | 5.0 | 0.1 | 14.2 | 4.0 | 500 | 101.1 | Mudstone | Leptic Rudosol | Mostly bare, scalded, and hard-set |
| D | 46 | 5.3 | 2.0 | 340.0 | 3.7 | 500 | 64.7 | Eroded mudstone | Leptic Rudosol | Medium cover, eroded, hard surfaced |
| B | 20 | 5.0 | 1.0 | 640.4 | 6.7 | 400 | 37.5 | Eroded mudstone | Leptic Rudosol | Bare areas, severely eroded, hard surfaced |
| | | | | | | | *Tree plots* | | | |
| 6 | 72 | 9.9 | 1.0 | 37.8 | 6.2 | 400 | 82.5 | Sandstone | Kandosol | High tree litter cover |
| 5 | 54 | 10.8 | 1.5 | 50.2 | 8.2 | 600 | 122.6 | Sandstone | Chromosol | Medium cover |
| 12 | 52 | 7.4 | 2.0 | 62.1 | 5.5 | 400 | 50.7 | Sandstone | Chromosol | Medium cover |
| | | | | | | | *Grazed* | | | |
| G1 | 18 | 3.3 | 0.3 | 27.5 | 7.2 | 600 | 108.4 | Mudstone/sandstone | Kandosol | Grazed heavily, hard-set |
| G2 | 11 | 1.3 | 0.5 | 61.0 | 8.0 | 600 | 119.9 | Sandstone | Orthic Tenosol | Grazed heavily, bare areas, hard-set |

[A] Average total cover (standing dry matter + litter) from 1987 to 1994.

[B] Plant available water capacity (mm).

[C] Isbell (1996), classified by Andrew Biggs, NR&M, Toowoomba (pers. comm.)

### *Soil water balance*

Soil water balance is calculated on a daily basis as the difference of inputs (rainfall) and outputs (runoff, drainage, soil evaporation, and transpiration by grass and trees). Soil is represented as 4 layers of variable thickness and water-holding characteristics. Soil water is updated on a daily basis by any rainfall exceeding predicted runoff. Loss of water from soil also occurs through deep drainage and evapotranspiration. Pasture and tree transpiration and soil evaporation are calculated separately using the concept of a potential rate adjusted for a soil water supply index (Rickert and McKeon 1982; Scanlan and McKeon 1993; Littleboy and McKeon 1997). Tree transpiration is based on a constant user-defined tree basal area, i.e. a tree water-use model not a tree growth model. Infiltrated water in excess of soil profile water-holding capacity is assumed to become deep drainage. That is, there is no limit to drainage due to soil hydraulic conductivity.

### *Runoff models*

There are 2 options for modelling runoff in GRASP: the Scanlan model and the Curve number model. The Scanlan model is an empirical model derived from runoff data from the Burdekin (Scanlan *et al.* 1991). The modified USDA curve number runoff model is a more general model that can be calibrated for all soils. The Curve number model was incorporated into GRASP to improve runoff prediction, to provide a more general model, and to be consistent with other agricultural water balance models in use such as PERFECT and APSIM (Keating *et al.* 2003).

*The Scanlan runoff model.* In the Scanlan model, rainfall is partitioned into runoff and infiltration using an empirical function derived from ground cover, daily rainfall, rainfall intensity, and soil water deficit:

$$\text{runoff} = \text{cover\_term} \times (\text{rain} - (1 - \text{rain\_intens}/110) \times \text{sw\_deficit}) \qquad (1)$$

where runoff is daily runoff (mm), cover_term is the cover calculated from standing biomass and litter, rain is daily rainfall (mm), rain_intens is maximum rainfall intensity in a 15-min period for the day (mm/h) (calculated within GRASP based on season and location), and sw_deficit is soil water deficit of the top 2 profile layers (mm). A detailed description of this model is given in the GRASP manual (Littleboy and McKeon 1997).

*The modified USDA Curve number runoff model.* The modified USDA Curve Number runoff method is taken from the PERFECT model (Littleboy *et al.* 1989), which was adapted from Williams and LaSeur (1976) and Knisel (1980). A detailed description of this runoff model is provided in the PERFECT manual (Littleboy *et al.* 1989). Runoff is calculated as a function of daily rainfall and soil water contents weighted by soil depth. The main input parameter is the curve number for average antecedent soil water ($CN_2$), a dimensionless parameter generally in the range 50 (little runoff) to 100 (all rain runs-off). Littleboy *et al.* (1989) added a user-defined limit to the soil depth used in the runoff–soil moisture calculation (hydrologic effective depth) and an equation to adjust $CN_2$ for cover, to account for changes in runoff potential with cover observed in studies of stubble management as described in Silburn and Freebairn (1992). The cover adjusted $CN_2$ is calculated for each day as:

$$CN_2 = CN_{2(\text{bare})} - [\ (\text{CN\_red}/\text{cov2}) * \text{MIN}(\text{cov2}, \text{tcov})\ ] \qquad (2)$$

where CN_red is the maximum reduction in curve number, cov2 is the cover above which cover no longer affects runoff [fraction 0–1], and tcov is total projected cover (standing plus visible litter) [fraction 0–1]. The user input parameters are $CN_{2(\text{bare})}$ describing runoff potential for bare soil, and CN_red and cov2 describing the runoff response to cover for the particular soil, vegetation, and management.

### *Pasture growth*

Daily pasture growth is calculated for both water-limited and radiation-limited conditions, with the most limiting factor determining pasture growth. Pasture growth under water-limiting conditions is determined from the product of transpiration and transpiration efficiency. Under radiation-limiting conditions, pasture growth is determined from intercepted solar radiation and radiation use efficiency. At low green cover, pasture growth is calculated as a function of potential regrowth, grass basal cover, and a growth index (after Fitzpatrick and Nix 1970). Three herbage pools are modelled: green, standing dead, and litter. Green biomass is capable of growing and transpiring and is used in the water balance for calculation of transpiration. Green biomass includes both green leaf and green stem and is reduced by animal intake, trampling, or plant death. Dead biomass is reduced by animal intake, trampling, or detachment from the plant to be added to the litter pool, which is then reduced by decay. Cover provided by total standing biomass and by litter is calculated using functions described in a later section.

### *Parameter measurement and estimation*

#### *Climate data*

The model was run from 1988 to 1994 using daily rainfall measured at Springvale and daily synthetic climate data from the SILO national interpolated climate surfaces (Jeffrey *et al*. 2001) for maximum and minimum temperature, pan evapouration, solar radiation, and vapour pressure deficit (VPD).

#### *Soil parameters*

Soil profile parameters required to run GRASP are soil layer thickness, air-dry moisture content, wilting point, and field capacity for the 4 soil layers. Air-dry moisture content values were obtained from soil dried at 40°C. Wilting point for each layer was taken as the minimum *in-situ* soil water content recorded from 1988 to 1994. To obtain field capacity (drained upper limit) and bulk density (used to calculate volumetric soil water), soil profiles near each plot were artificially wet, allowed to drain for 2 days, and sampled gravimetrically. Field capacity for each layer was taken as the maximum of *in-situ* soil moisture content recorded from 1988 to 1994 and the artificially wet profile moisture content. An upper limit to daily soil evapouration (EPLIM) of 4 mm/day was used, except for bare scalded plots, where 1 mm/day was used because of surface sealing and compaction. These EPLIM values were estimated from other studies (McKeon *et al*. 1982).

#### *Pasture growth parameters*

Initially all growth parameters were set to default values provided with GRASP. These are averages for pasture communities obtained from datasets collected at 74 sites throughout Queensland (Day *et al*. 1997), using a methodology specifically designed to obtain a minimum dataset for model parameterisation (McKeon *et al*. 1990; Philp and Day 1997) (source A, Table 2). Site-specific parameters were then derived by calibration against data from 2 studies at Springvale (sources B and C, Table 2). Source B parameters were derived using the standard methodology referred to above, using a mown exclosure near plot 8 (Table 1). Source C parameters were calibrated using a sequence of biomass and soil moisture data from an ungrazed, unmown area near the exclosure (beside plot 8). These parameters were used in simulations of each runoff plot, with measured site specific values of grass basal area and tree basal area (Table 1), pasture utilisation by grazing and soil parameters.

**Table 2. Parameter values used in GRASP for Springvale and values averaged for 5 pasture communities in Queensland (Day *et al.* 1997)**

Parameters were derived from several sources: A, from averages of 5 Queensland native pasture communities (Day *et al*. 1997); B, data from mown exclosure near plot Tr 8; C, model calibration to ungrazed and unmown pasture near plot Tr 8

| GRASP parameters (parameter number) | Source | Springvale | Average | Range |
|---|---|---|---|---|
| Potential regrowth per unit of grass basal cover (kg/(ha.day)) (p006) | A | 3.5 | 3.5 | 2–5 |
| Soil water index at which above-ground growth stops (p149) | A | 0.30 | 0.30 | 0.13–0.40 |
| % N at which growth stops (%) (p101) | B | 0.45 | 0.68 | 0.40–1.20 |
| Maximum annual N uptake (kg N/ha) (p099) | B | 20 | 20 | 16–24 |
| Green yield at which potential transpiration is 50% of potential ET (kg/ha) (p045) | B | 1600 | 1000 | 500–2000 |
| Transpiration efficiency kg/(ha.mm) @ 20 hPa (p007) | C | 15 | 13.5 | 7–20 |
| Detachment rate kg/(kg.day) warm season (p128) | C | 0.0017 | 0.0033 | 0.0017–0.005 |
| Detachment rate kg/(kg.day) cool season (p130) | C | 0.0015 | 0.0027 | 0.0017–0.004 |

Transpiration use efficiency (TUE) is a function of species, soil fertility, and diurnal distribution of vapour pressure deficit (McKeon *et al.* 1990; Day *et al.* 1997). The calibrated TUE value for Springvale (15 kg/(ha.mm) at 20 hPa VPD) was similar to the average of other native pasture sites in Queensland (13.5 kg/(ha.mm) at 20 hPa VPD). The calibrated pasture detachment rates (0.0017 kg/(kg.day) for warm season and 0.0015 kg/(kg.day) for cool season) were lower than the rates (0.003) found in other grazing trials across Queensland (Day *et al.* 1997), reflecting the high stem content of the dominant grass species *Bothriochloa ewartiana* and *Themeda triandra*. These rates are comparable to those found for buffel grass (0.0017) (Day *et al.* 1997). Similarly, the parameters 'green yield at which potential transpiration is 50% of potential ET' and '% N at which growth stops' reflect the high stem content of these pastures. These pasture growth parameters were used for all plots without further calibration.

### *Cover–biomass relationships for standing dry matter and litter*

Cover used in the curve number runoff sub-model (tcov) is calculated from biomass, with separate calculations for standing dry matter and litter, which are then combined to give total cover using an equation to account for standing cover overlaying litter cover (Yee Yet 1994). Prediction of cover from standing dry matter in GRASP uses the equation:

$$\text{can\_cov} = (\text{tsdm}^{\text{runoff\_power}}) / (\text{tsdm}^{\text{runoff\_power}} + \text{yld\_tcov50}^{\text{runoff\_power}}) \qquad (3)$$

where can_cov is proportion of cover provided by standing dry matter (tsdm kg/ha), runoff_power is a shape factor, and yld_tcov50 is standing dry matter at 50% cover (kg/ha). Parameters used in this equation were derived from quadrat cover and biomass data collected at Springvale (Fig. 1). Separate parameters were derived for grazed and ungrazed pastures with low tree density, and plots with high tree density (tree basal area—tba >6 $m^2$/ha), giving: yld_tcov50 of 1150, 3100, and 5000 kg/ha, respectively; and runoff_power of 0.95, 0.98, and 0.98, respectively. Cover standing dry matter data for grazed plots agreed with the equation derived by Scanlan and McIvor (1993). The lower dry matter required to give 50% cover under grazing than without grazing reflects biomass consumption and differences in growth habit and/or species under grazing (Ciesiolka 1987). The higher dry matter required to give 50% cover under trees reflects different grass species found under trees.

Litter was a high proportion of cover on some plots at Springvale, with sites under trees having up to 70% of litter cover and ungrazed open areas having up to 33% of litter cover. This large amount of litter had a considerable effect on runoff. To derive parameters for Eqn 3 from quadrat litter cover and biomass data, measured litter cover (i.e. litter visible through standing cover) was first converted to total litter cover using the equation:

$$\text{litter cover} = (\text{visible litter cover}) / (1 - \text{standing cover}) \qquad (4)$$

where all covers are fractions (0–1). These data for litter cover (from Eqn 4) and yield were used to derive a relationship of the form of Eqn 3. Resulting litter yield at 50% cover was 1800 kg/ha and runoff_power was 0.95 (Fig. 2).

GRASP predicts litter detached from grass but not from trees. For the purpose of modelling the runoff plots with significant tree density (tba >6 $m^2$/ha), where litter cover from trees was reasonably constant, a constant value of tree litter was added to total cover. This value of visible tree litter was obtained by subtracting mean predicted total cover (without tree litter) from mean measured total cover (standing grass + visible grass and tree litter). This approach will be used until the dynamic tree model (under development) is implemented in GRASP.

### *Runoff parameters*

Effective hydrological depth (soil depth considered in the runoff-soil moisture relationship) was fixed as the 2 upper layers as is used in PERFECT. The cover-curve number relationship (Eqn 2) was derived by model calibration as described below and is presented with the results. All parameters other than curve number were determined as described above and were not adjusted during calibration of the runoff parameters.

### *Sensitivity analysis*

Selection of model parameter values is more critical when a change in the parameter value causes large changes in predicted outputs. Conversely, some parameters have little effect on predicted outputs and a

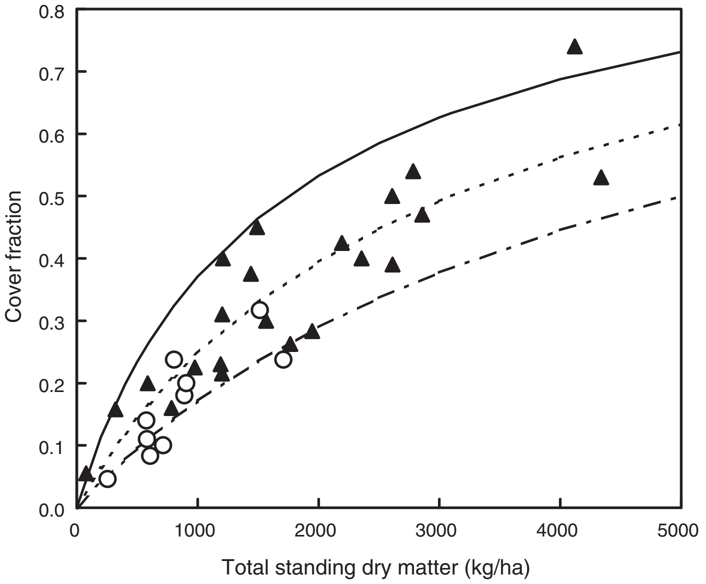

**Fig. 1.** Relationship between weight of standing dry matter and proportion of cover as used in GRASP and derived from Springvale data for ungrazed plots (- - -, ▲) and plots with higher tree density (tba >6 $m^2$/ ha) (_ . _ . _, ○). Points are means of 2–6 1-$m^2$ quadrats. The solid line (—) is the relationship for two grazed plots (data not shown), which agreed with the equation derived by Scanlan and McIvor (1993).

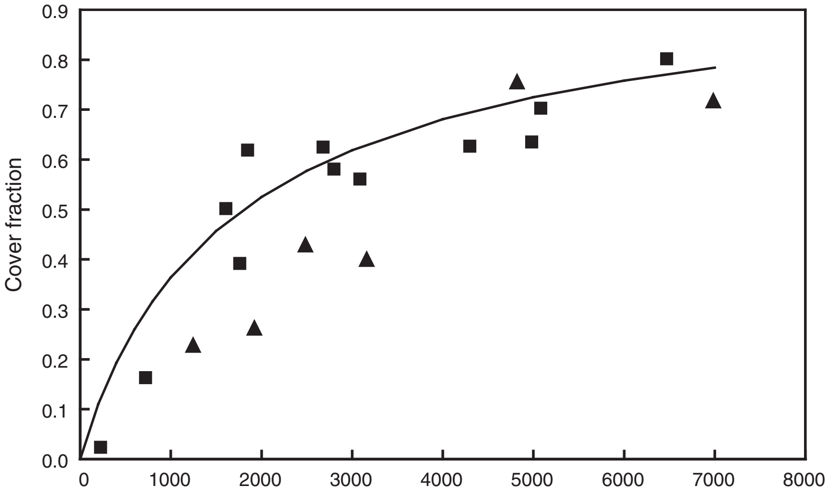

**Fig. 2.** Relationship between weight of litter and proportion of litter cover for grass plots (open) (■) and tree plots (tba >6 $m^2$/ha) (▲) derived from quadrat data at Springvale. Litter includes grass and tree litter. The line is Eqn 3 with yield at 50% cover = 1800 kg/ha and runoff_power = 0.95. Points are individual 1-$m^2$ quadrats.

**Table 3. Sensitivity of GRASP-Curve Number model mean annual outputs for water balance, pasture yield and cover to changes in parameter values for simulations of Springvale 1988–1994, for pastures with average cover of 50% or 2%**

Values indicate response classes for changes (up and down) in parameter value around the base value: 5, significant (output change ≥ parameter change); 1, slight (output change <10%) for a 50% change in parameter value. Pasture detachment rate parameters (data not shown) only slightly affected outputs, except for pasture yield (class 3), and cover (class 3) for low cover. Available water capacity of soil layer 3 (data not shown) only slightly affects outputs

| Parameter | $CN_{2bare}$[A] | CN_red[B] | Available soil moisture | | EPLIM [C] | GBA or potential regrowth rate [D] | Transpiration efficiency | Tree basal area |
|---|---|---|---|---|---|---|---|---|
| | | | Layer 1 | Layer 2 | | | | |
| Max. change about base: | –10%–+3% | +/–50% | +/–50% | +/–50% | +/–50% | +/–50% | +/–50% | +/–50% |
| *Pasture—50% cover* | | | | | | | | |
| Runoff | 4 | 4 | 1 | 4 | 1 | 4 | 1 | 1 |
| Deep drainage | 5 | 5 | 5 | 5 | 2 | 3 | 2 | 4 |
| Transpiration | 3 | 3 | 1 | 3 | 2 | 4 | 3 | 4 |
| Soil evaporation | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 |
| Tree transpiration | 2 | 2 | 3 | 2 | 1 | 1 | 1 | 3 |
| Pasture yield | 3 | 2 | 1 | 2 | 2 | 4 | 3 | 4 |
| Cover | 2 | 2 | 1 | 2 | 1 | 3 | 2 | 3 |
| *Pasture—2% cover* | | | | | | | | |
| Runoff | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Deep drainage | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Transpiration | 5 | 2 | 3 | 2 | 5 | 5 | 2 | 5 |
| Soil evaporation | 2 | 1 | 3 | 1 | 3 | 1 | 1 | 2 |
| Tree transpiration | 5 | 3 | 3 | 2 | 3 | 2 | 1 | 1 |
| Pasture yield | 5 | 1 | 3 | 2 | 4 | 5 | 3 | 4 |
| Cover | 5 | 1 | 3 | 2 | 4 | 5 | 3 | 4 |

[A] $CN_{2bare}$ in Eqn 2, is the runoff curve number for average antecedent soil moisture, for bare soil.

[B] CN_red in Eqn 2, is the reduction in CN2 (runoff potential) due to cover equal to cov2 (held constant).

[C] EPLIM is upper limit to daily bare soil evaporation.

[D] GBA (grass basal area) and potential daily regrowth rate had identical response classes.

reasonable estimate, or a default value which are provided for Queensland pastures in the case of GRASP (Littleboy and McKeon 1997), will suffice. Sensitivity to parameters can vary depending on the value of other parameters and inputs (e.g. climate, soil water-holding capacity) and on the predicted outputs of interest. Thus, a sensitivity analysis of the GRASP-Curve number model was used to determine effects of variation in parameters on predicted water balance, pasture yield and cover, for medium and low cover conditions at Springvale. The medium cover (average 50%) case had lower runoff potential and the low cover (average 2%) case had high runoff potential. A set of base parameters was selected for each condition, as described in the parameter derivation section, and the model was run for Springvale 1988–1994, with parameters varied individually around the base values. The sensitivity of model outputs, in terms of response classes, and class criteria used are given in Table 3.

The water balance in general was dominated by runoff curve number at low cover, but was sensitive to most parameters for the medium cover case (Table 3). Runoff and drainage were sensitive to changes in most parameters for the medium cover case, but insensitive to changes in all parameters except curve number for the low cover case. Pasture outputs and transpiration were less sensitive to model parameters for medium cover than for low cover, but were sensitive to potential regrowth rate and grass and tree basal areas in both cases. Transpiration by grass and trees was sensitive to runoff and soil evaporation parameters for the low cover case, but not *vice versa*, as runoff was controlling water supply. Soil evaporation was generally less sensitive to model parameters, especially under medium cover.

Predicted outputs were sensitive to relatively small changes in runoff parameter $CN_{2bare}$. CN_red represents the effect of cover on runoff and had little effect when cover was low, but was significant in determining runoff and system behaviour at higher cover. Soil water capacities had a significant effect on runoff and drainage when cover was present, presumably providing a ‘buffering capacity’, but these effects were moderated with low cover, as runoff limits water supply, and for deeper layers. Predicted outputs were also insensitive to the evaporation parameter (EPLIM) at medium cover. For the low cover case, a low value of EPLIM was used. As this parameter is an upper limit to evaporation, the model is more sensitive to changes around low values and insensitive to changes around high values. EPLIM for low cover affected outputs related to soil water use but not runoff and drainage. Grass basal area and potential regrowth rate had similar effects, impacting on most outputs at medium cover but only on transpiration and pasture yield and cover at low cover. Predicted outputs were insensitive to pasture detachment rates and capacity of soil layer 3 (data not shown), and to a lesser extent transpiration efficiency. Selection of these parameters is therefore not critical for predicting the outputs considered. The most critical parameters were runoff curve number, grass basal area, tree basal area, and potential regrowth rate, with CN_red and soil water capacities increasing in importance with higher cover.

### Model runs

The GRASP model with the Scanlan runoff sub-model was run for the 10 runoff plots for 7 years without any calibration of model parameters. For the same site and treatments, the GRASP model with the curve number runoff sub-model was run in 2 steps:

1. A value of runoff curve number ($CN_2$) was derived for each plot by calibration of the modified model to measured runoff and soil water, with no effect of cover on runoff. The model was run with $CN_2$ values in the range 0–100. The curve number that provided the best balance between runoff and soil water predictions, according to the criteria given below, was adopted. The 95% confidence limits on optimised curve numbers were computed using a procedure developed by P. Jones and G. Hammer (pers. comm.). The optimised curve numbers are an average for the cover present during the period. These optimised curve numbers were plotted against their mean cover to derive $CN_{2(bare)}$, CN_red and cov2 in Eqn 2. These final optimised runs are referred to as the CN-calibration runs.
2. The second set of runs was done with the curve number–cover equation derived in step 1, with GRASP predicting cover daily, providing a dynamic effect of cover on runoff. That is, a single set of runoff parameters was used for all plots, with differences in runoff behaviour driven by GRASP's predictions of cover. These runs are referred to as CN-dynamic cover-runoff runs.

The quality of predictions using GRASP with the 3 runoff sub-models (Scanlan, CN-calibration and CN-dynamic) was assessed by comparing predicted runoff, total soil water, cover, and pasture yield with measured values graphically and statistically (Mayer and Butler 1993). Root mean square error (RMSE) less than the measured mean was considered a good fit (Hedden 1986). Criteria for optimising prediction of runoff and soil water in step 1 were to minimise RMSE and average error and to balance predicted total to measured total. Graphs of measured against predicted runoff and soil water were also examined to see if the data had a good fit around the 1:1 line before deciding on the best curve number. The statistic $R^2$ about the 1:1 line (Mayer and Butler 1993) was preferred because the 'perfect fit' of the model lies on this line.

## Results and discussion

### Optimised runoff curve numbers

Optimised curve number ($CN_2$) values (and their 95% confidence limits) were considerably lower for plots with lower mean cover (Fig. 3), with a strong trend irrespective of soil types and treatments (grazing, tree density, etc.). Differences in curve number and thus runoff response appears to be related to total cover, rather than cover type (e.g. dominantly grass cover or tree litter) or the management that led to that cover. No differences are apparent between plots on mudstone- or sandstone-derived soils (Fig. 3), which is reasonable as they have similar A-horizon texture and structure and the model is already accounting for differences in PAWC (Table 1). The response of the eroded (plot B) and partly eroded (plot D) plots was also similar to the other soils. This is useful, as it means that, in simulations of effects of erosion on production for Springvale, it is reasonable to use the same runoff parameters while (simulated) erosion progressively reduces the (simulated) soil depth.

The confidence limits illustrate that there is no single 'optimal' curve number, rather, a range of curve numbers that give similarly acceptable predictions of the sum of squares of errors (SSE) for service period runoff amounts. The optimised $CN_2$ values are not in the

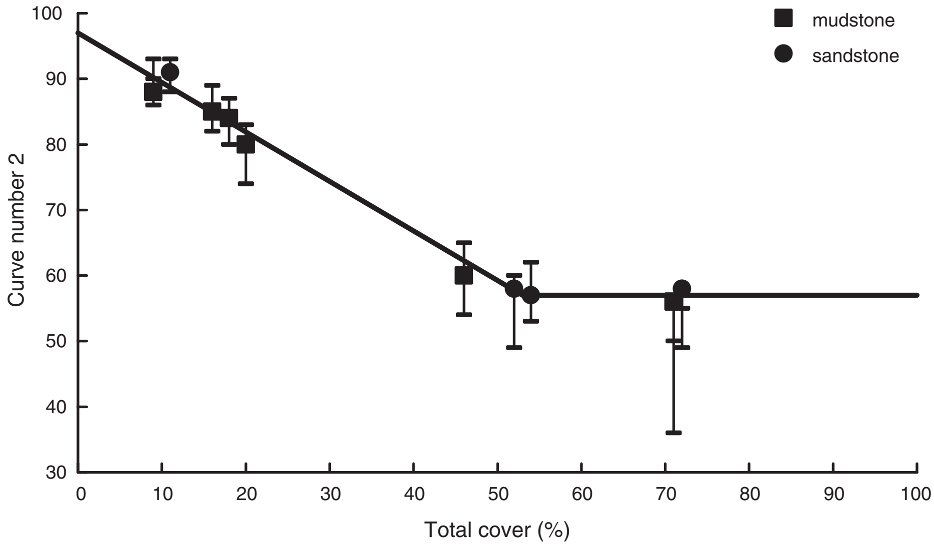

**Fig. 3.** Optimised $CN_2$ values plotted against the mean pasture cover for 10 runoff plots on hard setting soils at Springvale. Vertical bars are 95% confidence limits for the optimised $CN_2$ values. The solid line is the fitted Eqn 3 with $CN_{2(bare)} = 97$, CN_red = 40, and cov2 = 0.53 (cover as fraction). Optimised $CN_2$ values are not always in the centre of the confidence limits, as this was required to provide best predictions of total runoff and soil moisture.

centre of the confidence limit range for some plots, particularly for plots with higher cover, as this was required to provide best predictions of total runoff and soil moisture. Also the confidence limits are wider for plots with higher cover. This is partly because (*a*) higher cover plots produce less runoff and fewer runoff events, and therefore a less adequate sample of runoff events, (*b*) errors in prediction are larger relative to the lower runoff amounts, and (*c*) runoff is produced by a range of processes, including control at the surface during high intensity events and infiltration capacity excess (controlled by antecedent deficit and event size) during low intensity events. Conversely, for lower cover plots the sample of data is more adequate, events are larger and relative error smaller, and surface sealing and hardsetting largely control runoff.

### *Cover-curve number relationship*

The equation fitted to the curve number values derived by model calibration that links cover to curve numbers is:

$$CN_2 = 97 - [(40/0.53) \times \mathrm{MIN}\ (0.53, \mathrm{tcov})] \tag{5}$$

where tcov is the total projected cover (standing plus litter) and $CN_{2(bare)} = 97$, CN_red = 40, and cov2 = 0.53 (covers as fraction 0–1). Based on these results, a curve number ($CN_{2(bare)}$) of 97 was used for all soils. $CN_2$ decreased by 0.75 units for every 1% increase in average total cover to a threshold of 53% cover, irrespective of treatments and types of cover (grass cover or tree litter cover). The data are limited for higher cover; $CN_2$ was limited to a minimum value of 57 for cover >53% to suit the available data for higher cover and because additional cover should not lead to any greater reduction in runoff under higher cover, as runoff is more related to antecedent deficit and event size than to cover (McIvor *et al.* 1995; Scanlan *et al.* 1996).

### *Runoff predictions*

Using the Scanlan runoff sub-model in GRASP, total runoff was reasonably well predicted overall (ratio of predicted to observed runoff, P:O = 1.0). Runoff for 5 of the 10 plots was predicted to within 20% of the measured total, but for some plots was markedly underpredicted (plots 2 and 6) or overpredicted (plot 12) (Table 4). Similarly, runoff amounts were reasonably well predicted overall (RMSE < mean runoff, $r^2_{1:1} = 0.70$) but for several plots were predicted poorly (plot 6; $r^2_{1:1} < 0.20$) or only moderately well (plots 8, 2, 5, and 12; $r^2_{1:1} < 0.55$). In general, runoff amounts were better predicted for plots with lower cover (C, B, G1, G2), except that plot 2 with the lowest cover is poorly predicted, and poorly predicted for plots with higher cover (including plot 8 with high grass cover and plots 6, 5, and 12, with high tree density, high tree litter, and low grass cover). Total runoff from both eroded mudstone plots (plots B and D) was overpredicted by >20%. However, there is little consistency with regard to over- or under-prediction of total runoff (P:O total). Overall, the Scanlan model, which was transferred a large distance from its source in the Burdekin and used without calibration, provided a reasonable prediction of runoff from the Springvale soils.

There was a significant improvement in runoff prediction using the curve number method, with little difference between the calibration and dynamic cover-runoff runs. The $r^2_{1:1}$ for all plots increased from 0.70 to 0.87 (Fig. 4), explaining 87% of the variation between measured and predicted runoff. RMSE and average error were also reduced (Table 4). Runoff for 9 of the 10 plots was predicted to within 20% of the measured total, with runoff underpredicted for the medium covered tree plot (plot 5). The $r^2_{1:1}$ was greater than 74% for all plots except plot 12 (under trees, medium cover).

Using the dynamic cover effect on curve number (Eqn 5) had a slightly better fit around the 1:1 line and lower RMSE values than using constant $CN_2$ values for each plot. Significant improvements were seen for low cover plots where cover varies from 3% to 25% through time (grazed plots and plot 2). One plot in particular (plot 2), transformed from a $r^2_{1:1}$ of 62% from the CN-calibration runs to a $r^2_{1:1}$ of 81% using the CN-dynamic runs. Runoff is sensitive to cover and the dynamic model adjusts curve number daily according to the amount of total surface cover. Daily curve number adjustment provided more accurate runoff prediction in low cover situations.

### *Prediction of soil water*

Statistical analysis (Table 5) of predicted and measured soil water (total for all 3 soil layers) is presented for 8 plots (where sufficient soil water data were available) using both the Scanlan runoff sub-model from GRASP and the curve number model with dynamic cover-runoff. Figure 5 shows predicted total soil water against observed values for all 10 plots and Fig. 6 shows predicted and measured soil water through time for 2 plots, for the soil profile and for the soil surface 0–100 mm layer.

Prediction of soil water using the Scanlan runoff sub-model was good ($r^2_{1:1} = 0.88$). This indicates that errors in runoff prediction are not contributing significantly to soil water prediction. Larger errors in soil moisture prediction are in the mid range of measured soil moisture. High and low soil moisture conditions are predicted reasonably well (Fig. 5*a*).

Soil water predictions using the curve number model were similar ($r^2_{1:1} = 0.91$) to the Scanlan runoff sub-model. RMSE values were slightly lower in some cases. Errors in

**Table 4. Statistics for prediction of runoff (mm) for service periods using GRASP for three scenarios**

| Runoff sub-model | | Scanlan runoff sub-model in GRASP | | | | | Curve number method (using optimum curve number) | | | | | Curve number method with dynamic cover-runoff effect | | | | | Site description |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plot | $N$[A] | P:O total rnff[B] | RMSE[C] (mm) | RMSE/year[D] (mm/mm) | Average error (mm) | $R^2$ (1:1)[E] | P:O total rnff[B] | RMSE[C] (mm) | RMSE/year[D] (mm/mm) | Average error (mm) | $R^2$ (1:1)[E] | P:O total rnff[B] | RMSE[C] (mm) | RMSE/year[D] (mm/mm) | Average error (mm) | $R^2$ (1:1)[E] | |
| | | | | | | | | | *Ungrazed* | | | | | | | | |
| 8 | 22 | 1.0 | 9.0 | 1.1 | –0.1 | 0.42 | 1.0 | 8.8 | 1.1 | 0.0 | 0.77 | 1.0 | 8.9 | 1.1 | 0.4 | 0.77 | High grass cover |
| C | 32 | 0.9 | 15.3 | 0.5 | –4.4 | 0.85 | 0.9 | 13.4 | 0.4 | –4.2 | 0.87 | 0.9 | 15.1 | 0.5 | –3.6 | 0.85 | Bare scalded hard-set |
| 2 | 28 | 0.7 | 28.7 | 0.9 | –6.2 | 0.45 | 1.0 | 21.1 | 0.7 | 4.0 | 0.62 | 1.2 | 17.1 | 0.6 | 9.2 | 0.81 | Bare scalded hard-set |
| D | 26 | 1.3 | 10.6 | 0.9 | 3.9 | 0.71 | 0.8 | 8.3 | 0.7 | –1.7 | 0.80 | 0.8 | 7.5 | 0.7 | –1.9 | 0.83 | Eroded, medium cover |
| B | 32 | 1.4 | 16.5 | 0.7 | 8.8 | 0.81 | 1.0 | 11.1 | 0.5 | –0.2 | 0.89 | 1.1 | 12.4 | 0.5 | 1.7 | 0.88 | Bare, severely eroded |
| | | | | | | | | | *Tree plots* | | | | | | | | |
| 6 | 28 | 0.5 | 9.9 | 1.9 | –2.7 | 0.16 | 1.0 | 5.3 | 1.0 | –0.2 | 0.85 | 0.9 | 5.1 | 1.0 | –0.4 | 0.85 | Under trees, high tree litter |
| 5 | 19 | 1.3 | 8.1 | 1.9 | 2.6 | 0.52 | 0.6 | 3.7 | 0.8 | 0.3 | 0.71 | 0.7 | 3.7 | 0.9 | 0.8 | 0.74 | Under trees, medium cover |
| 12 | 27 | 2.6 | 12.4 | 3.1 | 8.1 | 0.54 | 0.7 | 4.9 | 1.2 | 1.8 | 0.52 | 0.8 | 4.6 | 1.1 | 2.0 | 0.58 | Under trees, medium cover |
| | | | | | | | | | *Grazed* | | | | | | | | |
| G1 | 6 | 1.2 | 15.1 | 0.6 | 5.2 | 0.78 | 1.0 | 9.3 | 0.4 | –0.9 | 0.77 | 1.1 | 7.5 | 0.3 | 2.5 | 0.86 | Heavily grazed |
| G2 | 24 | 0.8 | 31.7 | 0.8 | –8.9 | 0.62 | 1.1 | 23.1 | 0.5 | 2.8 | 0.81 | 1.0 | 22.4 | 0.5 | 1.3 | 0.85 | Heavily grazed |
| | | | | | | | | | *All plots* | | | | | | | | |
| All | 244 | 1.0 | 17.8 | 0.94 | –0.3 | 0.70 | 1.0 | 12.9 | 0.7 | –0.8 | 0.84 | 1.0 | 12.4 | 0.7 | 0.2 | 0.87 | All plots |

[A] Number of observations.

[B] Ratio of predicted to observed total runoff.

[C] Root mean square error (mm).

[D] Root mean square error relative to the observed mean (mm/mm).

[E] Co-efficient of determination ($R^2$) about the 1:1 line.

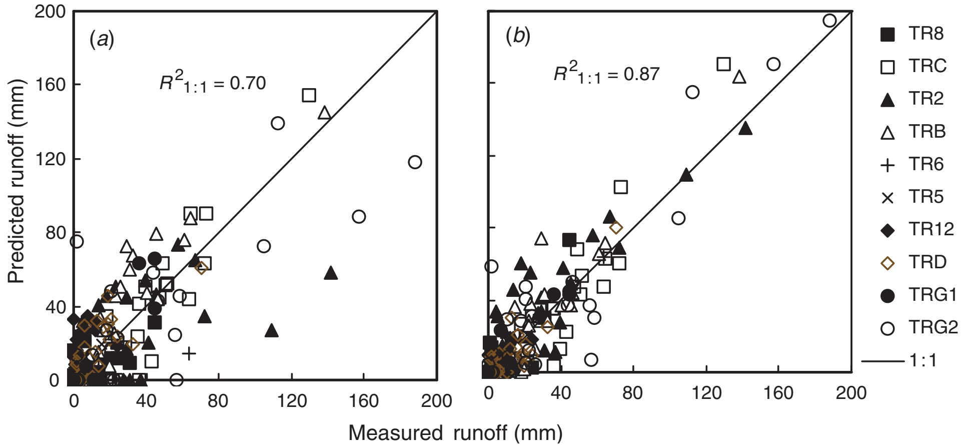

**Fig. 4.** Comparison of predicted and measured runoff (accumulated for service periods, mm) for 10 runoff plots using GRASP with (*a*) Scanlan runoff sub-model, and (*b*) Curve number runoff model with dynamic cover-runoff effect.

**Table 5. Statistics for prediction of soil water (total for three soil layers in mm) using GRASP with two runoff models**

Runoff plots B & D had insufficient data for soil water regression analysis

| Runoff sub-model Plot | *N*[A] | Scanlan runoff sub-model in GRASP P:O total soil water[B] | RMSE[C] (mm) | RMSE/year[D] (mm/mm) | $r^2$ (1:1)[E] | Curve number method with dynamic cover-runoff effect P:O total rnff[B] | RMSE[C] (mm) | RMSE/year[D] (mm/mm) | $r^2$ (1:1)[E] | Site description |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Ungrazed* | | | | | |
| 8 | 13 | 1.0 | 7.2 | 0.07 | 0.96 | 1.0 | 7.2 | 0.07 | 0.96 | High grass cover |
| C | 13 | 1.0 | 9.3 | 0.19 | 0.85 | 1.0 | 8.8 | 0.18 | 0.85 | Bare scalded hard set |
| 2 | 11 | 1.0 | 13.6 | 0.14 | 0.85 | 0.9 | 15.5 | 0.16 | 0.76 | Bare scalded hard set |
| | | | | | *Tree plots* | | | | | |
| 6 | 11 | 0.9 | 8.7 | 0.14 | 0.90 | 0.9 | 8.7 | 0.14 | 0.90 | Under trees, high tree litter |
| 5 | 7 | 0.9 | 16.4 | 0.14 | 0.37 | 0.9 | 16.6 | 0.14 | 0.37 | Under trees, medium cover |
| 12 | 5 | 0.9 | 8.9 | 0.17 | 0.57 | 0.9 | 7.6 | 0.15 | 0.67 | Under trees, medium cover |
| | | | | | *Grazed* | | | | | |
| G1 | 10 | 1.0 | 7.4 | 0.09 | 0.94 | 1.0 | 7.0 | 0.08 | 0.95 | Heavily grazed |
| G2 | 12 | 1.3 | 24.5 | 0.38 | 0.63 | 1.2 | 13.6 | 0.21 | 0.74 | Heavily grazed |
| | | | | | *All plots* | | | | | |
| All | 82 | 1.0 | 12.0 | 0.17 | 0.88 | 1.0 | 10.6 | 0.14 | 0.91 | All plots |

[A] Number of observations. [B] Ratio of predicted to observed total soil water. [C] Root mean square error (mm).
[D] Root mean square error relative to the observed mean (mm/mm). [E] Co-efficient of determination ($r^2$) about the 1:1 line.

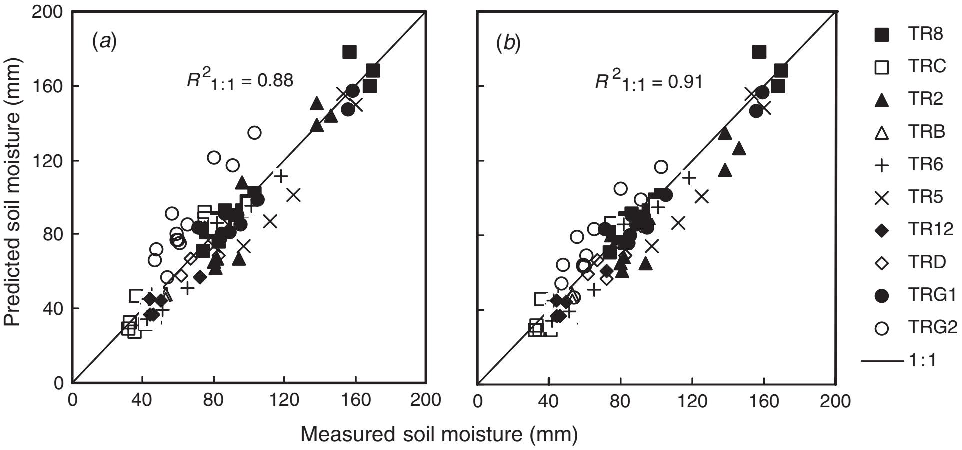

**Fig. 5.** Comparison of predicted and measured total soil water (mm) for all plots using (*a*) GRASP runoff model, and (*b*) Curve number runoff model with dynamic effect of cover.

predicting mid range soil moisture conditions were reduced (Fig. 5*b*). Quality of soil water prediction does not appear to be related systematically to plots conditions such as grazing, tree density, or soil type (Table 5). Soil water was predicted poorly by both models for plot 5 (though runoff was predicted reasonably well, Table 4), which may be related to errors in measured soil water data for one or more samplings or failure to adequately represent the soil, pasture, and/or tree characteristics of the plot.

Distribution of soil water through the profile was well predicted. For example, predictions for 0–100 mm layer for the high grass cover plot and bare scalded plot are presented in Fig. 6. The model predicts the soil water content of this very dynamic layer quite well for both low and high cover, giving confidence in the soil evapouration component of the model. Total soil water for the bare scald (plot C, Fig. 6), where evapotranspiration is mainly via soil evapouration and tree water use, was predicted well, giving confidence in the tree water use functions.

### *Predictions of cover and total standing dry matter*

Accurate predictions of cover are needed because model predictions of runoff are sensitive to cover. Pasture yield and total surface cover provided by standing dry matter and litter were well predicted for all treatments ($r^2_{1:1} > 0.90$). Since the results from all 3 models were similar, only the CN-dynamic model predictions are presented (Fig. 7). Variation in total cover was not well predicted for plots under trees (for example, see Tr6 and Tr5 in Fig. 7*b*). This is because GRASP currently does not model tree litter. Tree plots have a high proportion of ground covered with tree litter (e.g. Tr6 has an average of 50%, Tr5 with 35%). To get around this problem, a fixed value of average tree litter for the plot was added to the total cover. However, tree litter cover is evidently more dynamic than this, with total cover varying by ±15–20% cover through time.

## General discussion

### *Cover–curve number relationship*

The bare soil curve number ($CN_{2(bare)}$), the intercept at 0% cover in Fig. 8, describes the relative runoff potential of different soil types. Previous studies using similar runoff models

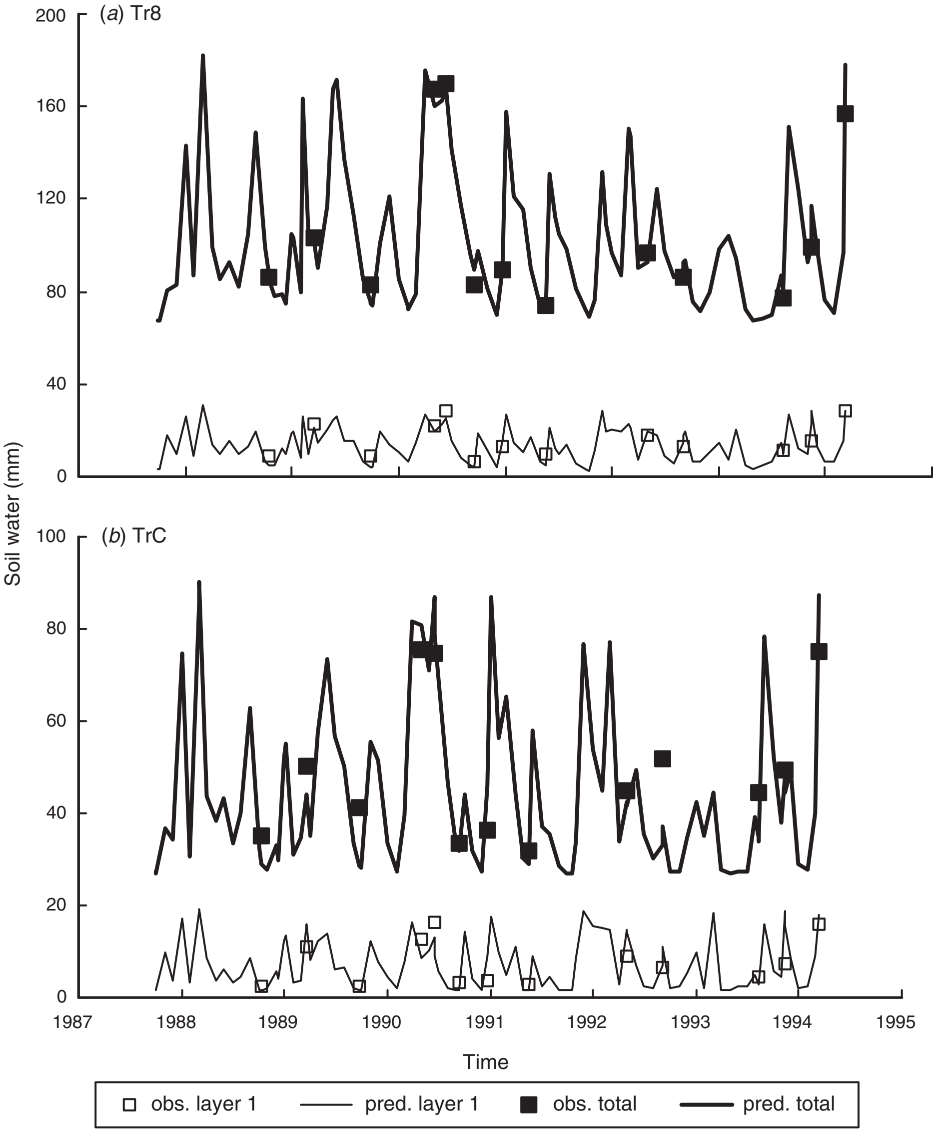

**Fig. 6.** Predicted (lines) and observed (points) total soil water and for layer 1 (0–100 mm) using GRASP with the curve number runoff model for 2 sites: (*a*) high cover, ungrazed plot; and (*b*) bare scalded plot.

derived $CN_{2(bare)}$ values of 73 for 3 cultivated cracking clays or Vertosols (black earth and grey clay, Darling Downs—Silburn and Freebairn 1992; black earth, Central Queensland—M. Littleboy, pers. comm.); 93 for a cultivated Alfisol in the wet tropics in The Philippines (Nelson *et al.* 1998); 94 for a cultivated hard-setting Alfisol (red earth, Kandosol) in India (Littleboy *et al.* 1996*a*); and 96 for a cultivated hard-setting Alfisol (red earth) in the Northern Territory (Motha *et al.* 1995*a*).

In comparison, the hard setting soils at Springvale have a much higher runoff potential ($CN_{2(bare)}$ = 97) than the cultivated clays and runoff potential equal to or slightly higher than the range of cultivated Alfisols.

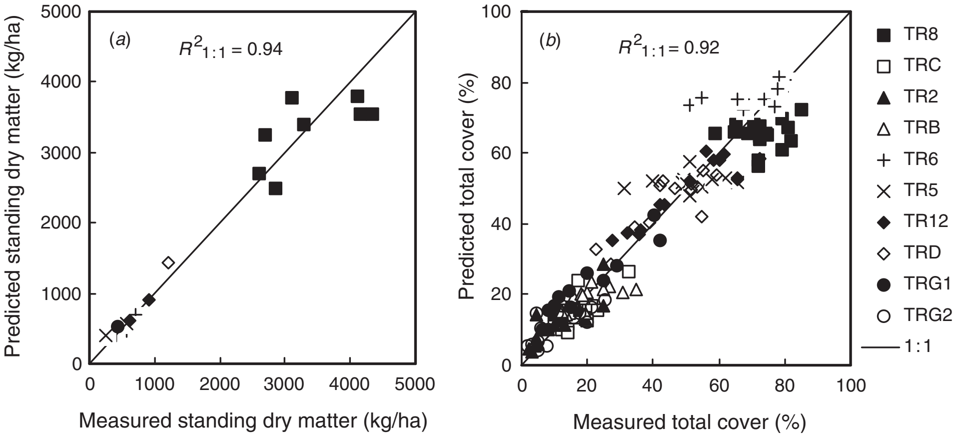

**Fig. 7.** Comparison of measured and predicted (*a*) standing dry matter (kg/ha), and (*b*) total cover (%) for all plots using the CN-dynamic model.

Motha *et al.* (1995*b*) derived curve numbers for the cultivated Alfisol in the Northern Territory after establishment of improved pasture, and for grazed native pasture woodland. Considering the improved pastures only, the bare soil curve number was 91 (our interpretation), lower than for the previous cultivated state, which may indicate that runoff potential was reduced by a pasture phase. The native pasture woodland, with an average of 40% cover, had a $CN_2$ that was 25 units lower than the line in Fig. 8 at 40% cover, indicating a much lower runoff potential. It is likely that the cultivation phase before the improved pasture caused considerable soil structural degradation and decline in infiltration (Connolly *et al.* 1997*b*) that had not occurred in the native pasture woodland.

The effect of cover on curve number (and runoff potential), as indicated by slope of the lines in Fig. 8, is less dramatic for the cultivated cases than pastures. For example, $CN_2$ decreases by 0.25 units per 1% increase in cover for the cultivated clays compared with

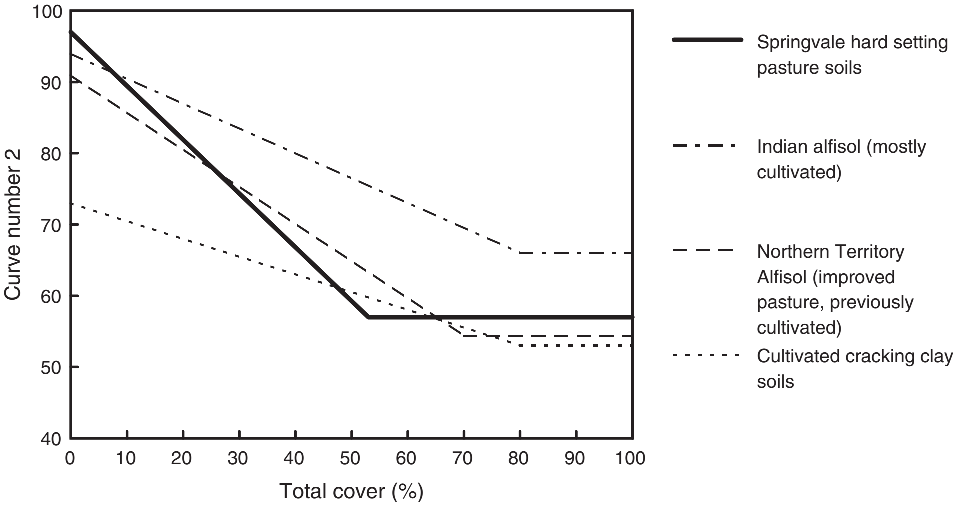

**Fig. 8.** Reduction in curve number 2 due to cover for various soils. The $CN_2$ value at 0% cover is the $CN_{2(bare)}$.

0.75 units per 1% increase in cover at Springvale. Cover in the cultivated cases is mainly associated with crop stubble during fallows, which protects the soil surface from raindrop impacts. Cover in pastures provides surface protection and is also associated with root and soil fauna activity, capable of modifying and maintaining the soil macroporosity and hydraulic properties (McIvor *et al.* 1995). Connolly *et al.* (1997*a*) concluded that infiltration responses to cover measured under simulated rainfall at Springvale were related to the vegetation status, and associated levels of root and soil insect activity creating larger pores, rather than protection of the soil surface from raindrop impact during the applied rain (as is the case with crop stubble on cultivated soils). This is illustrated in studies by C. Ciesiolka and S. Glanville (unpublished data) where addition of grass cuttings to bare scalded areas just prior to simulated rain did not increase infiltration compared with bare areas. Similarly, when all cover was removed from vegetated areas, infiltration did not decrease much compared with that on the intact vegetated areas. These differences in soil hydraulic properties associated with vegetation status are reflected in the CN–cover relationships. However, the time lag between removal or replacement of vegetation and change in soil hydraulic properties is poorly researched.

Total surface cover was found to be strongly related to curve number and runoff (Fig. 3). The types of cover (i.e. grass canopy, grass litter, or tree litter) was not an important source of variation. McIvor *et al.* (1995) also found that the differences in runoff between native woodlands and cleared areas, and between different pasture systems, were primarily the result of differences in ground cover and not necessarily the type of cover. Tree canopy cover (~20% at the highest tree basal area) was not considered in the model. Not representing tree canopy cover explicitly in the model did not prevent reasonable modelling of the hydrology; curve numbers related well to cover (on-ground) irrespective of canopy cover between 0 and 20% (Fig. 3). The most important aspects of the trees appear to be their contribution of litter to surface cover and use of soil water. Tree litter cover was not originally considered in the Scanlan runoff model, tree litter presumably being less prevalent in the more open woodlands studied in the Burdekin. When tree litter cover was not added to the cover term in the runoff equation, Yee Yet (1994) found the model overpredicted runoff and underpredicted soil water from Springvale plots with higher tree density. The consistency of runoff parameters derived for plots with high tree litter cover and high grass cover indicates that tree litter cover is similar in value to grass cover in reducing runoff. Thus, any model with a cover-runoff term would overpredict runoff from these plots if tree litter were neglected.

### *Runoff parameter estimation*

Sensitivity analysis in this study and by Littleboy *et al.* (1989) indicated that predictions of runoff, and drainage below the root-zone, using water balance models are very sensitive to choice of runoff parameter value. As runoff and drainage both (mostly) occur when the soil profile is wet there is an almost direct trade-off between runoff and drainage predictions—an error in runoff will cause an opposite error in drainage estimation, albeit somewhat buffered by the soil water storage capacity. For daily time-step models the most reliable estimates of runoff parameters are obtained by calibration of the model to hydrological data (Silburn and Freebairn 1992). However, there is a growing set of runoff parameters available in Australia, as described above, and a growing need for methods of generalisation, either by interpolating between values or through use of surrogate soil properties. Use of water balance models is expanding rapidly, in estimation of biomass and crop yields where runoff estimation maybe less important, and in runoff and deep drainage estimation where runoff estimation is important.

Littleboy *et al.* (1996*b*) derived a curve number–cover relation from rainfall simulator data that gave good predictions when used in a daily water balance model. However, further validation and development of the approach is required for water balance curve numbers to be derived reliably in this manner. The runoff, and calculated curve number, for a rainfall simulator storm are specific to the rainfall applied and antecedent conditions on the plot. Excluding cover, which can be incorporated in the model easily, results are strongly affected by soil moisture content and distribution in the profile. Other factors that affect runoff are rainfall intensity and duration, soil tilth and roughness, and prior rain-impact sealing (Silburn and Connolly 1995). Therefore, the antecedent conditions must be controlled to some specific but as yet undefined conditions representing the 'average' conditions applying for a catchment under a series of rainfall events and wetting and drying cycles. Alternatively, analytical techniques could be further developed to adjust rainfall simulator data for the prevailing antecedent conditions, for example to account for soil moisture status. This is not to say that reasonable estimates could not be made, only that it is not yet reliable and that comparison of rainfall simulator data with calibrated water balance curve numbers for a range of sites is needed. This may then allow the large amount of rainfall simulator data available to be used to extend the knowledge base of water balance curve number parameters.

The GRASP model used here does not limit soil water drainage using hydraulic conductivities (i.e. it is free draining). In modelling of the runoff plots, little drainage was calculated for low cover/high runoff plots and drainage had little effect on the soil water balance. For higher cover/lower runoff plots, somewhat greater drainage was calculated, e.g. 3% of rainfall, not inconsistent with estimates we have made using soil chloride. Reducing this drainage by including a drainage algorithm in the model would probably not greatly change the modelled water balance and the calibrated runoff parameters for the soils and climate in this study. Somewhat more water would go into evapotranspiration and possibly runoff, and slightly lower calibrated curve numbers may result, for high cover. However, for modelling of a wider range of conditions where runoff and especially drainage are important outcomes, inclusion of a drainage algorithm would give more control over the modelled outcomes and allow calibration/testing against drainage data (e.g. Tolmie and Silburn 2002).

The Scanlan runoff sub-model in GRASP was used without calibration. Results show that it is capable of producing satisfactory runoff prediction and good soil water prediction on soils, like those at Springvale, that are similar to those used in deriving the runoff equation (Scanlan *et al.* 1996). However, in order to simulate runoff-driven processes for a wider range of soils, more general runoff models, such as the curve number method, and parameter values for a wider range of soils, are required. This paper is one of a series of such model calibration studies under way for northern Australia.

## Conclusion

Good predictions of runoff, soil water, cover, and biomass were obtained with the modified GRASP model. The runoff parameter, curve number, was strongly related to total surface cover, while the type of cover (grass canopy, grass litter, or tree litter) was not an important source of variation. Inclusion of tree canopy cover (<20% cover) does not seem warranted in this case as it had little influence on runoff. However, water use by trees and tree litter on the soil was important and inclusion of a dynamic tree litter pool is recommended. Curve number for bare soil at average antecedent moisture conditions was 97. Total cover was shown to reduce curve number by a maximum of 40 units up to a threshold of 53% cover or 0.75 units per 1% cover increase. This cover–curve number equation applied for all soils (sandstone- and mudstone-derived) and for heavily eroded plots.

Using the curve number runoff method with a dynamic cover effect in GRASP produced better runoff predictions, and slightly better soil water predictions, than the Scanlan runoff sub-model. The reasonable predictions obtained with the un-calibrated Scanlan sub-model, derived for soils in the Burdekin region, indicate similarity in runoff behaviour of the soils. Both models capture the interaction between pasture cover and runoff dynamically to provide feedback between grazing, management, tree density, cover, and water balance components. However, the modified model has more generality (i.e. is not 'hardwired' for regional conditions), does not need rainfall intensity data, and is consistent with other agricultural water balance models in use.

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