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A two-step up-scaling method for mapping runoff and sediment production from pasture and woody encroachment on semi-arid hillslopes

Carlos Muñoz-Robles,[1,5]* Matthew Tighe,[1] Nick Reid,[1] Paul Frazier,[2] Sue V. Briggs[3] and Brian Wilson[4]

[1] *Ecosystem Management, School of Environmental and Rural Science, University of New England, Armidale NSW 2351, Australia*
[2] *Eco Logical Australia, 92 Taylor Street, PO Box 1927, Armidale NSW 2350, Australia*
[3] *Institute of Applied Ecology, University of Canberra, Canberra ACT 2601, Australia*
[4] *NSW Office of Environment and Heritage, PO Box U221, Armidale NSW 2351, Australia*
[5] *Instituto de Ecología, A. C. Carretera Antigua a Coatepec 351, El Haya, Xalapa 91070, Veracruz, México*

ABSTRACT

Management of woody encroachment and pasture to reduce runoff and sediment production is important in semi-arid areas. However, the study of relationships between vegetation and surface hydrology at hillslope scale is difficult because of cost and time constraints. Up-scaling eco-hydrological responses measured at fine scale can overcome these constraints and provide insights into runoff and erosion at scales relevant to management. In this study, runoff and sediment production were modelled on two adjacent hillslopes, one with woody encroachment (3500 stems ha^{-1}) and the other a volunteer pasture cultivated to oats 18 months previously. Spatial modelling was undertaken to integrate small-plot (1 m^2) rainfall simulation, slope and the spatial distribution of ground cover. The estimates of runoff and sediment production in the woody hillslope were considerably lower than in the pasture hillslope in both years of the study. Runoff and sediment production in the woody hillslope were similar in consecutive years, whereas the estimates of runoff and sediment production in the pasture hillslope were lower in the second year as a result of the establishment of a water spreading system of contour banks. The results showed the importance of measuring patchiness and connectivity of runoff source areas for runoff and sediment production. The spatial modelling approach allowed a description of fine-scale, surface eco-hydrological interactions on hillslopes, based on high resolution spatial data and experimental fine-scale rainfall simulations. A similar modelling approach could be used to explore runoff and sediment production resulting from varying management of semi-arid lands.

KEY WORDS contour banks; flow length; ground cover; hydrological connectivity; inter-patch; patchiness; Quickbird; resource retention; water spreading

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INTRODUCTION

Management of areas of woody plant encroachment and pasture is important to optimize their hydrological functionality and reduce runoff and sediment production. The primary mechanism of runoff generation in semi-arid landscapes is infiltration excess runoff (Selby, 1993) or Hortonian overland flow, which occurs when rainfall intensity exceeds infiltration rate (Horton, 1933). Flows of infiltration excess runoff are largely controlled by variations in the spatial arrangement and roughness of soil surface features (Mueller *et al.*, 2007). Woody vegetation and ground cover of herbage, litter, cryptogam and rocks greatly influence soil surface features, their spatial arrangement and resulting infiltration (Greene *et al.*, 2001; Michaelides *et al.*, 2009).

Semi-arid landscapes are characterized by a heterogeneous distribution of vegetation and ground cover, spatially organized as mosaics of vegetated patches interspersed with relatively bare areas or inter-patches (Montaña *et al.*, 2001). This configuration of patches and inter-patches influences the partitioning of incident rainfall into infiltration and runoff, and the related process of sediment production (Puigdefábregas, 2005; Bartley *et al.*, 2006). Because inter-patches generally have low infiltration rates because of surface crusting and low surface cover, they act as source zones of runoff and sediment. Vegetated patches typically have higher infiltration rates, lower bulk density and greater aggregate stability and porosity than inter-patches, and can obstruct surface flow, thus serving as sinks for the capture of runoff, sediments and nutrients from source areas (Ludwig and Tongway, 1995; Greene *et al.*, 2001). Ground cover is a surrogate for resource retention that enhances ecosystem productivity and functioning (Sala and Aguiar, 1995; Ludwig *et al.*, 2005) and can be used as an indicator of runoff processes (Cammeraat, 2004).

The ability to integrate the hydrological interactions of patches and inter-patches to reflect the redistribution of water at broad scales is an important foundation for predicting and managing resource retention in semi-arid

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*Correspondence to: C. Muñoz-Robles, Instituto de Ecología, A. C. Carretera Antigua a Coatepec 351, El Haya, Xalapa 91070, Veracruz, México.
E-mail: carlos.munoz@inecol.edu.mx; cmunoz.robles@gmail.com

systems (Puigdefábregas and Sanchez, 1996; Ludwig *et al.*, 2002). However, up-scaling hydrological and erosional responses measured at the fine patch scale (i.e. ~1 m^2) has received little attention in hydrological studies (Beeson *et al.*, 2001). The spatial heterogeneity of hydrological processes in semi-arid areas, influenced by the spatial distribution and size of patches as well as the length and the connectivity of runoff source areas, makes extrapolation from fine to broader scales difficult (Cammeraat, 2004; Maneta *et al.*, 2008). Hydrological connectivity, in particular, strongly influences runoff and erosion processes (Lesschen *et al.*, 2009; Michaelides and Chappell, 2009) but traditionally has been difficult to quantify.

A solution to this up-scaling issue is to integrate fine-scale responses and their spatial variability using surface conditions such as woody vegetation and ground cover and elevation data to simulate resource redistribution and ecosystem function at hillslope or small catchment scale (Ludwig *et al.*, 2004). Previous attempts to describe resource redistribution include those developed by Ludwig *et al.* (1999), who simulated resource retention in response to different patch/inter-patch distributions. Ludwig *et al.* (2007a) described a landscape leakiness index for monitoring changes in landscapes in response to real patch/inter-patch distributions, but their index did not estimate amounts of runoff and sediment production from hillslopes that could be provided via simulation modelling (e.g. Boer and Puigdefábregas, 2005). Spatial data can be integrated to represent the distribution of sinks and sources for runoff and erosion down hillslopes or small catchments to simulate the eco-hydrological processes that generate fluxes of water and sediment (Sidle, 2006; Maneta *et al.*, 2008).

High resolution remote sensing provides a means to characterize landscape spatial patterns, including woody vegetation and ground cover. Quickbird imagery provides high spatial resolution data (0.6 and 2.4 m in panchromatic and multispectral modes, respectively) and can be used to characterize landscape patterns at scales relevant to rangeland management (i.e. hillslope and paddock scales) (Ludwig *et al.*, 2007b; Xie *et al.*, 2008).

The hydrological and erosional responses of woody encroachment and pasture that establishes after removal of woody encroachment in semi-arid New South Wales have been investigated in several related studies (Muñoz-Robles *et al.*, 2011b,c), using fine-scale rainfall simulation. In one study, Muñoz-Robles *et al.* (2011a) used high resolution imagery (fused Quickbird data) to map ground cover, which is one of the inputs required to model runoff and sediment fluxes among areas of different ground cover (i.e. patches and inter-patches) in a spatially explicit way. The modelling described in the present paper used the high resolution images from two consecutive years of adjacent hillslopes, one an area of woody encroachment (hereafter referred to as the woody hillslope) and the other a volunteer pasture of native and naturalized species (hereafter referred to as the pasture hillslope). The pasture had a water-spreading system of contour banks installed in the second year, designed to slow down and spread runoff laterally, allowing water to pass through outlets in the banks and move in a stepwise fashion downslope. This system was designed to disrupt hydrological connectivity and increase ground cover (Thompson, 2008).

Our overall aim was to scale up the estimation of runoff and sediment production from fine-scale rainfall simulation plots to hillslopes to obtain a broader perspective of eco-hydrological responses. The specific objectives were to (1) develop and implement a spatially explicit, two-step, runoff and sediment production model, and (2) critique its application to two hillslopes with different amounts and distributions of ground cover and hence different eco-hydrological function. One hillslope was affected by woody encroachment and the other by pasture development.

METHODS

Study area

The two adjacent hillslopes in the central-eastern Cobar pediplain, New South Wales, Australia (Figure 1), had similar biophysical properties but different vegetation states (woody encroachment vs pasture). Slope was 1.1%

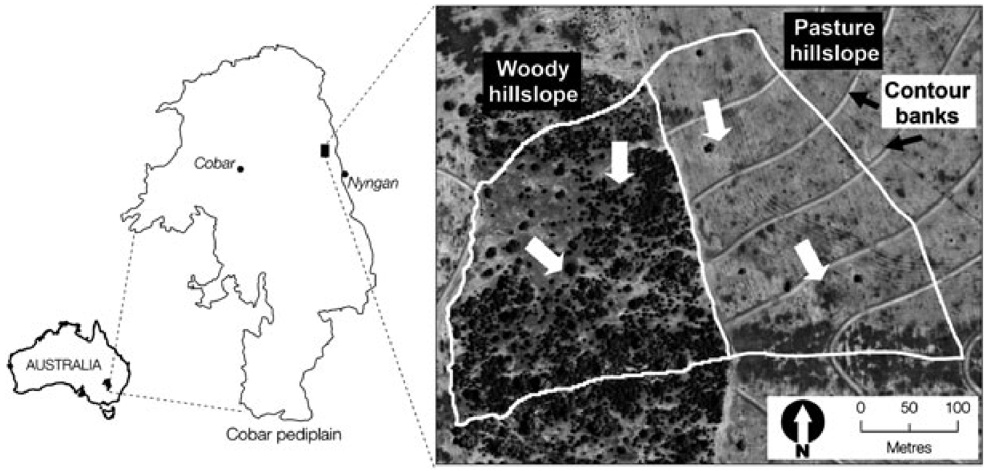


Figure 1. Location of the study site on the Cobar pediplain, NSW, Australia. Water spreading contour banks are evident in the pasture hillslope. White arrows indicate general slope direction.

and 1.3% in the woody and pasture hillslopes, respectively. The woody hillslope was dominated by *Callitris glaucophylla* and *Eremophila mitchellii* (3500 stems ha^{-1}). The pasture hillslope had been developed by clearing the woody vegetation 23 years previously and had been cultivated and sown to oats 1.5 years prior to field data collection in October 2008. The vegetation consisted of volunteer native and naturalized pasture species, and some volunteer oats. A water spreading system was established in August 2009 in the pasture hillslope.

Each hillslope was approximately 6.5 ha, at an elevation of 185 m above sea level, on a gently sloping (1%–3%), undulating area of Quaternary colluvium (Fleming and Zhang, 1999). The soil type at the site was a red Kandosol in the Australian soil classification system (Isbell, 1996) with surface topsoil soil texture (0–2 cm) varying from sandy clay loam to sandy loam. The woody hillslope was located partially (25% of its boundary) above the pasture hillslope so that some water ran off the woody hillslope along the bottom of the pasture hillslope. Grazing was excluded from both hillslopes after the establishment of the water spreading system. Rainfall at the study site is highly variable within and between years but, on average, is uniformly distributed throughout the year with an annual mean of 441 mm. Rainfall was 333 mm in 2008 and 395 mm in 2009. Minimum (July) and maximum (January) temperatures are 4 °C and 34 °C, respectively, at Nyngan, 40 km south-east of the study site (Bureau of Meteorology: Australian Government, 2008).

Data input

Imagery and ground cover. We used two sets of Quickbird data in this study: the first set was captured on 28 September 2008 and the second on 17 December 2009, before and after the establishment of the water spreading system, respectively. Very high resolution fused Quickbird images for each date were used to produce ground cover maps of both hillslopes (Muñoz-Robles *et al.*, 2011a). Pertinent details of the high resolution mapping of ground cover, previously described in the study conducted by Muñoz-Robles *et al.* (2011a), included the following: (1) only herbaceous and litter cover were considered as ground cover, as they form patches that obstruct, slow or trap runoff, and are important for resource retention at hillslope scale (Ludwig *et al.*, 2002; Tongway and Hindley, 2004; Ludwig *et al.*, 2005); (2) canopies of shrubs and trees on the woody hillslope obstructed the spectral responses of ground cover beneath them, thus canopy cover was used as a surrogate for ground cover under the tree and shrub canopies in this hillslope; and (3) the resulting ground cover maps, with a spatial resolution of 1 m, had average prediction errors (root mean square errors) of 16.1% and 14.1% in the woody and pasture hillslopes, respectively. The spatial resolution for all variables used in the modelling of runoff and sediment production was set to 1 -m^2 cells in order to match the fine scale of the rainfall simulation plots.

Digital elevation data. A contour map of the site produced by the Central West Catchment Management Authority, New South Wales, for the development of the water spreading system, was used in this study. The contour lines were digitized and interpolated to generate a digital elevation model (DEM) with a spatial resolution of 1 m using the function TOPOGRID in ARC/INFO 9.3 (ESRI, 2008). Standard DEM pre-processing procedures to minimize artefacts resulting from interpolation (infill of depressions and pit removal) were undertaken in TAUDEM 4.0 (Tarboton, 2008) to obtain a hydrologically corrected DEM.

Rainfall simulations. Fifty-five rainfall simulations (28 and 27 in the woody and pasture hillslopes, respectively) were undertaken in October 2009 to characterize rates of average runoff and final infiltration, initial abstractions (the amount of accumulated rainfall from the start of the rainfall simulation until runoff initiation) and sediment concentrations across the range in ground cover (0%–100% of herbaceous and litter cover) in the hillslopes. A Morin-type rotating-disc rainfall simulator (Morin and Cluff, 1980) was used. Rainfall was applied to 1 × 1 -m plots for 30 min at an average rainfall intensity of 34 mm h^{-1}, which resembled natural rain events with a 2-year return period in the region (NSW. Bureau of Meteorology: Australian Government, 2008). The rainfall simulation procedure followed the approach detailed in the study conducted by Muñoz-Robles *et al.*, 2011c). Average antecedent soil surface moisture (0–5 cm) was 4% w/w, determined on oven-dried (48 h at 105 °C) samples taken adjacent to each rainfall simulation plot.

Data analysis and spatial implementation

Spatial distribution of hydrological responses. Average runoff, final infiltration and initial abstraction were regressed on the amount of ground cover in each rainfall simulation plot. Log or square-root transformations of predictor or response variables were undertaken as required to meet normality assumptions. Analyses were undertaken in R version 2.9.0 (R Development Core Team, 2009). The regression models were run in ARC/INFO 9.3 (ESRI, 2008) to generate continuous grid maps of hydrological responses predicted from the 2008 and 2009 ground cover maps. All regressions were significant at the $P < 0.05$ level.

Modelling accumulated runoff and sediment production. Infiltration excess runoff was modelled for 2008 and 2009 using a two-step modelling approach, which consisted, first, of establishing the spatial distribution of hydrological responses in 1-m^2 cells (described in the previous section) and, second, modelling the transfer of runoff among cells (Figure 2). For modelling purposes, the two hillslopes were considered to be hydrologically unconnected (see site description section), as the main purpose of the modelling was to describe hydrological and erosional interactions within each hillslope and vegetation state. A simulated rainfall event with an intensity of 34 mm h^{-1} and duration of 30 min was the input at the start of the model runs.

Infiltration excess runoff was estimated for each cell from the applied rainfall, initial abstraction and final infiltration rate (explanations of each provided in Figure 2).

Initial abstraction accounted for processes that reduce runoff at the first stage of a rainfall event (interception by plants and litter, depression storage and initial infiltration). Final infiltration rate measured using rainfall simulation was assumed to be the saturated hydraulic conductivity value (Hillel, 2008) (examination of runoff hydrographs indicated that 90% of the rainfall simulations achieved steady state infiltration). In the first part of the modelling, infiltration excess runoff was estimated for each 1-m^2 cell without considering movement of the runoff downslope.

Runoff transfer among cells was modelled as a retention-limited accumulation function (Tarboton and Baker, 2009), which used a recursive algorithm for accumulating flow in any cell depending upon the accumulated flow of adjacent upslope cells and the infiltration capacity (final infiltration rates measured from rainfall simulation) of the cell. The retention-limited accumulation function used multiple flow directions derived from the DEM with the D-infinity (D∞) algorithm (Tarboton, 1997). To route flow, the D∞ algorithm partitioned flow based on the slope gradient between downslope neighbouring cells. Therefore, infiltration excess runoff at any cell was the sum of flow generated from that cell and flow from all contributing neighbouring cells, each weighted according to the proportion of flow the cell contributed, providing that the infiltration capacity was exceeded at each cell.

Two model runs were performed for the pasture hillslope in 2009. The first run included the effect of ground cover distribution, slope direction and contour banks, whereas the second excluded the physical effect of the contour banks on runoff. For the first run, the DEM was re-adjusted for bank height (0.6 m) and the width (2.0 m) and length (5.0 m) of the outlets along the contour banks. Accumulated runoff at each cell was multiplied by the average sediment concentration measured in rainfall simulation plots (3.05 g l^{-1}; data not shown) to obtain an estimate of sediment production (Little *et al.*, 2005; Roth *et al.*, 2003; Haan *et al.*, 2006). Sediment production provided an approximation of the total sediment loss based on the suspended sediment being routed together with the flow. Mean and maximum values of accumulated runoff and sediment production were computed for each hillslope and model run on a cell-by-cell basis. The resulting maps focus on the predicted eco-hydrological response within each hillslope rather than on resource export from either hillslope.

Patch metrics and hydrological connectivity. To assess spatial heterogeneity of ground cover, three categories of ground cover (<30%, 30%–65% and >65%) were mapped, representing low, medium and high ground cover levels, respectively (Muñoz-Robles *et al.*, 2011a). The areal proportion and patch density (patch metrics) of each ground cover category were calculated using FRAGSTATS 5.5 (McGarigal, 2008), a computer program that evaluates landscape metrics using categorical maps.

Hydrological connectivity was used as an indicator of resource leakiness. Low hydrological connectivity can reduce accumulated flow, as the opportunity for water to

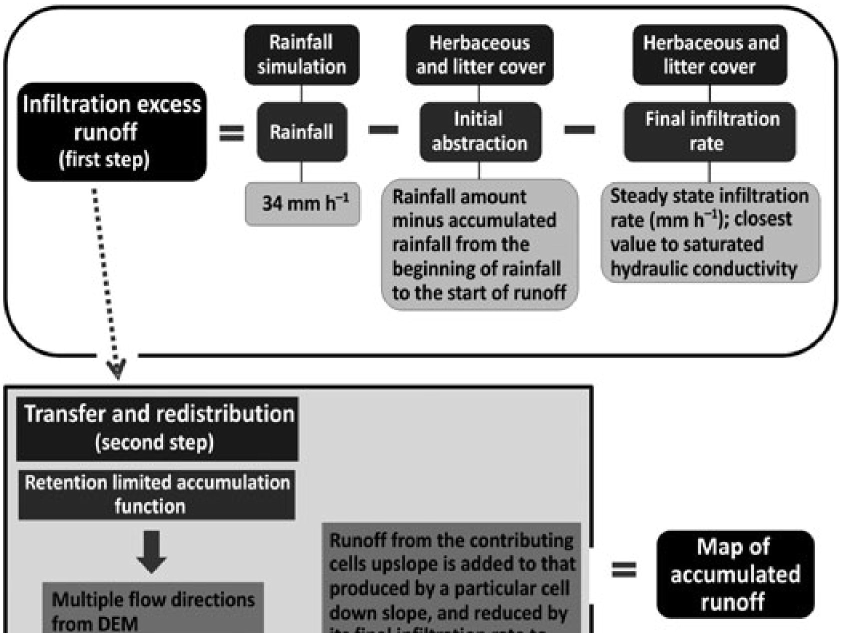


Figure 2. Flow chart of the two-step process for spatially modelling accumulated runoff. The first step consisted of estimating hydrological responses for each cell. The second step consisted of modelling runoff and sediment transfer among cells considering slope gradient, slope direction and runon. The sediment production map in Figure 3d was produced by multiplying the map of accumulated runoff by sediment concentration (see text for details).

infiltrate increases as runoff is impeded. The connectivity of runoff source areas was assessed with FLOW LENGTH (Mayor *et al.*, 2008). FLOW LENGTH determined the potential length of the runoff path from each cell, following the direction of the slope on binary maps representing runoff source areas and vegetated patches or sink areas. The result was an index of the average length of all the potential runoff pathways in the target area. A threshold value of ground cover was required for defining runoff source areas to run FLOW LENGTH. To determine the threshold of herbaceous and litter cover at which runoff changed significantly from zero, nonparametric regression analysis using base splines (degrees of freedom $df = 4$) was undertaken using data from the 55 rainfall simulations on the hillslopes. Binary maps of runoff sources and sinks were generated using the threshold ground cover value to evaluate the connectivity of runoff sources. FLOW LENGTH was run twice with the 2009 pasture hillslope binary maps. One run computed the connectivity of runoff areas including the effect of the contour banks and ground cover, whereas the second run excluded the effect of the banks.

RESULTS

Relationships between hydrological response and ground cover

Significant regression models estimating average runoff, final infiltration and initial abstraction were obtained using ground cover as the predictor variable ($P < 0.0001$) (Table I). Ground cover (herbaceous and litter cover) explained between 48% and 54% of the variability in hydrological response of the woody hillslope, whereas in the pasture hillslope, the variance explained by ground cover varied between 67% and 83%.

Spatial distribution of infiltration excess runoff and sediment production

The spatial distribution of the hydrological responses used in the modelling of infiltration excess runoff is shown in Figures 3a and 3b. These maps show the spatial distribution of runoff responses and final infiltration capacities on a 1-m^2 cell basis, without considering water transfers among cells. The 2008 maps of runoff and infiltration showed similar spatial patterns to those of ground cover because of the significant relationships between hydrological responses and ground cover. Areas producing high runoff coincided with areas of low ground cover, and high infiltration capacity corresponded to areas of high ground cover.

The modelling of infiltration excess runoff estimated the potential runoff sources on each hillslope at the two dates (Figure 3c), which resulted from the interactions among predicted runoff, infiltration capacity and slope direction. The largest area of high accumulated runoff on the woody hillslope in model runs for both years was in the north-west portion. However, 81.2% and 86.8% of the hillslope did not accumulate runoff in 2008 and 2009, respectively (Figure 4a). The modelling showed that the runoff produced in some areas of the woody hillslope infiltrated further downslope because of the presence of high infiltration capacity areas (i.e. patches under shrub and tree canopies). In the 2008 model run, the mean and maximum accumulated runoff on the woody hillslope was 3.6 and 132.0 $l\,m^{-2}$ per 0.5 h, respectively. These values decreased slightly in the 2009 model run, returning mean and maximum values of 3.0 and 121.0 $l\,m^{-2}$ per 0.5 h, respectively.

The pasture hillslope had mean and maximum runoff accumulations of 230.0 and 600.0 $l\,m^{-2}$ per 0.5 h, respectively, in 2008, with only 3.4% of the hillslope not producing runoff (Figure 4b). Infiltration capacities were exceeded by flow from upslope cells, increasing the accumulated flow across most of the pasture hillslope (Figure 3c). However, when the combined effect of the water spreading system and ground cover were modelled in 2009, the proportion of the hillslope that did not produce runoff increased to 24.0% (Figure 4b), and mean accumulated runoff declined by 68% (to 73.6 $l\,m^{-2}$ per 0.5 h) compared with 2008. Although accumulated runoff in parts of the pasture hillslope still reached 600.0 $L\,m^{-2}$ per 0.5 h in 2009, the proportion of area with high runoff ($>$120.0 $L\,m^{-2}$ per 0.5 h) decreased ~50% compared with 2008 (Figure 4b). The contour banks disrupted hydrological connectivity and decreased the length of the slopes producing runoff, contributing to the large reduction in runoff accumulation on the pasture hillslope.

Sediment production differed greatly between woody and pasture hillslopes in both 2008 and 2009 (Figure 3d) and, as expected, followed patterns similar to accumulated runoff.

The woody hillslope produced up to 0.4 $kg\,m^{-2}$ of sediment and a mean value of 0.01 $kg\,m^{-2}$ in 2008 and 2009, but about 80% of the hillslope did not produce sediment (Figure 4c). The pasture hillslope produced up to

Table I. Equations for average runoff, final infiltration rate and initial abstraction from forward stepwise multiple regression analysis.

Hillslope	Regression equation	Adjusted R^2	Model F	Significance P
Woody hillslope	$AR = 17.583 - 1.489\sqrt{GC}$	0.48	$F_{1,26} = 25.80$	<0.001
	$FIR = 5.717 + 2.038\sqrt{GC}$	0.50	$F_{1,26} = 28.00$	<0.001
	$ABS = 5.684 - 0.120\,GC + 0.002\,GC^2$	0.54	$F_{2,24} = 16.23$	<0.001
Pasture hillslope	$AR = 21.298 - 0.232\,GC$	0.81	$F_{1,24} = 109.00$	<0.001
	$FIR = 2.990 + 0.274\,GC$	0.67	$F_{1,24} = 52.10$	<0.001
	$\sqrt{ABS} = 1.330 + 0.030\,GC$	0.83	$F_{1,22} = 117.00$	<0.001

AR, average runoff; FIR, final infiltration rate; ABS, initial abstraction. GC, ground cover (herbaceous and litter cover).

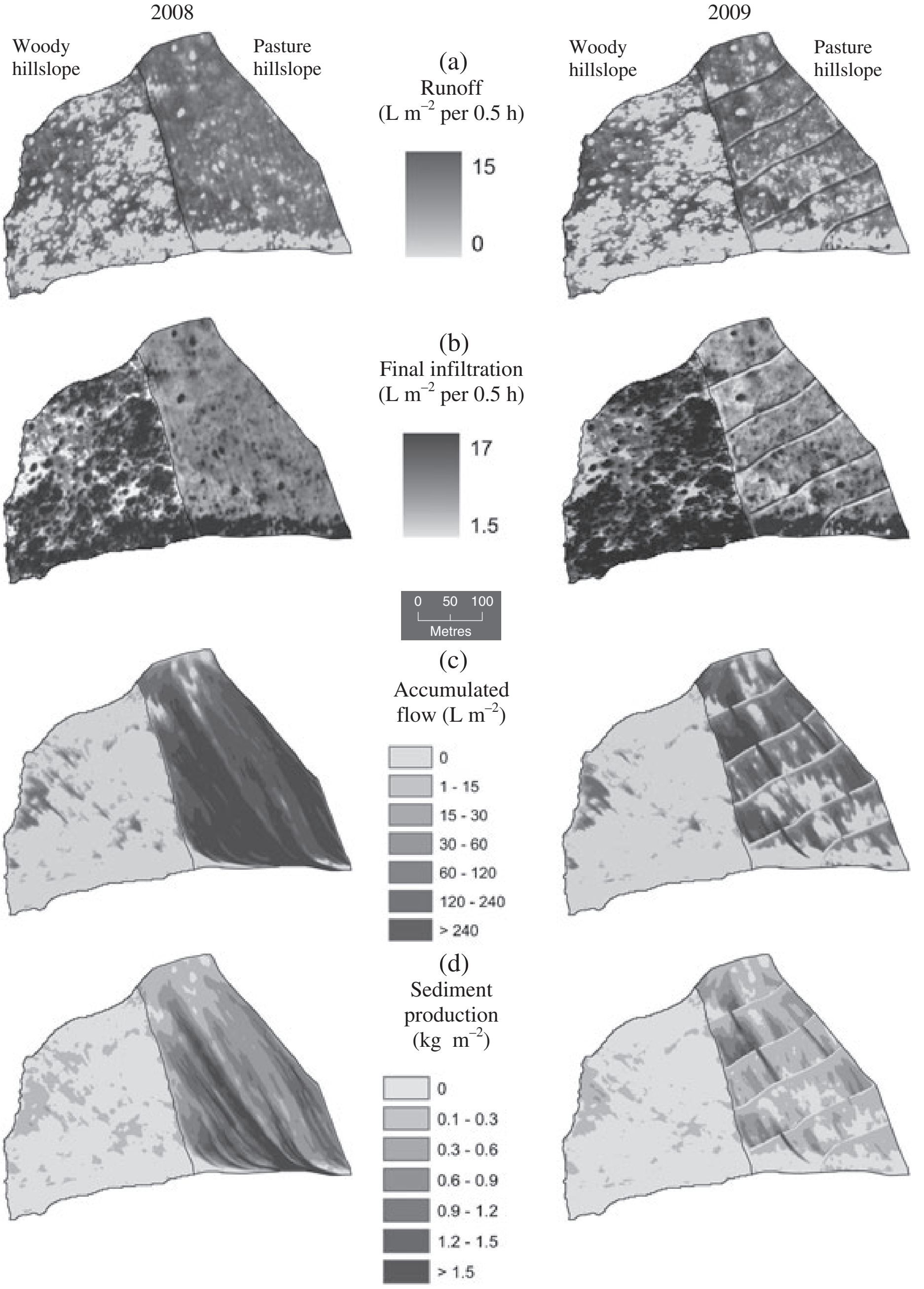


Figure 3. Spatial distribution of (a) runoff and (b) infiltration derived from regression models, (c) modelled accumulated runoff (retention limited) and (d) modelled sediment production.

$1.8\,\mathrm{kg\,m^{-2}}$ in 2008 and 2009, but the proportion of the hillslope that produced high amounts of sediment in 2009 (mean of $0.2\,\mathrm{kg\,m^{-2}}$) was lower than in 2008 (mean of $0.7\,\mathrm{kg\,m^{-2}}$; Figure 4d). Contour banks were effective in reducing sediment production because the increase in ground cover in 2009 on the pasture hillslope in the model run without the contour banks only slightly reduced sediment production compared with the run with contour banks (Figure 4d).

Runoff production, patchiness and hydrological connectivity

The percentage area of the woody hillslope with >65% ground cover was higher in 2009 than 2008, whereas the percentages of the woody hillslope with 30%–65% and <30% ground cover decreased between 2008 and 2009 (Figure 5a), consistent with the slightly lower average runoff accumulation in 2009 than 2008. The density of patches with >65% ground cover in the woody hillslope decreased in 2009 and did not appear to be related to accumulated runoff or sediment production. The percentage area of the pasture hillslope with <30% ground cover varied little between 2008 and 2009 (~5% higher in 2009, including the area of the water spreading banks, which accounted for 8% of the hillslope; Figure 5b), but accumulated runoff declined by 68% in 2009 compared with 2008 (Figure 4b). The percentage of the pasture hillslope with >65% ground cover increased twofold from 2008 to 2009, consistent with the reduction in estimated runoff in 2009.

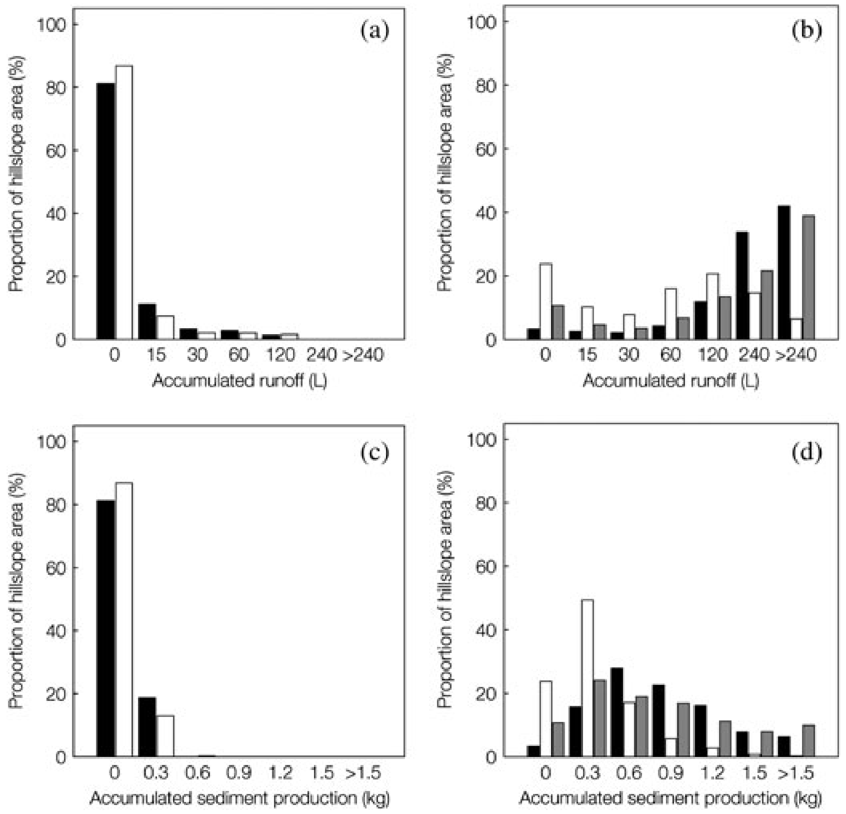


Figure 4. Distribution of accumulated runoff in (a) woody hillslope, (b) pasture hillslope and distribution of accumulated sediment production in (c) woody hillslope and (d) pasture hillslope. ■ = 2008 and □ = 2009 with contour banks and ▨= 2009 without contour banks on the pasture hillslope.

Comparing model runs between both hillslopes, an average of 64 times more runoff was generated by the pasture hillslope than the woody hillslope in 2008, although the difference in the percentage areas with <30% ground cover between hillslopes was only ~9% (Figures 5a and 5b). The density of inter-patches with <30% ground cover was similar in 2008 on both hillslopes at ~16 inter-patches ha^{-1}. More marked differences occurred in the areas of high ground cover. In 2008, the woody hillslope had five times the percentage area with >65% ground cover (46% and 9%, respectively) and twice the density of patches with >65% ground cover compared to the pasture hillslope (15 vs 7 patches ha^{-1}, respectively; Figures 5a and 5b).

In 2009, the pasture hillslope with contour banks generated 24 times more average runoff than the woody hillslope. The difference in the percentage area of hillslope with <30% ground cover was ~3% in 2009 (Figures 5a and 5b). The density of inter-patches with <30% ground cover was similar in 2009 on both hillslopes at ~15 inter-patches ha^{-1}. The woody hillslope had three times the percentage area of high (>65%) ground cover as the pasture hillslope (57% vs 19%, respectively), whereas the density of patches with >65% ground cover was 12 and 21 patches ha^{-1} in the woody and pasture hillslopes, respectively (Figures 5a and 5b).

Runoff as a spline function of ground cover ($P < 0.001$; Figure 6) indicated a runoff threshold at ~84% herbaceous and litter cover, determined by the lower confidence interval of the spline curve. Runoff was not significantly different from zero above this value but was significantly greater than zero below this cover. Therefore, in this study, areas with ground cover <84% in the hillslopes were likely to produce runoff (and were runoff sources), whereas areas with ground cover ≥84% disrupted the connectivity of runoff source areas and produced no or very little runoff.

The connectivity of runoff sources as measured using FLOW LENGTH indicated lower mean flow lengths (less connectivity) in 2009 than in 2008 on both hillslopes (Figures 7a and 7b). Mean flow length in the woody and pasture hillslopes decreased by 50% and 78%, respectively, from 2008 to 2009. When the topographic effect of the contour banks was excluded, mean flow length on the pasture hillslope increased by 45% from 2008 to 2009.

DISCUSSION

The main aim of this study was to simulate spatial, eco-hydrological responses of hillslopes in different vegetation states to obtain a broader perspective than the scale of rainfall simulation plots (1 m^2). The results captured the major controls of runoff and sediment production at the hillslope scale because surface flow during moderate storm intensities (such as that simulated in this study) is controlled principally by surface condition and spatial heterogeneity of infiltration, influenced in turn by ground cover and its spatial configuration (Puigdefábregas, 2005). Other influences on runoff, such as topsoil texture and slope, were similar in both hillslopes and were unlikely to account for differences in runoff and sediment production estimates.

Areas with high ground cover captured runoff from low ground cover areas upslope because of their high

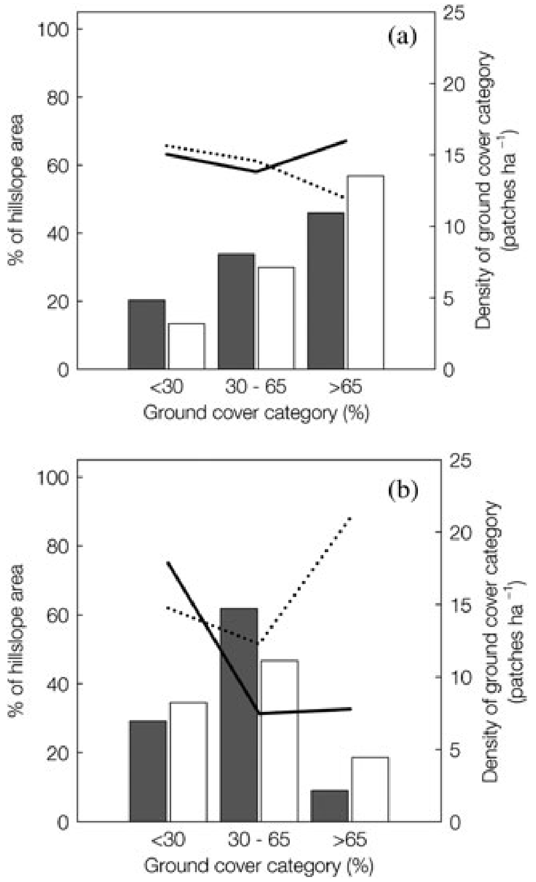


Figure 5. Ground cover categories (herbaceous and litter cover) in (a) woody and (b) pasture hillslopes: proportion of ground cover categories in ■ 2008 and □ 2009; density of ground cover classes (solid line = 2008; dotted line = 2009).

infiltration capacity. Areas with high ground cover can reduce flow velocity and obstruct runoff, allowing for effective retention of sediments and nutrients (Ludwig *et al.*, 2005). These eco-hydrological functions of vegetated patches and inter-patches in semi-arid areas have been documented in many studies (Greene *et al.*, 2001; Ludwig *et al.*, 2005; Mayor *et al.*, 2009), including the study region (Muñoz-Robles *et al.* 2011c). In addition, the modelling results suggest that retention capacity increases as the areal proportion of vegetated patches increases, as suggested by Tongway and Ludwig (1997). This study indicated that hillslopes with a high percentage area of ground cover $>65\%$ were particularly associated with reduced runoff within and between hillslopes in the 2 years.

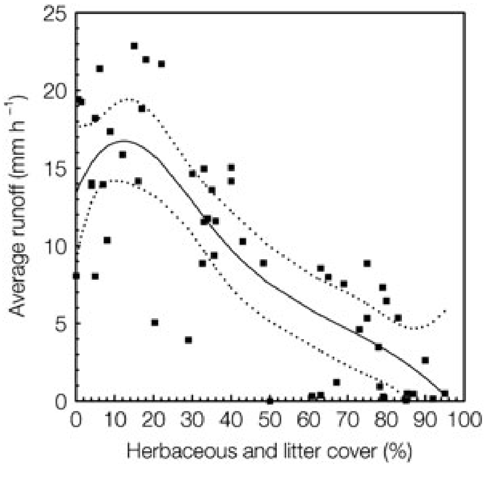
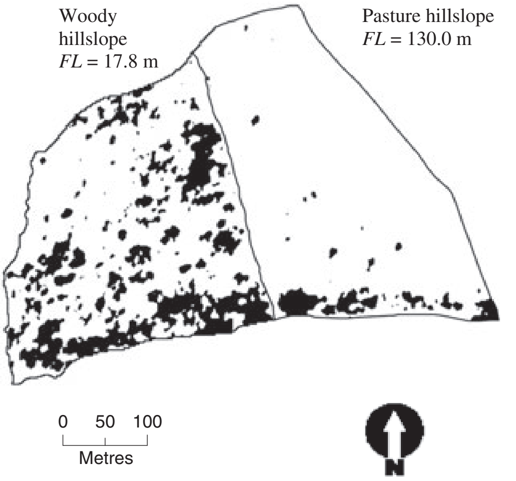


Figure 6. Average runoff as a function of herbaceous and litter cover in the hillslopes. The fitted spline relationship is significant ($P \leq 0.001$). Dotted lines are 95% confidence intervals.

(a) 2008



(b) 2009

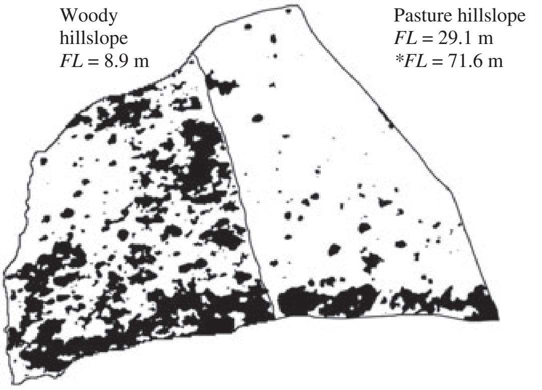


Figure 7. Mean connected flow length (*FL*) of runoff sources in (a) 2008 and (b) 2009. Binary maps show runoff source areas with $<84\%$ ground cover (□) and vegetated areas (runon or sink area) with $\geq 84\%$ ground cover (■). **FL* = excluding the effect of contour banks.

The effects of spatial patterns of patches and inter-patches in patterned semi-arid landscapes at the plot and catchment scales have been demonstrated by Bautista *et al.* (2007), Bergkamp (1998), Boer and Puidefábregas (2005) and Puigdefábregas (2005). The results of this study are consistent with their findings. Runoff was lower where the proportion and density of areas with high infiltration capacity were large. For instance, the areas of high infiltration capacity under shrub and tree canopies on the woody hillslope retained most of the runoff produced in the inter-canopy zone. Measurements from runoff plots in other areas have demonstrated that clumps of shrubs can absorb runoff produced in the inter-canopy zone (Johns, 1981). Similar behaviour was observed in the 2009 pasture model runs, when the proportion and density of high infiltration capacity areas increased from those in 2008. This occurred especially in the mid and lower slopes where all runoff and sediment were retained in some places. The presence of high ground cover at the bottom of both hillslopes helped prevent runoff and sediment loss from both systems, except when the accumulation of runoff along the bottom of the hillslope exceeded infiltration capacity, such as in the pasture hillslope in 2008.

The higher rainfall and livestock exclusion in 2009 compared with 2008 enhanced herbaceous ground cover in the pasture hillslope (Muñoz-Robles *et al.*, 2011a). The construction of the contour banks in the pasture hillslope contributed to disrupting the connectivity of runoff source areas in 2009. This was evident when the model runs of both years were compared. In both years, the proportion of areas of low ground cover was similar, but these areas were more connected in 2008 than in 2009, resulting in a reduction of runoff in 2009. Therefore, the distribution of connected low ground cover areas (i.e. hydrologically connected areas) may affect runoff production, as suggested by the FLOW LENGTH results. The physical barrier of the contour banks in the pasture hillslope 3 months after their introduction in 2009 reduced connectivity of runoff sources by 78% compared with that in 2008 without contour banks. This pasture management initiative is likely to decrease runoff and increase sediment retention, subject to appropriate grazing and cultivation management.

The woody hillslope did not have contour banks, but the higher ground cover in the second year resulted in lower runoff and sediment production than the pasture hillslope. The increase in ground cover in the woody hillslope between 2008 and 2009 was probably because of higher rainfall in 2009 and livestock exclusion in both hillslopes after establishment of the water spreading system in the pasture (Muñoz-Robles *et al.*, 2011a).

The lower proportions of variance in average runoff, final infiltration and initial abstraction explained by ground cover on the woody hillslope compared with the pasture hillslope suggest that complex interactions may exist at fine scale that lead to higher variability in the woody hillslope than the pasture hillslope. The obstruction of the spectral signature of ground cover under the canopies of shrubs and trees could also make ground cover predictions less accurate in the woody hillslope than in the pasture hillslope (Muñoz-Robles *et al.*, 2011a).

Factors such as higher surface roughness and more heterogeneous types and distribution of ground cover may influence hydrological responses on the woody hillslope (Muñoz-Robles *et al.*, 2011c). Notwithstanding these factors, litter and herbaceous vegetation were good predictors of hydrological response and allowed the spatial distribution of runoff and infiltration to be estimated on both hillslopes.

The spatial resolution of remotely sensed data must match the scale of the processes being studied (Muñoz-Robles *et al.*, 2007b). Hydrological responses and sediment concentrations were measured in fine-scale rainfall simulation plots in this study. At this scale, surface conditions such as ground cover, soil texture, micro-topography and surface crusting are the main determinants of runoff and sediment generation (Eldridge and Rothon, 1992; Petersen and Stringham, 2008; Michaelides *et al.*, 2009). However, as the spatial scale becomes coarser, other factors that influence infiltration capacity, water routing and sediment transport become important, such as the spatial distribution of vegetated patches, the connectivity of bare areas and length of slope. These affect runoff and sediment production because larger sediment storage and water infiltration opportunities exist at coarser scales (Connolly *et al.*, 2002; Cammeraat, 2004).

In the present study, factors affecting eco-hydrological response at both fine scale (1 m^2) and the hillslope scale were incorporated in spatial modelling. For instance, the runoff produced from inter-patches on the woody hillslope infiltrated in the areas downslope, as larger patches with high infiltration capacity were present in these areas. The ground cover (herbage and litter) associated with zero runoff was determined to be 84% in this study, which is high but within the levels (50%–90%) reported to minimize runoff in other semi-arid areas (Gifford, 1985; Gutierrez and Hernandez, 1996; Chartier *et al.*, 2009). There were still reductions in runoff below this ground cover (albeit not to zero). In the pasture hillslope, in particular, this effect of runoff reduction was evident in the 2009 model run (in conjunction with the effect of spatial scale on infiltration): the contour banks and the increases in proportion of hillslope with >65% ground cover and patch density provided areas for water to infiltrate at intervals down the slope, changing the hydrological pattern in the pasture in 2009 compared with that in 2008.

Antecedent soil conditions (i.e. soil moisture content, soil water holding capacity and infiltration properties of soil layers) and rainfall affect flow behaviour (Connolly *et al.*, 2002). The results of the spatial modelling in this study applied to the following set of circumstances and assumptions: (1) average surface soil moisture of 4% w/w before rainfall simulations; (2) a constant, moderate rainfall intensity across the two hillslopes; (3) the assumption that ground cover is a surrogate for other soil physical properties (i.e. bulk density, texture and porosity) that influence hydrological responses; and (4) the relationships between runoff and herbaceous and litter cover across both hillslopes. Divergence from these circumstances and assumptions, as well as higher surface roughness and more heterogeneous types and distribution of ground cover, may have influenced hydrological response on the woody hillslope (Muñoz-Robles *et al.*, 2011c).

The relevance of including hydrological connectivity as an important factor controlling resource redistribution in patchy semi-arid landscapes was noted by Mueller *et al.* (2007) and Mayor *et al.* (2008). The modelling approach presented in this paper accounted for connectivity of runoff source areas and showed how spatial flow paths were formed as low ground cover cells in upslope areas connected with runoff sources downslope until high infiltration patches were reached, interrupting connectivity. The FLOW LENGTH results highlighted these patterns, as high values of mean flow length were associated with greater runoff compared with less connected runoff sources with low mean flow length. This approach is useful for describing spatial patterns of runoff down patchy hillslopes, and the rapid field assessment of flow length may be useful for management.

MANAGEMENT IMPLICATIONS

Understanding eco-hydrological interactions at different scales is essential for developing management principles for restoring and managing eco-hydrologically functional landscapes, including increasing the area and density of vegetated patches. The woody encroachment hillslope had higher resource retention capacity than the pasture hillslope over the 2-year period because of the higher proportion of the hillslope with high ground cover patches and their spatial distribution. Hillslopes with a high proportion of high ground cover areas and thus with less connected runoff source areas provide more runon and infiltration opportunities, enhancing plant growth pulses (Ludwig *et al*., 2005).

The water spreading system described in this paper is an example of effective pasture management based on eco-hydrological processes in this semi-arid landscape. The contour banks established in the pasture hillslope in 2009 disrupted connected runoff sources and slowed down flow velocity, resulting in runoff retention and less topsoil and nutrient loss than without contour banks, leading to higher pasture cover. It is likely that the density and cover of areas with high ground cover will increase in the pasture hillslope with the water spreading system, under appropriate grazing and cultivation management. Monitoring of the site via remote sensing and more on-ground verification (e.g. rainfall simulations) would help validate this spatial modelling approach across a range of climatic conditions, hydrological responses and ground cover changes.

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