Runoff and water quality from steep hills in south-eastern Australia

Malcolm McCaskill[A], Zhongnan Nie[A], Reto Zollinger[A] and David Nash[B]

[A]Future Farming Systems Research Division, Department of Primary Industries, Private Bag 105, Hamilton, VIC, 3300, Australia, Email malcolm.mccaskill@dpi.vic.gov.au
[B]Future Farming Systems Research Division, Department of Primary Industries, Ellinbank Centre, 1301 Hazeldean Road. VIC, 3821, Australia.

Abstract
To understand the mechanisms of surface runoff and the impact of phosphorus (P) fertiliser on runoff quality, a 4-year catchment study was conducted near Ararat in western Victoria. Four small catchments and two larger catchments with slopes of 9-33% were selected in the upper Hopkins basin. Superphosphate was applied at 40 kg P/ha once to two of the small catchments, and water quality samples taken from all the small catchments. Soil moisture was measured by a neutron moisture meter and reflectometers. Each surface runoff event was classified into terciles based on antecedent soil moisture. In four of the catchments, more flow occurred in the dry or intermediate terciles than in the moist tercile. This indicates that Hortonian flow (runoff while the soil is partially dry) is important in the study environment. We attribute this flow to a combination of water repellence of the topsoil, and low detention storage on the steep slopes. Catchments to which superphosphate was applied had nearly double the concentration of P in runoff water.

Key Words
Hill-slope hydrology, Hortonian flow, infiltration-excess runoff.

Introduction
Extensive pastures on hills grazed by sheep form a large proportion of the catchments of rivers in south-eastern Australia. Management of these hill areas can have a large influence on stream water quality and quantity. Paddock-scale catchment studies in the winter-dominant rainfall zone have shown that application of phosphorus (P) fertiliser increases the P concentration of runoff water, but has little impact on runoff quantity (Ridley *et al.* 2003; Melland *et al.* 2008). In these studies, nearly all runoff occurred in the winter-spring period after the soil profile had filled. This is a time of year when there is generally good ground cover. Most of these studies were conducted on low to moderate slopes (<5%). There remains a need to understand the runoff mechanisms and consequences of fertiliser application on steeper areas. To test whether the timing of flow and impact of fertiliser also applied to steep hills, a study was initiated in the upper Hopkins basin near Ararat in western Victoria. This paper reports a 4-year study of runoff quantity and quality from a series of small catchments in the upper Hopkins basin.

Methods
Catchments
Four small catchments and two larger ones were selected on a sheep grazing property within a steep hill landscape near Ararat in western Victoria. All 4 small catchments were selected to be as similar as possible in aspect and slope, but varied in their stocking rate and fertiliser rate (Table 1). Catchments B-D were adjacent and about 1km from Catchment A. Catchment D drained into Catchment E, and Catchment A into Catchment F. Catchments C and D received 40 kg/ha of P as superphosphate applied once early in the trial (June 2004).

Table 1. Grazing management, size, elevation and orientation of the 6 study catchments.

Catchment	Stocking rate (sheep/ha)	Fertiliser rates (kg P/ha)	Catchment area (ha)	Bottom elevation (m)	Top elevation (m)	Mean slope (%)	Orientation	Drainage line
A	2.5	0	1.2	426	481	33	ENE	Well defined
B	4.4	0	0.9	397	442	29	ESE	Poorly defined
C	4.4	40	1.6	395	446	24	ESE	Intermediate
D	5.3	40	1.7	395	451	27	S	Well defined
E	4.5	~20	8.1	376	380	20	SSE	Intermediate
F	~4	~10	258	347	446	9	SSE	Well defined

According to the Australian Soil Classification (Isbell 1996), the soil is a Bleached-mottled, Magnesic, Yellow Chromosol, and consisted of sandy clay loam topsoil with an organic matter content of 6-16%, overlying a medium clay subsoil. All catchments were vegetated with native and naturalised pastures (mainly *Austrodanthonia* spp, *Themeda triandra, Hypochoeris* spp. *Rumex* spp. and *Trifolium subterraneum*). Vegetation cover exceeded 70% throughout the study, except on Catchment A in autumn 2007 when it declined to 42%. Rainfall was recorded every 15 minutes by an automatic weather station.

Measurements

Polythene and stainless steel flow barriers were installed at the bottom of each of the four small catchments and runoff was directed into stainless steel flumes (Clemmens *et al*. 1984). The height of water flowing through each flume was recorded by capacitance water height recorders and logged every 2-5 minutes. Water height was related to flow by means of a published calibration relationship (Clemmens *et al*. 1984). Below the weir, flow was directed into a stainless steel after-weir from which samples were collected by an automated water sampler, activated every 30 minutes when water was detected (ISCO 3700 sampler and 1640 liquid level actuators, Teledyne ISCO, Lincoln, Nebraska, USA). As a backup to the automatic samplers, 6 rising stage samplers were installed at 10 mm increments above the level at which water flowed over the flume. Catchment E was monitored hourly at a farm dam by a pressure-sensitive recorder. A topographic survey of the dam was used to convert water height into storage volume. Catchment F (the Hopkins River) was monitored by a V-notch weir installed within a gully control structure. Water heights were converted into flow using a published calibration relationship (Grant and Dawson 2001). Water quality samples were not collected from catchments E and F. Water samples were digested in potassium persulfate (Clesceri *et al.* 1998; method 4500-P B) followed by total P determination by auto analyser at 882 nm using ascorbic acid as the reductant (Clesceri *et al.* 1998; method 4500-P E). To measure total nitrogen, NO_3^- in the digested samples was reduced to NO_2^- in a copperized Cd column, and the NO_2^- was determined by auto analyser at 520 nm (Clesceri *et al.* 1998; method 4500-NO_3^- E). The concentration of solids was determined by evaporation and weighing (Greenberg *et al*. 1992; methods 2540 B and D).

Soil water

In catchments B, C and D, 4-5 aluminium access tubes were installed 10-30 m upslope of the flow barriers, and soil moisture measurements made using a neutron moisture meter (NMM) at intervals of 4-12 weeks. Reading depths were 150 mm, 300 mm, then at 200 mm intervals to the bottom of the access tube at between 900 and 1500 mm depth. Frequency domain reflectometers (CS615, Campbell Scientific, Inc., Logan, Utah, USA) were installed at a single location close to the weather station and logged hourly. These were placed at depths of 0-100 mm (sloped upwards from the installation pit), 100-200 mm, 400 mm and 800 mm. Soil moisture storage was calculated on a daily basis from reflectometer data for the 0-1m depth range.

Results

Mean annual runoff showed a 100-fold range between catchments from 0.14 mm/yr on Catchment B, to 14.5 mm/yr on Catchment A (Table 2). Some catchments produced runoff even in 2006, which was a year of exceptionally low rainfall. Runoff was greatest on catchments with well defined drainage lines. Rainfall during the study period was well below the long-term average (1900-2006) of 613 mm/yr.

Table 2. Summary of annual rainfall and overland flow (mm/year) from the catchments.

Year	Rainfall (mm/yr)	Catchment A	B	C	D	E	F
		Overland flow (mm/year)					
2003*	416	8.2	0.00	0.37	10.10	1.81	5.5
2004	427	21.8	0.42	0.37	5.75	4.06	1.2
2005	605	24.8	0.26	1.35	6.02	4.27	13.4
2006	368	3.2	0.00	0.00	0.54	0.38	0.02
2007*		13.1	0.01	0.00	3.02	0.49	15.9
Mean 2004-2006	467	14.5	0.14	0.42	5.58	2.63	5.0

* Flow data were only recorded for partial years

Soil moisture followed a general pattern of wetting up during autumn and winter, and drying in spring and early summer, but there were short-term maxima following summer storms (Figure 1). In 2006 the soil did not fill to the same extent as in previous years. Soil moisture recorded by the reflectometers (at a single position) was consistent with that from the NMM reading (13 positions), except for one storm in January

2005. Since the reflectometer dataset, which was available on a daily timestep, was generally consistent with the NMM data, and included the 0-100mm layer (which could not be read by the NMM), it was used to classify overland flow by antecedent soil moisture. These data show that in four of the catchments, more flow occurred in the dry or intermediate tercile than in the moist tercile (Table 3). The P concentration from catchments to which P fertiliser had been added was nearly double those of unfertilized catchments (Table 4). The greatest loads were from Catchment A, which had the greatest total flow.

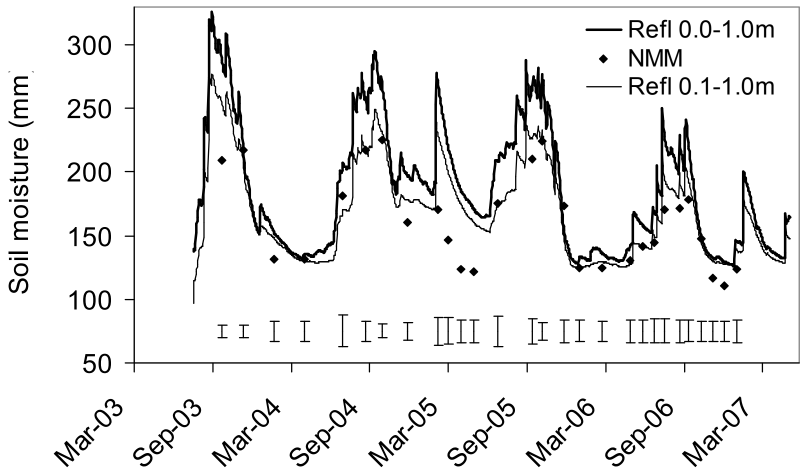

Figure 1. Soil moisture recorded by reflectometers at catchment C (0.0-1.0 m and 0.1-1.0 m), compared to neutron moisture meter (NMM) data averaged across B, C and D catchments (0.1-1.0 m). Error bars are the standard error of the site mean soil moisture for each NMM reading date.

Table 3. Overland flow January 2004 to May 2007, classified according to antecedent soil moisture.

Soil moisture tercile	Catchment					
	A	B	C	D	E	F
	Total overland flow (mm)					
Dry	24.7	0.30	0.34	4.15	1.85	15.9
Intermediate	28.7	0.39	0.08	2.05	4.48	5.88
Moist	9.5	0.0	1.31	9.14	2.89	8.74

Table 4. Flow-weighted concentrations (±standard error) and loads from January 2004 to December 2006.

	Catchment			
	A	B	C	D
	Concentration (mg/L)			
Total P	0.52 (0.13)	0.48	0.96	0.88
Total N	5.03 (0.69)	1.42	3.88	2.97
Suspended solids	50 (12)	33	24	16
Total solids	171 (20)	66	214	141
Total dissolved solids	104 (9)	33	189	107
	Load (kg/ha.yr)[1]			
Total P	0.085	0.001	0.005	0.036
Total N	0.847	0.003	0.022	0.122
Suspended solids	6.39	0.075	0.14	0.66
Total solids	22.9	0.15	1.23	5.80
Total dissolved solids	15.5	0.07	1.08	4.42

[1]Does not include bed load

Discussion

A high proportion of total runoff occurred when the soil was in the dry tercile, whereas in previous studies on gentler slopes, most flow occurred when the soil was moist. This indicates that Hortonian flow (infiltration-excess flow that occurs before the soil fully wets up) is an important flow generation mechanism in our steep hill environment. Other studies of steep areas (1-16% slopes) in uniform rainfall environments in New South Wales have also shown runoff occurring when the soil was still partially dry (Lane *et al.* 1994; Hughes *et al.* 2008). Our landholder noted that during the 2006 drought, some dam-fill occurred on his hill country, but not on the flatter catchments.

In the dry tercile, surface flow was initiated by rainfall intensities as low as 2.6 mm/hr (data not shown). We observed water repellence during light rain on 29 March 2003, when water flowed across the soil surface despite the underlying topsoil being dry. Repellence is common on topsoils such as those in this study that are high in organic matter but low in clay (Ritsema and Dekker 1996). In water-repellent soils, infiltration initially occurs through preferred pathways within the topsoil until the soil wets from below, breaking the repellence of the surface layers (Ritsema and Dekker 1996). Detention storage would therefore be important in the initial wetting of the soil. However, on steep slopes this storage would be limited. We attribute the Hortonian flow to the combination of low detention storage on steep slopes and water repellence of the topsoil when dry.

There was large variation in runoff from the various catchments, with those on defined drainage lines contributing the most runoff. This is consistent with Barling *et al.* (1994) and Melland *et al.* (2008), who reported that surface runoff was preferentially generated from areas of convergent topography. These convergent areas are clearly preferable as catchments for farm dams. Catchments to which superphosphate was applied had nearly double the concentration of P in runoff water. This is also consistent with other studies where similar rates of P were applied (Ridley *et al.* 2003; Melland *et al.* 2008). In the environment of this study, fertiliser did not generate sufficient additional pasture growth to justify the cost (data not shown), and is not a necessary part of hill country management other than replacing the P removed by grazing livestock.

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References

Barling RD, Moore ID, Grayson RB (1994) A quasi-dynamic wetness index for characterising the spatial distribution of zones of surface saturation and soil water content. *Water Resources Research* **30**, 1029-1044.

Clemmens AJ, Bos MG, Repgole JA (1984) Portable RBC flumes for furrows and earthern channels. *Transactions of the* ASAE **27**, 1016-1021.

Clesceri LS, Greenberg AE, Eaton AD (Eds) (1998) 'Standard methods for the examination of water and wastewater.' (APHA, AWWA, WEF: USA).

Grant DM, Dawson BD (2001) ‘ISCO Open Channel Flow Measurement Handbook, 5th Edition’. (ISCO Inc.: Lincoln, Nebraska).

Greenberg AE, Rice AD, Eugene W (1992) Standard Methods for the Examination of Water and Wastewater, 18th Edition. (APHA AWWA, WEF, Washington DC, USA).

Hughes JD, Packer IJ, Michalk DL, Dowling PM, King WMcG, Brisbane S, Millar GD, Priest SM, Kemp DR, Koen TB (2006) Sustainable grazing systems for the Central Tablelands of New South Wales. 4. Soil water dynamics and runoff events for differently-managed pasture types. *Australian Journal of Experimental Agriculture* **46,** 483-494.

Isbell RF (1996) ‘The Australian Soil Classification’. (CSIRO Publishing: Melbourne Australia).

Lane PNJ, Nandakumar N, Mackenzie DH, Nethery M (1994) Flow pathways in an experimental catchment and the implications for groundwater recharge. Water Down Under 94. Adelaide 21-25 November 1994. Preprints Vol 1. (The Institute of Engineers: Barton, Australia).

Melland AR, McCaskill MR, White RE, Chapman DF (2008) Loss of phosphorus and nitrogen in runoff and subsurface drainage from high and low input pastures grazed by sheep in southern Australia. *Australian Journal of Soil Research* **46**, 161-172.

Ridley AM, Christy BP, White RE, McLean T, Green R (2003) North-east Victoria SGS National Experiment site: water and nutrient losses from grazing systems on contrasting soil types and levels of inputs. *Australian Journal of Experimental Agriculture* **43**, 799-815

Ritsema CJ, Decker LW (1996) Water repellency and its role in forming preferred flow paths in soils. *Australian Journal of Soil Research* **34**, 475-487.