Calibration of GRASP runoff parameters and evaluation of two runoff sub-models using Gordonstone catchment monitoring data.

Report for Paddock to Reef Integrated Monitoring, Modelling and Reporting program funded through the Australian Government's Caring for Our Country Reef Rescue

Report compiled by Giselle Whish of Animal Science, Department of Agriculture, Fisheries and Forestry. 2014.

Citation

Whish G. (2014) *Calibration of GRASP runoff parameters and evaluation of two runoff sub-models using Gordonstone catchment monitoring data*. Technical Report to Paddock to Reef Integrated Monitoring, Modelling and Reporting program funded through the Australian Government's Caring for Our Country Reef Rescue. Department of Agriculture, Fisheries and Forestry, Queensland, Australia.

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Introduction

As part of the Paddock to Reef Integrated Monitoring, Modelling and Reporting (PRIMMR) program, or Paddock to Reef Program (Carroll *et al*. 2012), monitoring and modelling of grazing systems in the Great Barrier Reef catchments was undertaken to provide links between management practices, water quality and reef health, and to report on and achieve explicit Reef Plan water quality and management practice targets (Anon 2009, 2013). Improvements in water quality through the adoption of improved grazing management practices was determined by linking 'paddock' model times series outputs to 'catchment' models.

The GRASP pasture growth model (McKeon *et al.* 2000, Rickert *et al.* 2000) was used to provide paddock time-series ground cover data for use in the Paddock to Reef Program grazing industry portions of the 'catchment' models (see Whish 2012). The GRASP model has been used extensively across Australian rangelands to evaluate a wide range of grazing management issues (stocking rate, safe carrying capacities, land degradation) and the impacts of climate variability on, predominantly, pasture productivity. GRASP modelling was used in the Paddock to Reef Program to help establish the effectiveness of grazing management practices in controlling sediment and nutrient losses and improving water quality outcomes (Shaw *et al*. 2013).

The soil-water model in GRASP uses a simple one-dimensional multi-layered soil model. Rainfall is partitioned into infiltration and runoff. Infiltration occurs from layer to layer once the field capacity of each layer is reach. Runoff is calculated before infiltration. Hillslope runoff was predicted in GRASP using a non-linear empirical relationship between cover and runoff found in analyses by Scanlan *et al.* (1996) using runoff data collected from neutral duplex soils in Burdekin catchment. Surface cover, daily rainfall, rainfall intensity and soil water deficit were used to derive the relationships. Surface cover was a function of total standing dry matter and includes grass litter but not tree litter. The contribution that trees make to surface litter was captured in GRASP through a relationship that produces a 'minimum' surface cover in treed landscapes. A parameter within GRASP defines the 'effectiveness' of the tree litter component that contributes to the minimum surface cover in runoff predictions using a scale 0 (no effect) to 1 (total effect).

The GRASP parameters used to simulate runoff in the grazing Paddock to Reef modelling were the same for all land types except for the parameter (p273) that defines the maximum runoff of rainfall from a wet profile with no surface cover (see Whish 2012). For the Paddock to Reef (P2R) modelling, runoff from Black basalt cracking clay land type was set (p273) to be a third of that for all other land types. Monitoring runoff data from an Open downs land type site in the Fitzroy basin, which is similar to P2R Black basalt in Burdekin, provided an opportunity to calibrate and evaluate the GRASP runoff parameters for lightly grazed bluegrass pastures on cracking clays; to assess management and runoff relationships for bluegrass pastures on cracking clays, and provide recommendations for future Paddock to Reef GRASP modelling of the grazing systems.

Methods

Site description

Ten years of monitoring runoff data (15/3/2002 to 2/6/2012) was collected from a 120 ha sub-catchment at Bowhunters (-23° 16 S 148° 6 E) within the Gordonstone Creek catchment (south of Capella) in the Fitzroy Basin (Figure 1) (Rogusz *et al*. 2013). The Bowhunters site was 'typical' undulating, treeless Open downs with bluegrass pastures on cracking clays (see mapped Open downs Figure 2), with similar soil and pasture to the Black Basalt land type modelled for P2R. The pastures at Bowhunters were in good condition and considered only very lightly grazed. However, a subsequent regional comparison of remotely-sensed data for the 120 ha Open downs sub-catchment (Figure 3) provided by DSITIA revealed between 2000 and 2007 ground cover (%) at Bowhunters was predominantly in the 5-20 percentile for the region. Between 2007 and 2013 ground cover at Bowhunters was consistently high compared to the surrounding region (50-80 and 80-95 percentiles). The regional ground cover comparison suggests that the Bowhunters sub-catchment was heavily grazed until 2007 and lightly grazed after this period.

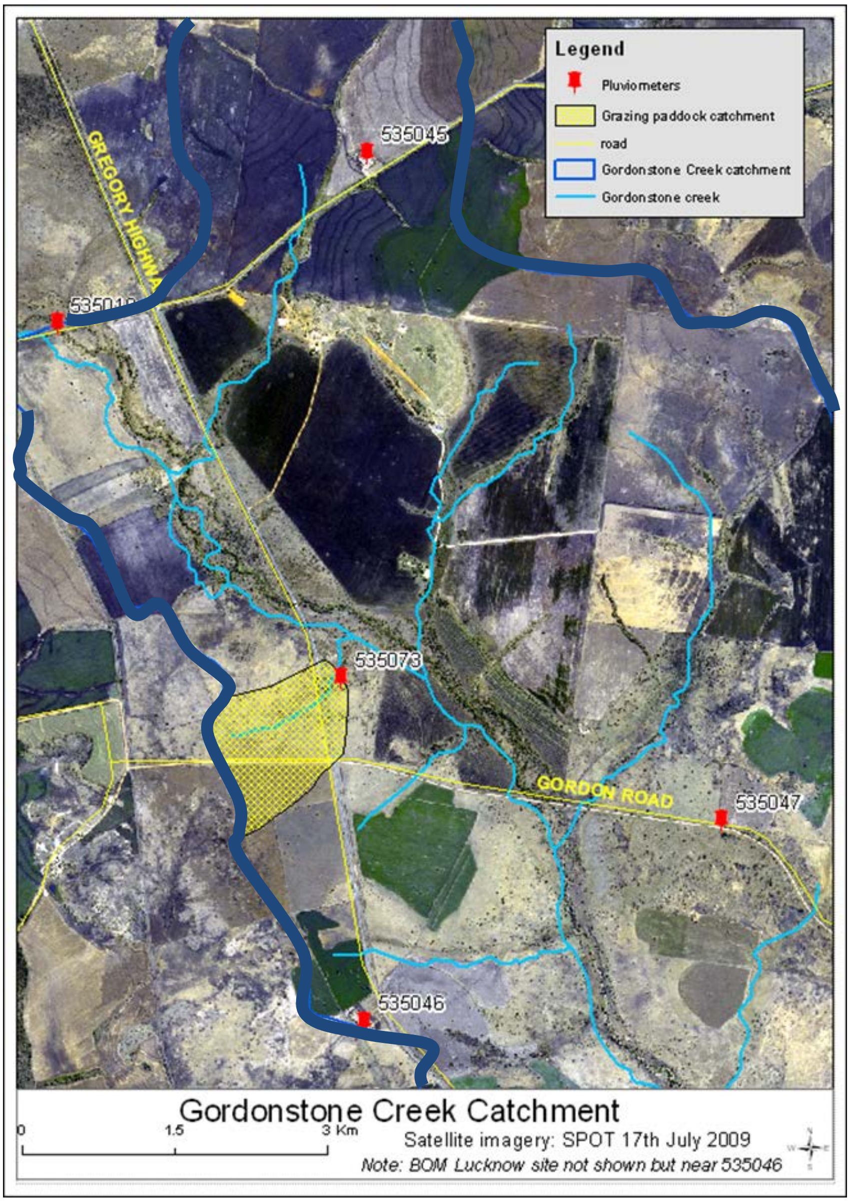

Figure 1. 120 ha grazed sub-catchment (yellow) at Bowhunters (535073 pluviometer) monitoring site within the Gordonstone creek catchment (dark blue line), south of Capella in the Fitzroy Basin.

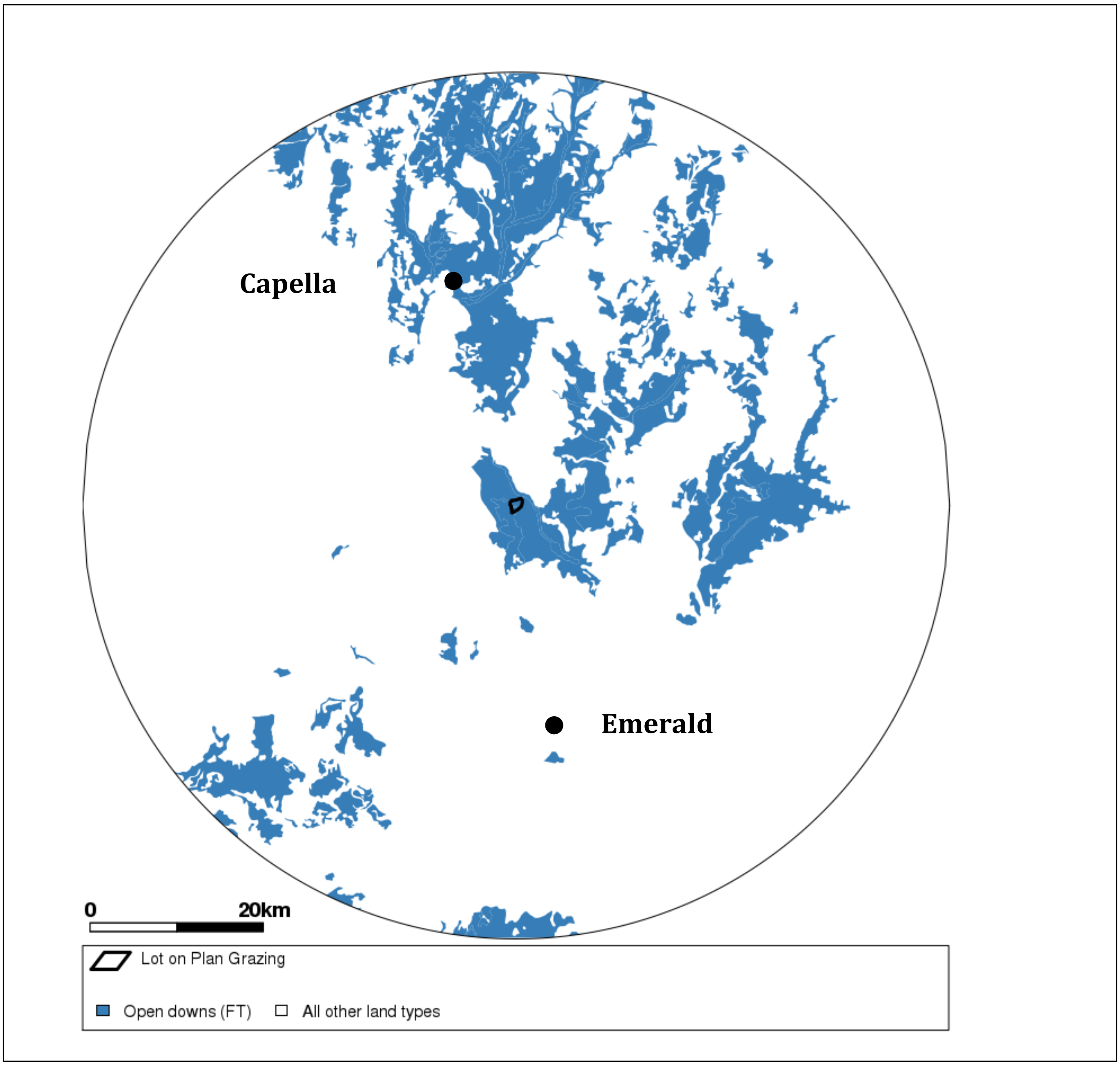

Figure 2. 120 ha grazed Open downs sub-catchment (black outline) at Bowhunters monitoring site and areas of similar Open downs land type in the area around Capella and Emerald in the Fitzroy Basin.

Observations of daily rainfall (previous 24 hours to 9:00 am) from the on-site pluviometer at Bowhunters were supplemented with data from the nearby Lucknow (-23° 18 S 148° 6 E) Bureau of Meteorology site (near 535046 pluviometer, Figure 1) for the 999 days (26.1%) that were missing rainfall. Over the ten years monitoring data were collected at Bowhunters, annual rainfall averaged 572 mm, and 7.0% of total rainfall (6086 mm) was measured as runoff (427 mm). From 15/3/2002 until 15/02/2012 measured runoff (314 mm) occurred on 1% of the total monitoring days (3334), with no actual runoff (0 mm) measured until 17/1/2008 despite the monitoring equipment being in place and working. Between 15/2/2012 to 2/6/2012 113 mm runoff was measured on 39% of the total monitoring days (108 days). Measured runoff between April and June 2012 was unusual, and consisted of small frequent quantities (<1-2mm) of runoff each day although there were only 3 significant rainfall events (approximately 25-30 mm) during this two month period. At the time of this report it was unknown whether the runoff was actually seepage. Due to the difficulties of calibrating daily rainfall to measured runoff, for this 63 day period only runoff data that correlated to rain days was included for calibration (9.3 mm runoff for 96.6 mm of rain).

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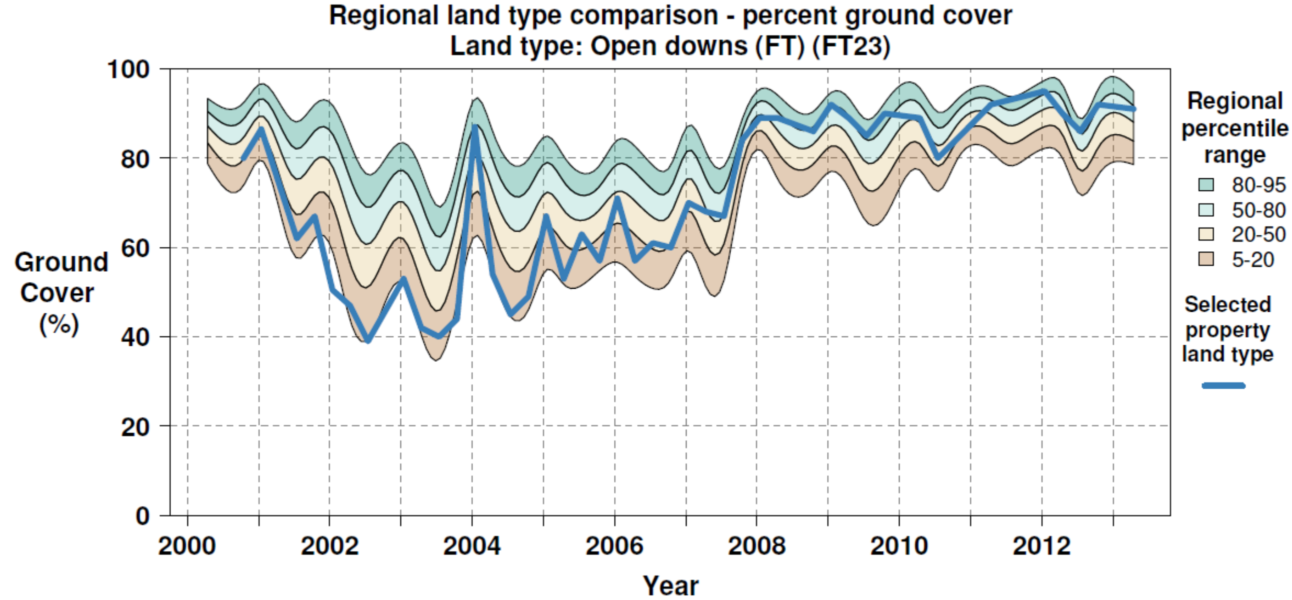

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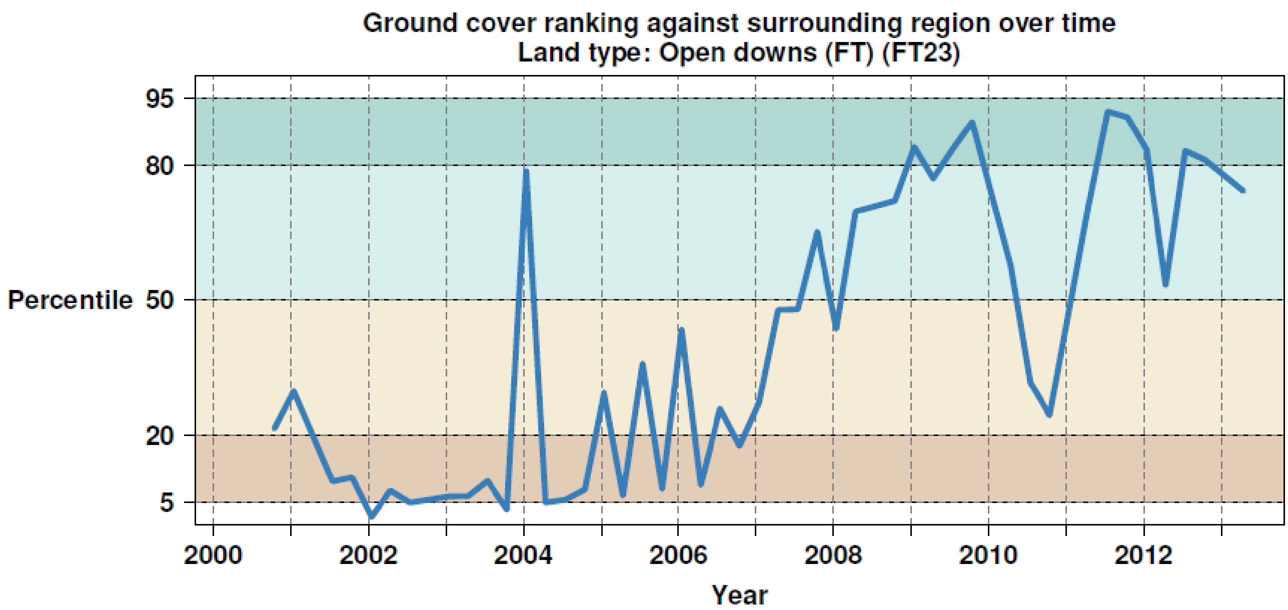


Figure 3. Regional comparison of a) percent ground cover and b) percentile ground cover ranking at 120 ha grazed Open downs sub-catchment at Bowhunters monitoring site within the Gordonstone creek catchment, south of Capella in the Fitzroy Basin.

There were 291 days between 8/5/2005 to 23/2/2006 of missing pasture runoff data (including no flow periods). During this period, only 15 mm of runoff was measured from cropping land within Gordonstone catchment (535019 pluviometer, Figure 1), which is known to runoff more than pastures (Rogusz *et al*. 2013).

Monitoring data was reviewed to identify any unusual events that may indicate a failure of the site equipment (eg. pluviometers, flumes). Three days during the summer of 2010/11 (4/12/2010, 28/12/2010, 6/1/2011) had between 12-25 mm of measured runoff each day but less than 11 mm of rainfall recorded on any occasion. On these days the model was predicting less than 1 mm of runoff. Removal of these ‘missing rainfall days’ from the data improved the R^2 and Pearson's *r* measures but did not alter the Root Mean Square Error (RSME) or Predicted to Observed ratio (P:O) measured criteria.

Remotely-sensed fractional cover for each season was provided by DSITIA for the Bowhunters site in Gordonstone catchment in July 2013. The seasonal fractional cover (total, green, bare ground) was calculated from the median of all images within a season for the period 1987-2012 (Figure 4). From 1987-2012 the average total ground cover (green and dry) at Bowhunters site was 72%, of which green cover contributed 26% and dry cover 46%, with 27% of bare ground (Table 1). Runoff monitoring data was collected for ten years between 15/3/2002 to 2/6/2012. During the first six years of the monitoring period from 2002-2007, the average total ground cover (green and dry) at Bowhunters site was 60%, of which dry cover contributed 40%, and bare ground 38%. During the last four years of the monitoring period, when almost 3/5 of the total rain fell (2008-2012), ground cover was higher with an average total ground cover of 89%, with green cover contributing 37%, dry cover 52%, and only 9% bare ground (Table 1).

There was no additional measured site data (eg. yields, ground cover, stocking rate, soil profile or water measurements) available for calibration.

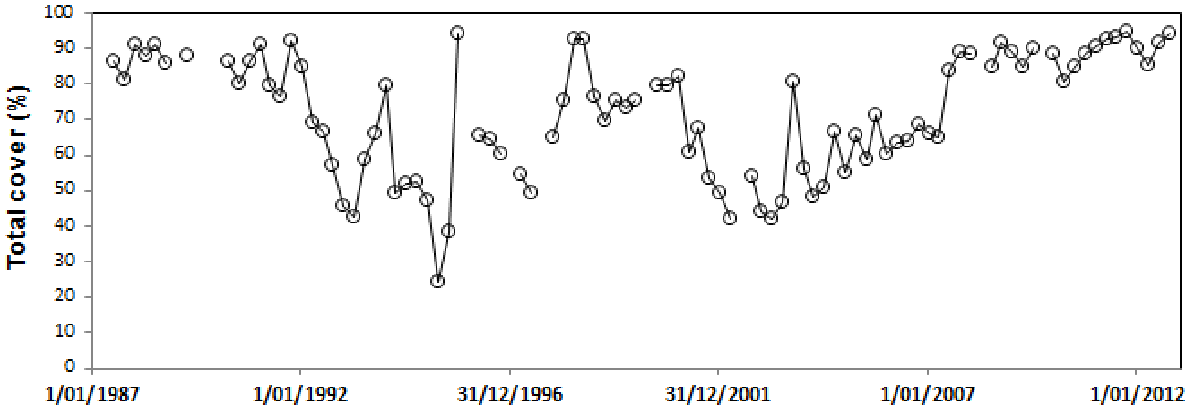
Table 1. Average seasonal (median) fractional cover (total, bare, green, dry) for Bowhunters monitoring site for 1987-2012, 2002-2006, and 2007-2012.

1987-2012	**Total cover (%)**	**Bare ground (%)**	**Green cover (%)**	**Dry cover (%)**
Season				
autumn	72	26	32	40
spring	72	27	21	51
summer	77	21	34	43
winter	66	33	16	50
Average	**72**	**27**	**26**	**46**
2002-2007				
Season				
autumn	55	44	15	40
spring	61	38	21	40
summer	72	27	33	39
winter	54	45	12	42
Average	**60**	**38**	**20**	**40**
2008-2012				
Season				
autumn	89	9	53	37
spring	89	9	25	64
summer	92	6	55	41
winter	86	12	16	70
Average	**89**	**9**	**37**	**52**

Calibration of Open downs GRASP parameters

Open downs, a bluegrass on cracking clays Fitzroy region land type (Whish 2011), was representative of the grazing land type at Bowhunters monitoring site. The Open downs GRASP model was calibrated to determine the 'best fit' of parameters to Bowhunters monitoring runoff data using the runoff relationship (Scanlan *et al.* 1996) derived from

Burdekin sites ("JS equation"). Calibration of the Open downs model focused on four components (grazing pressure, pasture condition, soil evaporation from cracking clay soils, maximum runoff from bare wet profile) that impact the non-linear empirical relationship used to predict runoff.



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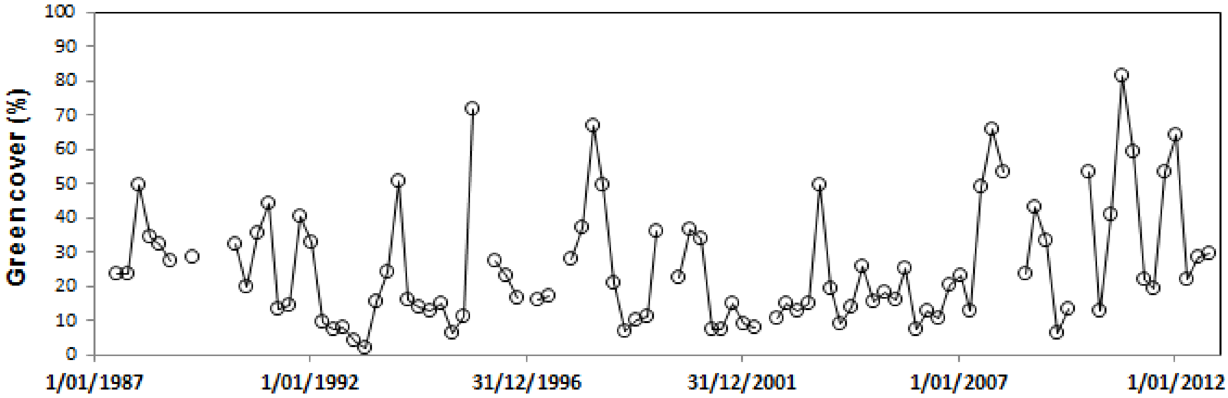

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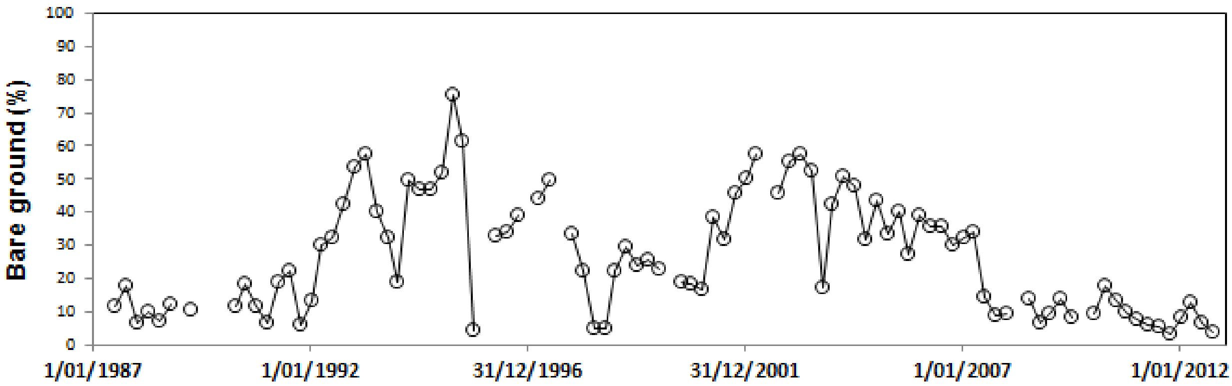

c)

Figure 4. Remotely-sensed seasonal cover (average for each season shown) a) total, b) green, c) bare ground cover for 120 ha grazed Open downs sub-catchment at Bowhunters monitoring site for 1987 to 2012.

Simulations were run from 1980-2012 to correspond with the P2R modelling (1980-2010) and to capture all monitoring data collected up until 2012. Determination of the 'best fit' parameters that minimised RSME and achieved a balance between predicted total to measured total included assessing daily, monthly and annual predicted runoff with measured values as:

- Runoff as percentage of rainfall
- Ratio of predicted to observed (P:O)
- Root mean square error (RSME)
- R squared (R^2), and;
- Pearson's product-moment correlation coefficient (Pearson's *r*).

The calibrated Open downs modelled cover output was compared to the seasonal cover data for Bowhunters.

Evaluation of Curve Number model

A second runoff sub-model, the modified USDA Curve Number model (Owens *et al*. 2003), was also used to predict runoff. The Curve Number model does not use the maximum runoff from bare wet profile GRASP parameter that was evaluated for the non-linear empirical runoff model (JS equation). The 'best-fit' Open downs model with calibrated Curve Number parameters was used to compare the quality of runoff predictions. A range of curve numbers (97-0) were run to derive the calibrated curve number (CN_1) for average antecedent soil water (Owens *et al*. 2003) that provided the best prediction of runoff according to the above criteria. Further modelling was undertaken to include the dynamic effect of cover with differences in runoff being driven by the daily cover predicted by GRASP. The calibrated curve number (CN_1) (p383) was used for cover above a specified threshold (p384). A range of curve numbers (CN_1 to 97) were run to derive the CN_2 (p322) for cover below a specified threshold (p382) that provided the best prediction of runoff according to the above criteria. The dynamic cover simulations used recommended cover threshold levels of 20% (p382) and 80% (p384), below and above which cover no longer has an effect on runoff.

Management and runoff relationships

Long-term response curves for runoff and cover were derived for the calibrated Open downs non-linear empirical (JS equation) and Curve Number runoff models to evaluate management-cover relationships. GRASP simulations were run over the last 50 years, for a range of fixed stocking rates (0.5 to 50 head / 100ha), using various grass basal area (constant, annual and monthly dynamic) and 'degradation recovery' (on or off) sub-routines. Simulation of the fixed stocking rates provided a much wider range of surface covers and subsequent runoff than available from site data. Modelling 50 years of climate ensures long-term runoff-cover response curves are not specific to a particular dry or wet period. However, the outcomes of these long-term simulations are specific to the climate of the initial years and do not capture the full impact of high fixed stocking rates.

Results

Calibration of Open downs GRASP parameters

Calibration of the Open downs GRASP model focused on four components (grazing pressure, pasture condition, soil evaporation from cracking clay soils, maximum runoff from bare wet profile) that impact on the non-linear empirical relationship used to predict runoff.

Daily GRASP predicted runoff and associated outputs (eg. cover) for rainfall events >1mm were compared to the measured runoff data (following removal of 3 'missing rainfall' days) from Bowhunters site. Over the ten years (15/3/2002 to 2/6/2012) measured runoff (372.5

mm) for rainfall events >1mm was approximately 6.2% of total rainfall (6025 mm), and average surface cover for the same period was predicted to be 56% (see Table 2). Measured runoff at Bowhunters was similar to that recorded for well managed pastures on heavy clays soils (average annual runoff of 2-5% of rainfall) (see Silburn *et al*. 2011).

The 'best fit' Open downs GRASP parameters (see Table 2, Figure 5) for predicting runoff at Bowhunters monitoring site from 15/3/2002 to 2/6/2012 were determined to be:

- moderate 'B' pasture condition;
- lightly grazed (25% utilisation of total standing dry matter at the end of the growing season) at a utilisation that was less than the recommended long-term 'safe' utilisation rate for this productive land type;
- 0.5 mm/day soil evaporation from the cracking clays; and
- maximum runoff from bare wet profile (p273) between 0.6-1.0

Over the ten years from 2002, the predicted to observed ratio and runoff as a percentage of rainfall that most closely matched measured data was achieved by the Open downs GRASP model with p273 (maximum runoff from bare wet profile) set to 0.7 (see Table 2). The lowest RSME was achieved when p273 (maximum runoff) was set to 0.8. Predicted runoff was best correlated with observed data when p273=1.0 (no reduction in maximum runoff, see Figure 5).

Remotely-sensed seasonal (median) fractional cover was compared to GRASP predicted seasonal average cover achieved with 'best fit' Open downs parameters and no reduction in maximum runoff (p273=1.0). The 1987-2012 time-series and 2002-2012 correlation of seasonal fractional cover and GRASP predicted cover are shown in Figure 6 and 7 respectively. GRASP seasonal cover tracks the remotely-sensed total cover well over the 25 years, although predicted cover is consistently less than remotely-sensed cover (Figure 6), and is well correlated (R^2 0.68 fitted line, Figure 7) to seasonal fractional total cover. GRASP predicted seasonal green cover is also well correlated (R^2 0.74 fitted line, Figure 7) to seasonal fractional green cover. There was no correlation (R^2 0.05 fitted line, Figure 7) between predicted cover and fractional dry cover with the disparity accentuated during the wetter years of late 1990s and 2000s (Figure 6).

Table 2. Predicted runoff (non-linear empirical runoff model JS equation), cover and 'best fit' criteria (Root square mean error RSME, Predicted:Observed, R^2 fitted line) for Open downs GRASP model (B condition, 25% utilisation of total standing dry matter, 0.5 mm/day soil evaporation) with maximum runoff from bare wet profile (p273) index values of 0.6, 0.7, 0.8 and 1.0 for the full ten year period (15/2/2002 to 2/6/2012) and last four + years (17/1/2008-2/6/2012). () indicates criteria values when 3 missing rainfall data are removed. Pearson's *r* of 0.65 (0.69 when 3 missing rainfall data were removed) were calculated for all predicted runoff simulations.

Data period	Maximum runoff from wet bare profile index (p273)	Rainfall mm	Max Rainfall mm/day	Average surface cover (%)	Runoff (predicted) mm	Runoff (observed) mm	Root square mean error RSME	Observed runoff % rainfall	Predicted runoff % rainfall	Predicted: Observed P:O	R^2 fitted line
Full period											
15/2/2002-2/6/2012	0.6	6025	155.4	56	322.4	372.5	8.72	6.18	5.35	0.87	41.9 (47.2)
15/2/2002-2/6/2012	0.7	6025	155.4	56	381.1	372.5	8.48	6.18	6.33	1.02	42.0 (47.4)
15/2/2002-2/6/2012	0.8	6025	155.4	56	442.7	372.5	8.39	6.18	7.35	1.19	42.1 (47.5)
15/2/2002-2/6/2012	1.0	6025	155.4	55	564.6	372.5	8.46	6.18	9.37	1.52	42.3 (47.7)
Last 4+ years											
17/1/2008-2/6/2012	0.6	3538	155.4	81	208.5	372.5	8.72	10.53	5.89	0.56	41.9 (47.2)
17/1/2008-2/6/2012	0.7	3538	155.4	81	246.6	372.5	8.48	10.53	6.97	0.66	42.0 (47.4)
17/1/2008-2/6/2012	0.8	3538	155.4	81	286.6	372.5	8.39	10.53	8.10	0.77	42.1 (47.5)
17/1/2008-2/6/2012	1.0	3538	155.4	80	364.9	372.5	8.46	10.53	10.31	0.98	42.3 (47.7)

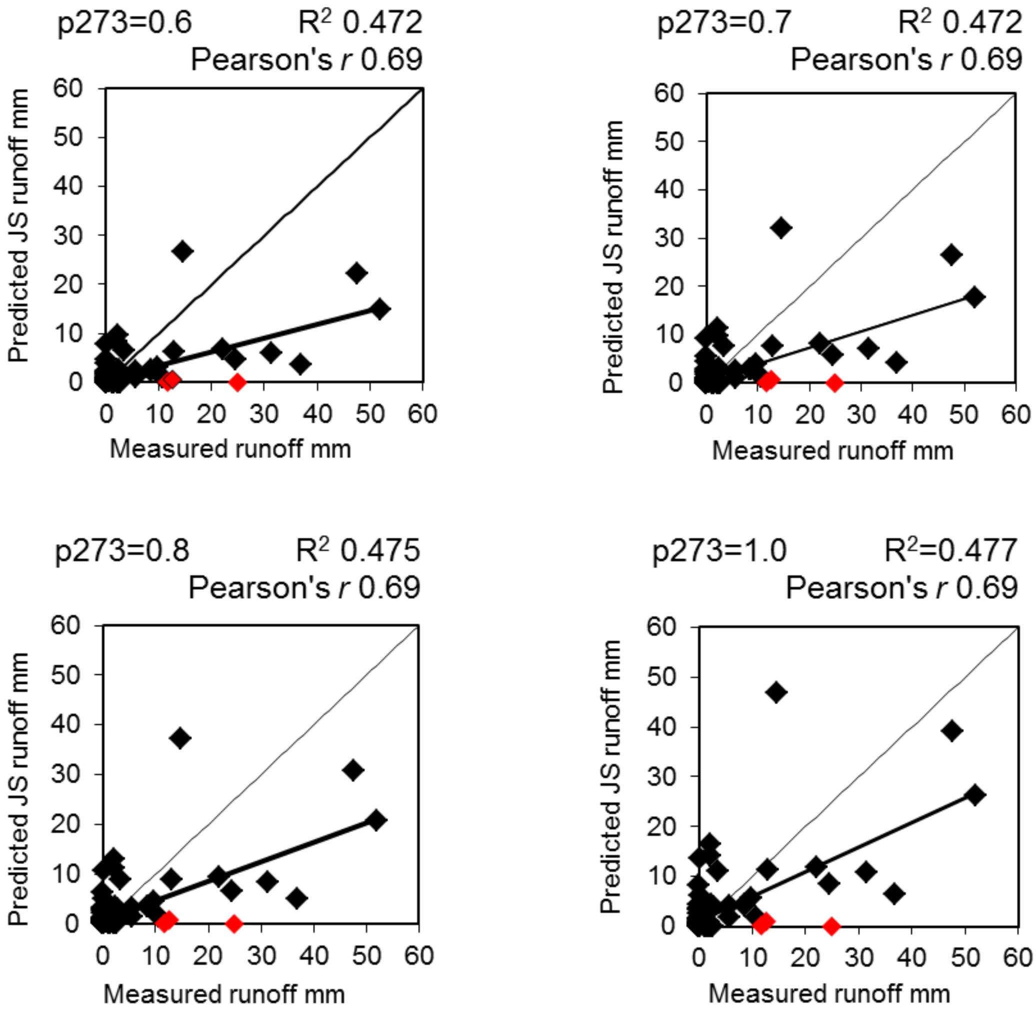

Figure 5. R squared of fitted linear line and Pearson's *r* for observed and predicted daily runoff (non-linear empirical runoff model JS equation) for Open downs GRASP model (B condition, 25% utilisation of total standing dry matter, 0.5 mm/day soil evaporation) with maximum runoff from bare wet profile (p273) index values of 0.6, 0.7, 0.8 and 1.0 for ten years (15/2/2002 to 2/6/2012). ◆ indicate the removed 3 'missing rainfall' data. 1:1 line is shown.

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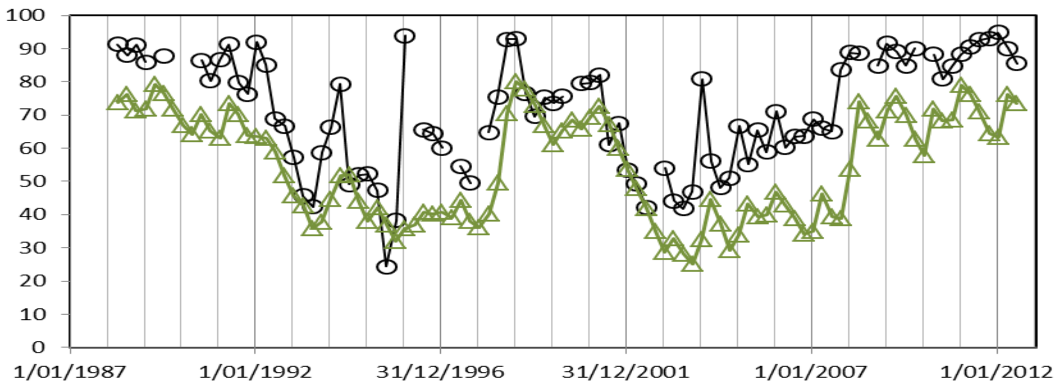

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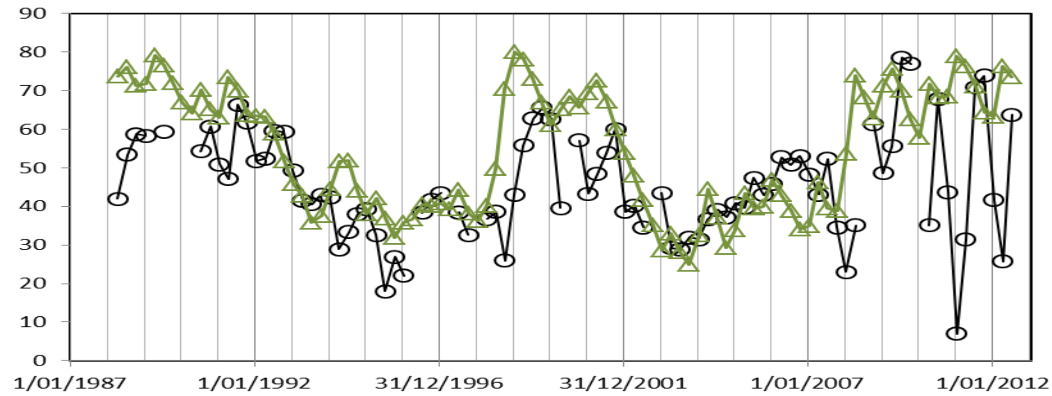

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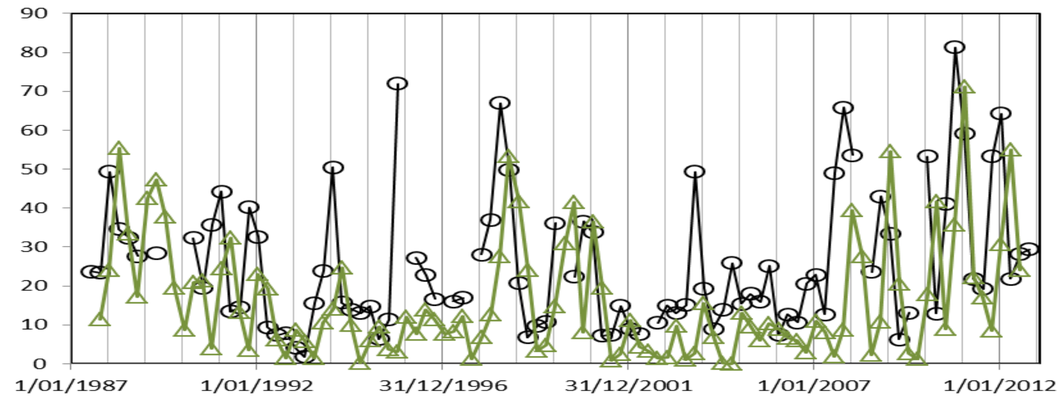

Figure 6. 1987-2012 time-series of remotely-sensed median seasonal fractional cover (—o—) and GRASP predicted average seasonal cover (—△—) for Open downs GRASP model (B condition, 25% utilisation of total standing dry matter, 0.5 mm/day soil evaporation, with maximum runoff from bare wet profile). a) Fractional and GRASP total cover, b) Fractional dry cover and GRASP total cover, c) Fractional and GRASP green cover. Each point is median (Fractional) or average (GRASP) for a season.

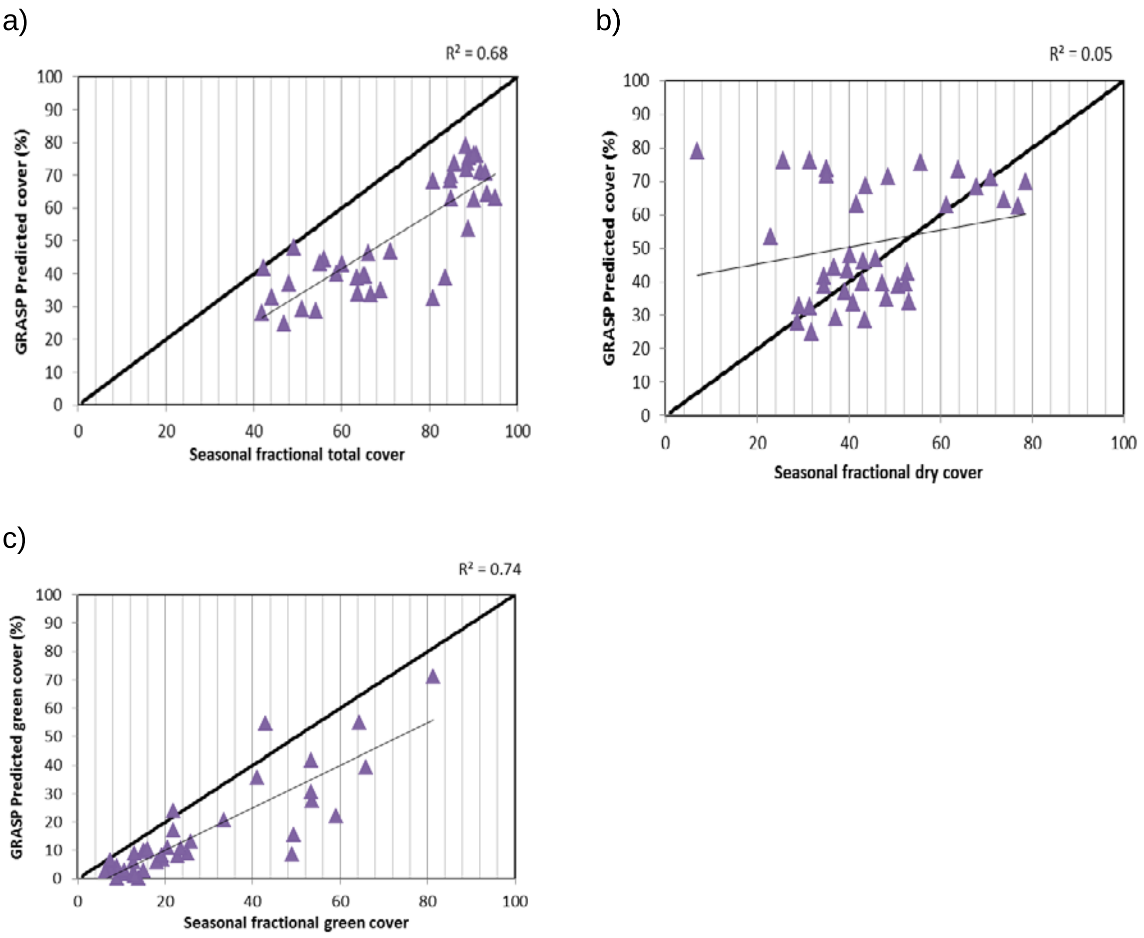

Figure 7. R squared of fitted linear line for remotely-sensed median seasonal fractional cover and GRASP predicted average cover for Open downs GRASP model (B condition, 25% utilisation of total standing dry matter, 0.5 mm/day soil evaporation) with maximum runoff from bare wet profile for ten years (15/2/2002 to 2/6/2012). a) Fractional and GRASP total cover, b) Fractional dry cover and GRASP total cover, c) Fractional and GRASP green cover. Each point is median (Fractional) or average (GRASP) for a season.

During the first six years of monitoring data (15/2/2002 to 17/1/2008) there was no measured runoff, however, predicted runoff was up to approximately 8% of total rainfall (2487 mm) (Figure 8) with an average predicted cover of 38%. Remotely-sensed average seasonal total cover (60%) was two-thirds more than that predicted by GRASP for these years (Table 3).

Table 3. Average remotely-sensed fractional and GRASP predicted green and total cover for the first six years (15/2/2002 to 17/1/2008) and last five years (17/1/2008 to 2/6/2012) of runoff data from Bowhunters site.

Monitoring Period	Remotely-sensed fractional data		GRASP predicted	
	Green cover	Total cover	Green cover	Total cover
15/2/2002 to 17/1/2008	20	60	7	38
17/1/2008 to 2/6/2012	36	89	25	70

GRASP predicted cover was more closely related to the seasonal average dry cover of 40% (see Table 1, Figure 6). For these years (15/2/2002 to 17/1/2008), average seasonal cover varied between 39-42% for dry cover and between 54-72% for total cover. For these first six years of monitoring, average fractional green cover for winter was 12% whilst GRASP predicted only 3% of green cover in winter. Green cover comprised a third of the remotely sensed total cover, whilst GRASP predicted green cover was only a fifth or sixth of total cover (Table 3). As the calibrated GRASP model was simulating the growth of C4 summer growing perennial pasture species, it is likely the disparity between GRASP predicted cover and remotely-sensed cover is due to the presence of winter growing herbage that was not simulated in the model but captured in the remote sensed data. Additionally, in the model 100% of green cover is killed by the occurrence of frost. As such, it is likely that GRASP predicted runoff during these years was greater than that measured at Bowhunters because the model was not simulating the contribution of winter herbage to total cover and soil moisture use.

Simulations were undertaken to determine whether increasing the level of grazing pressure during the 2002-2007 (to match the regional comparison data assessment, Figure 3) would provide better runoff predictions. As expected, increasing the grazing pressure during this period resulted in less cover and more runoff, and poorer runoff predictions; this may be a result of GRASP not simulating winter herbage production.

During the last five years of runoff data (17/1/2008-2/6/2012) cover was higher than the preceding years although the differences between remotely-sensed and GRASP predicted covers remained similar (Table 3). The higher cover levels during this period provided a much better correlation between predicted and measured runoff (Figure 8).

The predicted to observed ratio (0.98) and runoff as a percentage of rainfall (10.31) that most closely matched measured data was achieved when p273 = 1.0 (no reduction in maximum runoff, see Table 2). During these years annual average rainfall was 710 mm (compared to 415 mm/year for preceding period) and average cover was predicted to be 70%. The lowest RSME was achieved when p273 was set to 0.8.

Despite a decrease in annual rainfall from 2011 to 2012 and a predicted average cover of 70% for 2012, observed annual runoff was higher than that predicted for the first 6 months of 2012 (Figure 8).

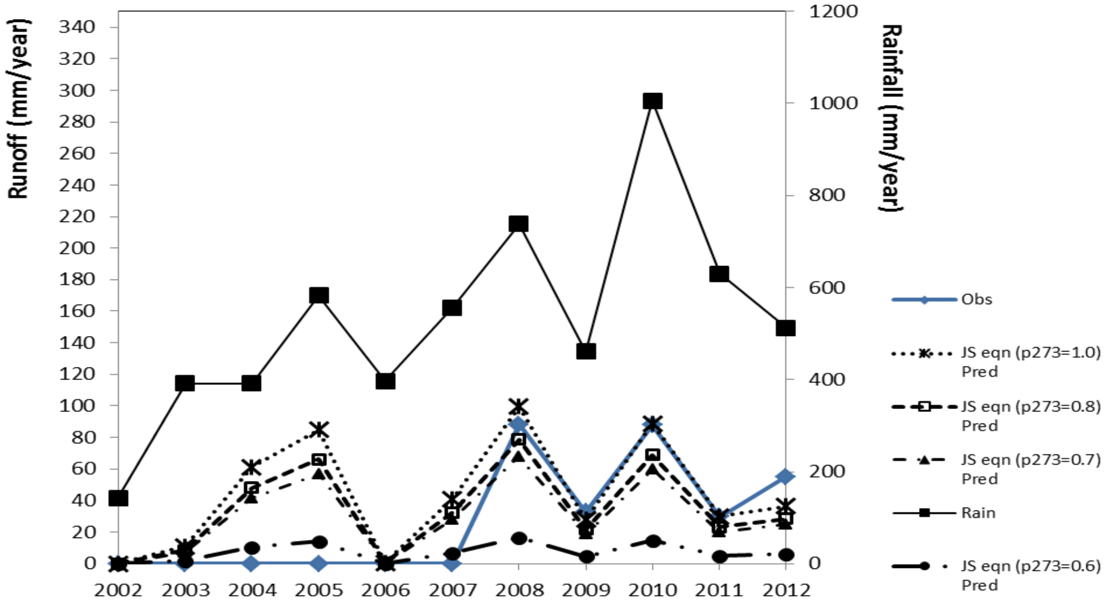

Figure 8. Annual rainfall, observed and predicted runoff (non-linear empirical runoff model JS equation) for Open downs GRASP model (B condition, 25% utilisation of total standing dry matter, 0.5 mm/day soil evaporation) with maximum runoff from bare wet profile (p273) index values of 0.6, 0.7, 0.8 and 1.0. NB. There was no observed runoff from 2002-2007 despite the monitoring equipment being in place and working.

Monitoring data from April to July 2012 recorded small quantities (<1-2mm) of runoff each day although there were only 2 significant rainfall events (approximately 30 mm) during this four month period. There was no predicted runoff during the same period. The possibility that the measured runoff included 'seepage' renders the comparison between daily event data meaningless and requires further investigation.

Annual GRASP predicted runoff was compared to annual measured runoff data from Bowhunters site (Figure 9). Predicted runoff using the non-linear empirical relationship (JS equation) was highly correlated (R^2 0.90 fitted line, Pearson's *r* 0.96) with measured runoff between 17/1/2008-2/6/2012. Predicted runoff with no reduction in maximum runoff (p273=1.0) provided the best fit around the 1:1 line, although between 0 – 85 mm/year of runoff was predicted in the preceding years when no runoff was measured (Figure 9d).

Evaluation of Curve Number model

The 'best fit' Open Downs parameters (B condition, lightly grazed 25% utilisation of TSDM, 0.5 mm/day soil evaporation from cracking clays) with the modified USDA Curve Number model was used to predict runoff. The Curve Number model does not use the maximum runoff from bare wet profile GRASP parameter used with the non-linear empirical relationship. The modified USDA model was calibrated to measured runoff with no effect of cover on runoff. A range of curve number values (97-0) were modelled to determine the curve number (p383, CN1) that provided the best prediction of runoff according to the aforementioned criteria – minimising RSME and to balance predicted total to measured total. Further modelling was then undertaken to include the dynamic effect of cover with differences in runoff being driven by the daily cover predicted by GRASP).

The optimal curve number for predicting runoff with the 'best fit' Open downs parameters was CN49 (p383) with 'no cover' effect. For the ten (15/2/2002 to 17/1/2008) and five-year (17/1/2008-2/6/2012) periods, CN49 predicted runoff to be 7.4% and 11.9% of rainfall respectively, with a predicted to observed ratio of 1.20 and 1.13 respectively, and RSME of 9.72 (Table 4). These measured criteria are less than those achieved using the non-linear empirical model (JS equation) with predicted runoff 6.2% and 10.5% of rainfall respectively, and a predicted to observed ratio of 1.02 and 0.98 respectively, and RSME of 8.46 (see Table 2) The R squared of the fitted line for CN49 with no cover effect predicted runoff for ten years of monitoring data was 52.4 and Pearson's *r* 0.72 (Table 4, Figure 10), a slightly better fit around the 1:1 line and correlation than achieved with JS equation (see Table 2, Figure 5). Inclusion of a cover effect (critical cover at 80% and 20%) in the USDA Curve Number model (CN1 = p383, CN2 = p322) resulted in over estimation of runoff for CN49 CN79 and CN49 CN89 (see Table 4 and Figure 10).

Curve numbers and runoff response vary in relation to total cover, with curve numbers lower with higher cover (Owens *et al.* 2003). The calibrated curve number 49 (CN_1) for Open downs at Bowhunters site corresponded to average cover of 47% for ten years (14/2/2002-2/6/2012) and 66% for five years of measured runoff (17/1/2008-2/6/2012). At Springvale, runoff prediction using a minimum curve number of 57 (for a total cover of 53%) produced the best fit to site data, with little difference in the runoff prediction between calibrated (no cover effect) and dynamic cover-runoff runs (Owens *et al.* 2003). However, at Bowhunters, the USDA modified curve number runoff predictions were poorer (runoff as % of rainfall, ratio of predicted to observed runoff, RSME) with a dynamic cover- runoff response (Table 4). The adjustment of daily curve number for cover that provided more accurate runoff predictions in low cover situations at Springvale requires further investigation for high cover experienced at Bowhunters.

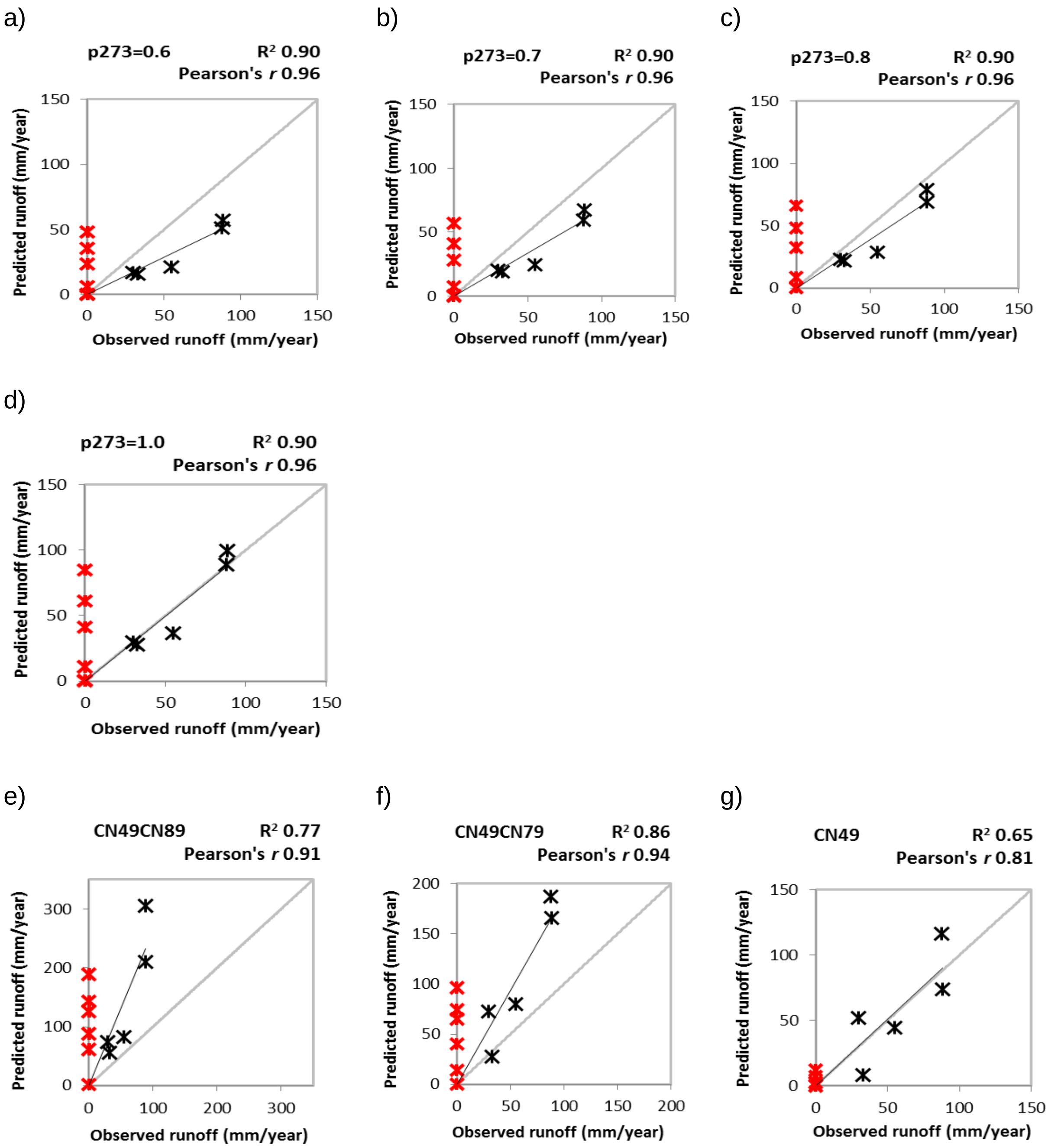

Figure 9. R squared of fitted linear line and Pearson's *r* for observed and predicted runoff for five years of monitoring data (17/1/2008-2/6/2012) for Open downs GRASP model (B condition, 25% utilisation of total standing dry matter, 0.5 mm/day soil evaporation). Predicted runoff using the non-linear empirical (JS equation) model with maximum runoff from bare wet profile (p273) index values of 0.6, 0.7, 0.8 and 1.0 (a-d), and using the modified USDA Curve Number model CN_1CN_2 (e-g). 1:1 line is shown. Predicted runoff for years with no measured runoff (*) are also shown but not include in analyses.

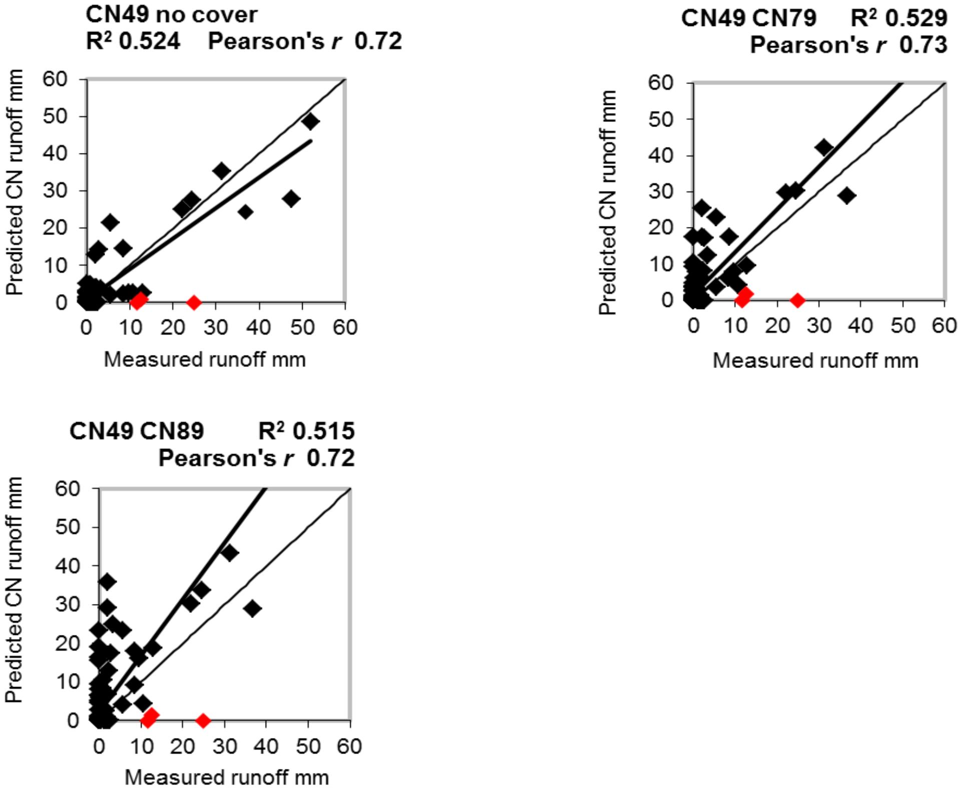

Figure 10. R squared of fitted linear line and Pearson's *r* for observed and predicted USDA Curve Number runoff for Open downs GRASP model (B condition, 25% utilisation of total standing dry matter, 0.5 mm/day soil evaporation) for ten years (15/2/2002 to 2/6/2012). ◆ indicate the removed 3 'missing rainfall' data. 1:1 line is shown.

During the first six years of monitoring data (15/2/2002 to 17/1/2008) there was no measured runoff despite monitoring equipment being in place and working; however, CN predicted runoff ranged from approximately 1% to 12% of total rainfall (2487 mm) (Figure 11). Using CN1=49 (p383) gave the best fit and lowest RSME for annual predicted to observed ratio (1.13) and runoff as a percentage of rainfall (11.9) (see Table 4), and the best fit around the 1:1 line (Figure 9g), although a better fit around the 1:1 line was achieved with JS equation p278=1.0 (Figure 9d). Curve number 49 with a dynamic cover- runoff response over-estimated runoff, however, annual predicted runoff was more strongly correlated (Figure 9f; R^2 0.86 fitted line, Pearson's *r* 0.94) to annual measured runoff data (17/1/2008-2/6/2012) than the calibrated curve number with no cover effect (Figure 9g; R^2 0.65 fitted line, Pearson's *r* 0.81).

Table 4. Predicted runoff with the modified USDA Curve Number model, cover and 'best fit' criteria (Root square mean error RSME, Predicted:Observed, R^2 fitted line, Person's *r*) for Open downs GRASP model (B condition, 25% utilisation of total standing dry matter, 0.5 mm/day soil evaporation) for the full ten year period (15/2/2002 to 2/6/2012) and the last 4+ years (17/1/2008-2/6/2012). () indicates criteria values when 3 missing rainfall data are removed.

Data period	Curve Number	Cover effect	Rainfall mm	Max Rainfall mm/day	Average surface cover (%)	Runoff (predicted) mm	Runoff (observed) mm	Root square mean error RSME	Observed runoff % rainfall	Predicted runoff % rainfall	Predicted: Observed P:O	R^2 fitted line	Pearson's *r*
Full period													
15/2/2002-2/6/2012	49	No	6025	155.4	47	445.7	372.5	9.72	6.18	7.40	1.20	52.4 (58.6)	0.72 (0.77)
15/2/2002-2/6/2012	49 79	80, 20	6025	155.4	39	997.1	372.5	12.26	6.18	16.55	2.68	52.9 (59.4)	0.73 (0.77)
15/2/2002-2/6/2012	49 89	80, 20	6025	155.4	35	1538.5	372.5	15.59	6.18	25.54	4.13	51.2 (58.1)	0.72 (0.76)
Last 4+ years													
17/1/2008-2/6/2012	49	No	3538	155.4	66	422.2	372.5	9.72	10.53	11.93	1.13	52.4 (58.6)	0.72 (0.77)
17/1/2008-2/6/2012	49 79	80, 20	3538	155.4	62	708.8	372.5	12.26	10.53	20.04	1.90	52.9 (59.4)	0.73 (0.77)
17/1/2008-2/6/2012	49 89	80, 20	3538	155.4	67	922.3	372.5	15.59	10.53	26.07	2.48	51.2 (58.1)	0.72 (0.76)

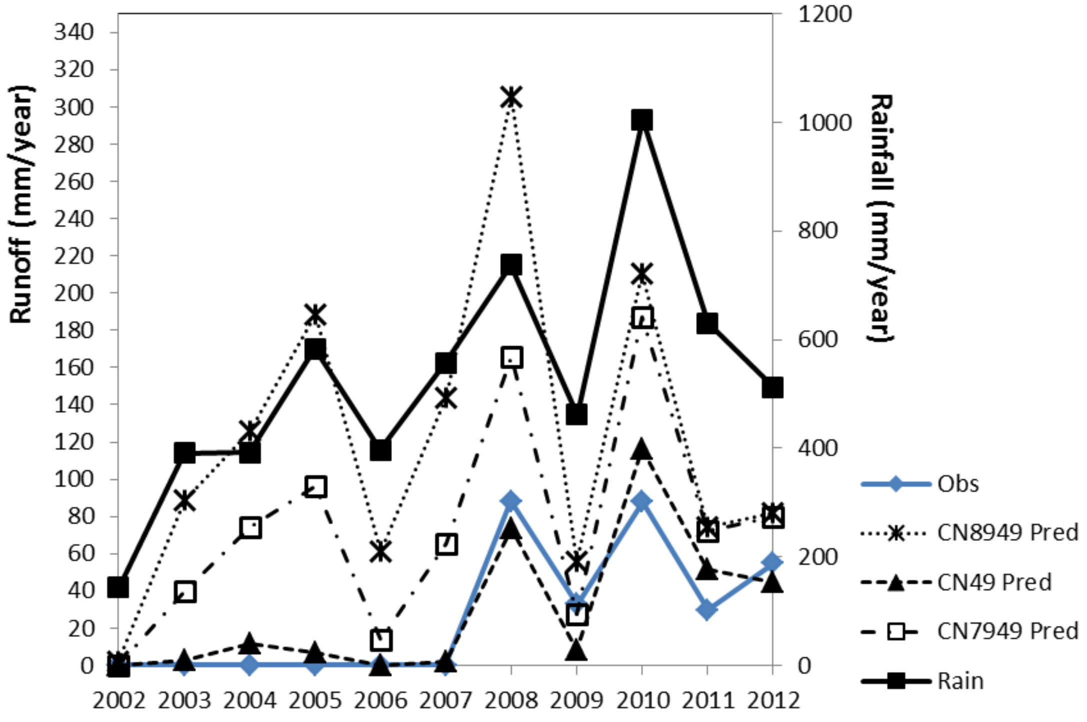

Figure 11. Annual rainfall, observed and predicted runoff (USDA modified Curve Number) for Open downs GRASP model (B condition, 25% utilisation of total standing dry matter, 0.5 mm/day soil evaporation).

Additional simulations were undertaken to determine optimal Curve Numbers for variants of the Open downs GRASP models where some sub-models were not used or some parameters were fixed for simulation runs. The soil evaporation from cracking clays parameter (p36) was fixed at three different values (0, 0.5, 1.0 mm/day), and Open downs model with minimal feedback from grazing (dynamic grass basal area, degradation and recovery sub-models switched off) were evaluated. The optimal curve number increased in value as less moisture was lost through soil cracks (Table 5), with CN55 for 0 mm/day of soil evaporation from cracks achieving the lowest RSME and sum of differences between observed and predicted, and highest R^2 of the fitted linear line. Curve numbers of CN55 CN75 have been reported for cultivated cracking clay pastures (see Owens *et al.* 2003) that could correspond to the lightly grazed, high cover bluegrass pastures on cracking clay soils at Bowhunters.

Table 5. Optimal (Root square mean error RSME, sum of differences between observed and predicted runoff ∑(x-y), and R^2 fitted line) curve numbers for variate Open downs GRASP models with minimal feedback from grazing (dynamic grass basal area and degradation and recovery sub-models off) and 3 levels of soil evaporation from cracking clays (0,0.5,1.0 mm/day).

Dynamic grass basal area, Degradation and recovery sub-models	Soil evaporation from cracking clays mm/day	CN1	CN2	Root square mean error RSME	∑(x-y)	R^2 fitted line
Off	1	49	49	11.98	-1.07	43
Off	1	49	69	13.30	-44.34	43
Off	0.5	53	53	10.42	1.2	50
Off	0.5	53	73	10.82	-14.15	49
Off	0	55	55	10.13	-0.31	53
Off	0	55	75	10.31	-4.89	52

Management and runoff relationships

The implications of changing grazing land management for catchment hydrology were simulated using the 'best fit' open downs parameters identified in calibration and evaluation of Bowhunters monitoring runoff data. The 'best fit' Open downs GRASP parameters (0.5 mm/day soil evaporation from cracking clays, maximum runoff from bare wet profile index of 1, moderate B pasture condition) were simulated using non-linear empirical (JS equation) and modified USDA Curve Number runoff models with fixed stocking rates that ranged from 0.5 to 50 head/100 over 50 years (1963-2012).

The impacts of heavy fixed stocking SR (50hd/100ha) for 50 years resulted in an average annual surface cover index of 0.1 and 160 mm of runoff using the non-linear empirical runoff model (Figure 12a), and 140 mm with Curve number and dynamic cover effect (Figure 12c). The high predicted (JS equation and Curve Number) runoff with low cover (approximately 27% and 24% of rainfall respectively) was within range of measured runoff from hillslopes with low cover by Silburn *et al.* 2011. At the other extreme, very light grazing (0.5 head/100ha) resulted in high annual cover (0.8) and minimal annual runoff (10 mm) using JS equation (Figure 12a), and 58 mm of runoff predicted with curve number with dynamic cover response (Figure 12c). As expected, curve number 49 with no effect of cover resulted in a dampened runoff response-cover curve with runoff ranging between 40-60 mm for the surface cover extremes (Figure 12b). Antecedent soil water is the main driver of runoff for the curve number approach and without the influence of cover on runoff (CN49, Figure 12b) results in more predicted runoff (≈ 50-54 mm) when transpiration was high (low stocking rates, high pasture cover) than when there was little pasture cover and less transpiration (≈ 44-48 mm).

Linear trendlines were fitted to the derived JS equation and CN with dynamic cover runoff-cover response curves shown in Figure 12a and 12c. Using these fitted linear equations, runoff, and the difference between runoff for JS equation and Curve Number models, was calculated for a range of surface cover indices (0.1 to 0.8) (Table 6).

Table 6. Fitted linear relationships used to calculate runoff for range of surface cover indices, and the difference between predicted runoff, for non-linear empirical (JS equation) and modified USDA curve number Open downs models for Bowhunters site. Fitted linear trendline and R^2 of fitted line are shown.

Surface cover index	Non-linear empirical model (JS equation) trendline for runoff cover response curve $y = -226.53x + 184.54$ R^2 0.9992	Curve number with dynamic cover model trendline for runoff cover response curve $y = -123.47x + 149.72$ R^2 0.9939	Difference between predicted runoff for JS equation and Curve Number models
0.1	161.89	137.37	24.51
0.15	150.56	131.20	19.36
0.2	139.23	125.03	14.21
0.25	127.91	118.85	9.06
0.3	116.581	112.68	3.90
0.35	105.26	106.50	-1.25
0.4	93.93	100.33	-6.40
0.45	82.60	94.16	-11.56
0.5	71.28	87.99	-16.71
0.55	59.95	81.81	-21.86
0.6	48.62	75.64	-27.02
0.65	37.30	69.46	-32.17
0.7	25.97	63.29	-37.32
0.75	14.64	57.12	-42.48
0.8	3.32	50.94	-47.63
0.85		44.77	-52.78
0.9		38.60	-57.93

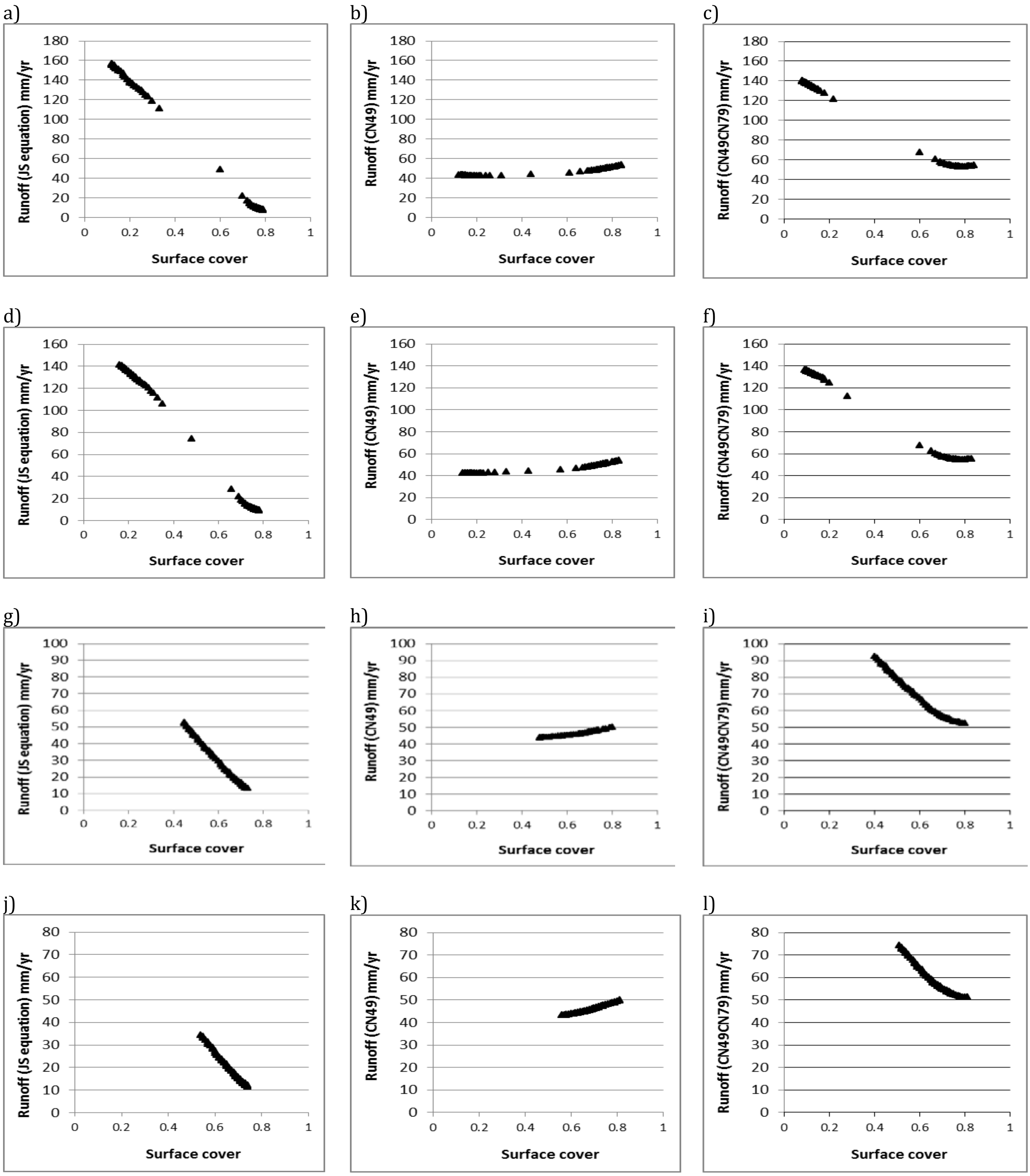

Figure 12. Runoff-cover response curves for Open downs GRASP model (B condition, 0.5 mm/day soil evaporation) using non-linear empirical (JS equation) and modified USDA Curve Number runoff models for a range of fixed stocking rates (0.5-50 head/100ha) over the last 50 years (1963-2012) at Bowhunters site. Response-curves using 'degradation and recovery' and monthly dynamic grass basal area sub-routines (a-c); 'degradation and recovery' and annual dynamic grass basal area sub-routines (d-f); no 'degradation and recovery' and annual dynamic grass basal area sub-routine (g-i); and constant grass basal area with no 'degradation and recovery' sub-routine (j-l).

The slope of the fitted linear trendline (-226) for JS equation model was approximately double that of the curve number with dynamic cover (-123) with the greatest divergence in predicted runoff occurring with low stocking rates and high cover (Table 6). At low surface cover (0.1), JS equation predicted runoff was approximately 15% greater than that predicted with Curve Number, but with high cover (0.8) predicted runoff using JS equation was 1/15 of the runoff using the Curve Number model (Table 6).

The calibrated GRASP Open downs models included two sub-routines that capture the processes of (1) pasture degradation (high grazing pressure reduces grass basal area, reduces potential pasture growth and surface cover, with subsequent increases in runoff and soil loss) and (2) the known biological response to grazing during the growing season (see Whish 2012 for details). The runoff-cover response curves derived using the less dynamic sub-routines were dampened as fewer impacts of heavy grazing were simulated (Figure 12). When the impacts of heavy grazing (50hd/100ha) are the same throughout the year (annual dynamic grass basal area), simulations using the non-linear empirical model predicted slightly higher surface cover (0.16 *cf*. 0.12 respectively) and slightly lower runoff (141 *cf*. 157 mm respectively) than when the more dynamic monthly grass basal area sub-routine was simulated. The removal of the more dynamic grass basal area sub-routine only marginally changed curve number predicted runoff (Figure 12f).

Simulations with models where grazing pressure has little impact on pasture growth (annual dynamic grass basal area, annual constant grass basal area) resulted in a constrained surface cover (0.4-0.8) and runoff (range of 30-40 mm), with JS equation predicted runoff approximately 40 mm less than runoff with curve number (Figure 12 gi-l). The narrowest range, and least amount, of runoff was predicted when only a constant grass basal area sub-routine was simulated (Figure 12 i-l).

Predicted (JS equation and Curve Number models) and measured runoff at Bowhunters was highly correlated (see Figure 9) during the wetter (annual rainfall 710 mm for 2008 to 2012 *cf*. 415 mm for 2002 to 2008) years when surface cover (average 70% *cf*. 37%) was high. However, both models predicted runoff during the first six years of monitoring data (2002-2008) when there was no measured runoff. The best-fit Open downs parameters included both the ‘degradation and recovery’ and ‘monthly dynamic grass basal area’ sub-routines that dynamically capture the impacts of grazing and resulted in the largest range of surface cover and runoff. Pasture productivity, surface cover and runoff are more variable during dry seasons and/or when grazing pressure is high. Calibration of the model with measured data during dry years and/or when pastures are heavily grazed should enable further evaluation of the performance of these sub-routines and GRASP runoff parameters.

Conclusion

Monitoring runoff data from Bowhunters site in the Gordonstone catchment near Capella, provided an opportunity to calibrate GRASP runoff parameters, and to evaluate the non-linear empirical (JS equation) and modified USDA curve number runoff sub-models for grazed bluegrass pastures on cracking clays. The optimal combination of runoff parameters for the Open downs GRASP model for Bowhunters site included 25% utilisation of total standing dry matter, moderate pasture condition (B), 0.5 mm/day of soil evaporation from cracking clays, and capture of the impacts of grazing using the modified ‘degradation and recovery’ and monthly grass basal area sub-routines.

Runoff prediction using the non-linear empirical sub-model (JS equation) when there was maximum runoff from bare wet profile was very good (R^2 0.90, Pearson’s *r* 0.96, good fit around 1:1 line) during years when both annual rainfall and surface cover were high. However, with the inclusion of five years of low annual rainfall and surface cover, and when there was apparently no runoff whatsoever, predicted runoff (JS equation) needed to be reduced by 30% to achieve a good prediction of total runoff (P:O 1.02) but only a fair correlation of runoff events (R^2 0.47). The fair to very good runoff predictions using the non-linear empirical sub-model indicate that the cracking clay soils (Vertosols) in Fitzroy basin had similar runoff responses to duplex soils (Chromosols) in the Burdekin where the runoff model was derived.

The calibrated Curve Number (CN49) model, where there was no effect of cover, resulted in a better prediction of runoff events (closer fit to 1:1 line) and total runoff (P:O 1.20 cf. P:O 1.52 JS equation with p273=1.0) than the non-linear empirical runoff equation for the tem years of monitoring data. However, runoff prediction was poorer (P:O 1.13) than the non-linear empirical sub-model (JS equation P:O 0.98, closer fit around 1:1 line) during years when both annual rainfall and surface cover were high. Inclusion of a cover effect (critical cover at 80% and 20%) in the USDA Curve Number model (CN49 CN79) resulted in over-estimation of runoff greater than that predicted with the JS equation.

Predicted (JS equation) cover was well correlated to the remotely-sensed seasonal fractional cover (R^2 0.68-0.74). Evaluation of the data indicates that disparities in remotely-sensed and GRASP predicted cover levels is due to winter herbage, intertussock forbs, and annual growth which were not simulated in the calibrated Open downs GRASP model. The over-estimation of runoff by GRASP model during the early years of monitoring is most likely due in part to an under-estimation of cover and soil moisture use due to the exclusion of winter herbage.

In modelling for the Paddock to Reef Program, runoff from the bare, but rough surface of Black basalt cracking clay soils (Vertosols) was modelled to be only a third of that for all other land types. At Bowhunters, predicted runoff was highly correlated to measured runoff when there was maximum runoff from bare wet profile, indicating that the runoff-cover relationship for cracking clay soils is the same as for all other soils. Until future evaluation suggests otherwise, it is recommended when using the non-linear empirical runoff sub-model that there be no adjustment of maximum runoff from bare, wet profile for cracking clays.

An important aim of Paddock to Reef program was to identify grazing management practices that provide the most effective control of water quality. Level of cover is a major driver of hillslope runoff and catchment water quality of grazing lands, and achieving a minimum of 50% late dry season groundcover is an important target to improve water quality in the Great Barrier Reef. Runoff from cracking clay soils with high surface cover (> 0.60) can be well predicted using both the non-linear empirical and Curve Number runoff sub-models. At Bowhunters, whilst runoff was over-estimated during the drier years when surface cover was moderately low (0.40), predicted runoff at very low cover (0.1) was lower but within range of reported data from other sites in central Queensland. Predicted runoff from cover levels below the Reef Plan target of 50% appear reasonable, and can help identify grazing management practices to achieve Reef Plan water quality targets. Further calibration of the model with measured data collected during dry years and/or when pastures are heavily grazed (where available) would provide confidence to the predictions of runoff at low cover.

Finally, the evaluation of the two runoff models using monitoring data from Bowhunter's site suggests the non-linear empirical approach will perform well in most situations, especially high cover. The best runoff predictions using the curve number approach were only achieved with the calibrated model with no cover effect.

Acknowledgements

The research presented in this report was undertaken as part of the Paddock to Reef Integrated Monitoring, Modelling and Reporting program and was funded by the Australian Government through the Caring for Our Country initiative. I would like to thank Rebecca Trevithick and Dan Tindall of DSITIA for the provision of remotely-sensed data. Also thanks to the DNRM team (Deb Rogusz, Peter Burger, Tim Murphy, Cam Dougall) for collecting and providing the Bowhunters rainfall and runoff data, and informative site descriptions. Finally, I would like to thank Mark Silburn, Grant Fraser, Chris Stokes, Joe Scanlan and Cam Dougall for their advice, comments and review of this report.

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