Rainfall simulation underestimates runoff phosphorus concentrations from dairy pastures

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Abstract
Concentrations of phosphorus (P) in runoff from intensively managed pastures such as those used for dairying are high. Soil P has a large influence on runoff P concentrations. The most common technique used to derive soil P–runoff P relationships is rainfall simulation. A project is underway to test the utility of combining soil P-runoff P relationships with landscape hydrological models to assist in identifying areas for priority remedial action to reduce runoff P losses. However, there have been conflicting reports on the reliability of rainfall simulation to predict runoff P concentrations under natural rainfall at broader scales, e.g. hill-slope or sub-catchment. This paper reports a comparison of two methods of measuring runoff P concentrations, a) large plots (1250 m^2) with low intensity simulated rainfall (8 mm/hr) and, b) small plots (1.5 m^2) with high intensity simulated rainfall (80 mm/hr). Measurements were made on two occasions and over a range of soil P concentrations. There was a highly significant ($P<0.01$) effect of the method of measuring runoff P concentration. Runoff P concentrations from the small plots were approximately half of those derived from large plots. We hypothesize that these differences are the result of differences in contact times between the P source and runoff. However, the processes of mobilisation and subsequent forms of P are similar for both methods. Rainfall simulation may be used in the prediction of runoff P concentrations at scales broader than plot, e.g. at hillslope, if the effect of hydrological and chemical interactions are considered.

Keywords
Phosphorus, runoff, scale, hillslope plots, mobilisation, process

Introduction
Excessive concentrations of phosphorus in surface water may contribute to the development of toxic algal blooms. The dairy industry has been identified as a net accumulator of P, primarily on areas of the farm receiving high P inputs (Lawrie *et al.* 2004). Furthermore, various authors have observed concentrations of P in runoff from pastures used for dairying are high and are above acceptable P concentrations set for waterways (typically 0.05 mg/L). Phosphorus concentrations in runoff from Australian pastures used for dairying have been observed to range from approximately 1-50 mg/L (Nash and Murdoch 1997; Fleming and Cox 1998). The lowest concentrations are well above water quality targets.

A project is underway to test the utility of combining soil P-runoff P relationships with landscape hydrological models to assist in identifying areas for priority remedial action to reduce runoff P losses (Fleming *et al.* 2003). Various methods have been used to examine the effect of management on the concentrations of P in runoff and soil P-runoff P relationships. The most common methods include rainfall simulation (small plots subjected to high intensity rainfall), and large plots or small catchments where runoff is generated under natural rainfall. Rainfall simulation offers the advantage that it is relatively cheap to make a large number of measurements whilst controlling a range of variables. However, the high rainfall intensity used, the high kinetic energy of the simulated rainfall and the high runoff co-efficient may alter the processes of P mobilisation and provide estimates of runoff P concentration that differ from those provided by field or hillslope studies of P mobilisation. In a comparison of rainfall simulation at two scales (2 and 10 m long plots) with simulated rainfall applied at 75 mm/hr, concentrations of dissolved reactive P (DRP) in runoff from the small plots were higher than those from the larger plots (Sharpley and Kleinman 2003). They attributed this to higher concentrations of sediment in the large plots that was controlling DRP concentration in runoff. In a comparison of runoff P concentrations from small plots (3 m long) and sub-catchments, similar concentrations of P in runoff were observed across a range of scales, from 3m^2 to 140 ha (Cornish *et al.* 2002). They concluded that simulated rainfall at 150 mm/hr on small $1m^2$ plots provided similar values to those from the paddock scale.

The aims of the research reported in this paper were to: a) compare the processes of mobilisation and subsequent concentrations of P in runoff derived from rainfall simulation with those derived under more realistic rainfall/runoff conditions, and b) examine soil P-runoff P relationships.

Methods

Two methods of examining the processes of P mobilisation in runoff and the subsequent concentrations of P in runoff were studied. These two methods are referred to as LL (large plot, low rainfall intensity), SH (small plot, high rainfall intensity). These are described in more detail in the following sections.

Location and site management

The study was located at Camden, 60 km south west of Sydney. Fertiliser P was applied to grazed ryegrass/clover pastures in Autumn and Spring of each year to achieve annual application rates of 0, 20, 40 and 80 kg/ha P. There were six runoff plots, there being one each of the 0 and 80 plots and 2 each of the 20 and 40 plots. The plots had been under this management regime for 3 ½ years prior to the commencement of this experiment.

Runoff plots

All rainfall simulations (both LL and SH) were undertaken within large runoff plots. These plots were 50 m long × 25 m wide, on an average slope of 5% (± 0.5%) and were located in a mid–slope position. The soils at the site are Brown Chromosols (Isbell 1997), or Red and Yellow Podzolics according to Stace *et al*. (1968). Surface runoff from the plots was collected in a PVC channel running the width of the plots at their low end.

Water used in the rainfall simulations was obtained from the nearby Nepean River. It was necessary to use river water due to the large volumes of water required for the LL simulations (several hundred thousand litres). The artificially irrigated events (LL) were needed to supplement data gathered from the natural events. For these artificial runoff events, bike–shift sprinklers were used to apply river water to the whole runoff plot at a rate of approximately 8 mm/hr for 10 hours. These events constituted a rainfall event with an average recurrence interval 1 in 5 years (Pilgrim 1987). The concentrations of P in runoff from these artificial events was shown not to be significantly different ($P<0.05$) from those occurring under natural rainfall when artificial and natural events occurred within several days of each other on two occasions (data not shown).

Small-scale rainfall simulation (SH) was carried out using a swinging boom simulator (Loch *et al.* 2001). Rainfall was applied at a target rainfall intensity of 80 mm/hr and was applied for 20 minutes after the commencement of runoff. Typically this represented a 1 in 10 yr rainfall event for this location (Pilgrim 1987). Plots 1, 3 and 5 (40, 80 and 0 kg P/ha/yr) were used for small-scale rainfall simulations. Within each of the 3 plots at each of the two times, 4 simulations were carried out and averages calculated for each of the plots. The simulations at T_1 were undertaken 30 days after fertiliser application whilst those at T_2 were undertaken 190 days after fertiliser application.

Runoff sample handling and analysis

All runoff samples were filtered (<0.45 µm) immediately upon collection, chilled to 4^oC, and subsequently analysed for dissolved reactive P (DRP) within 24 hours of collection. Unfiltered and filtered samples were stored frozen for later analysis of total dissolved (TDP) and total P (TP). Samples were digested for TP and TDP by persulfate oxidation (Anon, 1992). Phosphorus was determined colorimetrically (Murphy and Riley 1962). The TP concentration of the irrigation water was <0.1 mg/L. Total phosphorus concentrations in these artificial events were consistently at least an order of magnitude higher than those in the river water; consequently no adjustment was made to the runoff concentrations.

Soil sampling and analysis

Soil samples for the LL simulations were taken by collecting thirty cores (2.5 cm diameter and 2 cm deep) along a permanent sampling transect within each large plot and composited. Similarly, for the SH simulations, 25 soil samples were taken on a grid pattern within each small rainfall simulation area. All soil samples were air–dried (40°C in a forced draught) and then ground and passed through a 2 mm sieve to remove stones and plant debris. The samples were then stored at 4°C prior to analysis.

Soils samples were analysed for Olsen P (Olsen *et al.* 1954), and water soluble P (WSP_{Ca}) (Pote *et al.* 1996). WSP_{Ca} was determined by shaking 8 g of soil with 40 mL of 0.01 M $CaCl_2$ on an end–over–end shaker for 30 mins. The solution was then centrifuged and filtered through a 0.45 μm filter before analysis for molybdate reactive P (Murphy and Riley 1962).

Results
A summary of the major soil chemical properties at the time of the simulations (average across all plots) is presented in Table 1. The Olsen P concentrations span a wide range and importantly include the typical optimum for pastures such as these of 20-25 mg/kg.

Table 1. Average soil characteristics of the plots used in the experiments (figures in brackets are the range of values).

Depth (cm)	0-2	0-10
Texture	na	Clay loam
pH_{Ca}	6.1 (6.1-6.2)	5.6 (5.4-5.7)
EC (dS/m)	0.23 (0.19-0.34)	0.2 (0.14-0.22)
OC (%)	3.2 (2.4–3.1)	2.7 (2–3.8)
ECEC ($cmol_c$/kg)	15 (9.4–17.9)	14.1 (7.3–16.2)
Olsen P (mg/kg)	53 (23-91)	29 (10-56)

na – not available

Key characteristics of the river water used in the simulations are shown in Table 2. The water contained low concentrations of phosphorus and suspended sediments.

Table 2. Major characteristics of water used in rainfall simulations.

	T_1	T_2
pH	8.12	8.05
EC (dS/m)	0.35	0.29
TP (mg/L)	<0.1	<0.1
SS (mg/L)	<10	<10

The high intensity rainfall applied in the small-scale simulations (SH) resulted in higher runoff rates. Average runoff rates were 1.5 and 1.2 mm/hr for large plots at T_1 and T_2 respectively and 22 and 20 mm/hr for the small plots at T_1 and T_2 respectively. The velocity of runoff on the plots was estimated using knowledge of the runoff rates (L/s) and basic overland flow hydrological theory. Average residence time of runoff (average for both T_1 and T_2) was estimated to be approximately 1 and 20 minutes for the small plots (SH) and large plots (LL) respectively. These times were consistent with observations using tracers and hydrograph interpretation on other occasions. The estimated average depth of water running off the plots was very similar for both the SH and LL simulations.

There was a very highly significant effect ($P<0.001$) of soil P (WSP_{Ca}), method (LL and SH) and time (T_1 and T_2) on the concentration of TP, TDP and DRP in the runoff (Table 3). There was also a significant effect of WSP_{Ca} and time on the percentage of runoff P as DRP and a significant effect of size on % DRP. The concentration of DRP, TDP and TP increased with increasing soil WSP_{Ca}. The percentage of DRP as a percentage of TP) increased with increasing WSP_{Ca}, although in all cases DRP % was >90%. The effect on TP and TDP of the interaction between size and WSP_{Ca} was significant only at the $P<0.1$ level and for DRP at the $P<0.2$ level.

Table 3. Summary of statistical significance of effect of WSP_{Ca}, time and scale factors on concentration of various P fractions in runoff.

	TP	TDP	DRP	%DP	%DRP
WSP_{Ca} (0-2 cm)	***	***	***	ns	*
Time	***	***	***	ns	ns
Size	**	***	**	*	*

ns-not significant
*P<0.05, **P<0.01, ***P<0.001

The relationship between soil P and runoff P at time T_1 and T_2 are shown in Figure 1. The concentrations of P in runoff from the large plots were consistently higher than those from the small plots. Typically, the concentrations of P in the runoff from the small plots were approximately half those of the large plots.

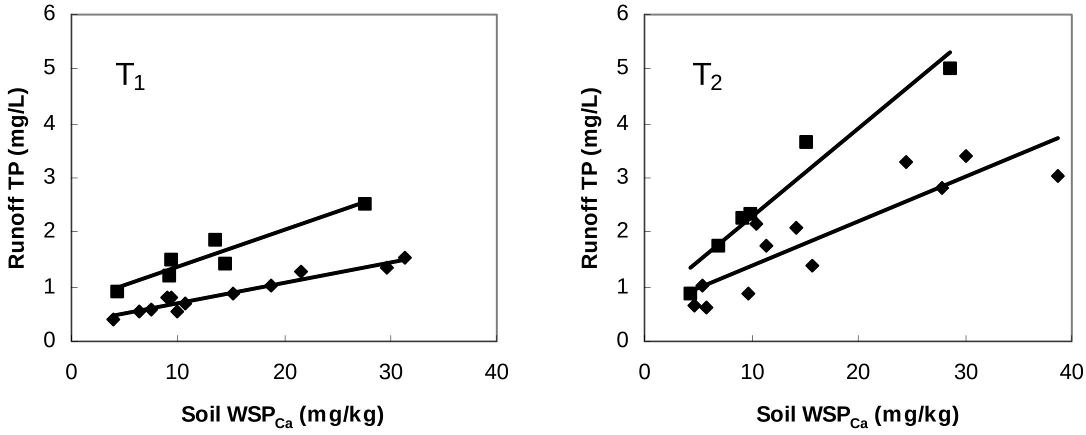

Figure 1. Relationship between WSP_{Ca} and TP in runoff at T_1 and T_2. (■ – large plots LL; ♦ - small plots SH).

Discussion

The concentrations of dissolved reactive P in runoff from the small plots with high intensity rainfall (SH) are approximately half of those derived from large scale (LL) plots under low intensity rainfall. There is a weakly significant effect ($P<0.1$) of the interaction between size and WSP_{Ca} although the small number of data points precludes a statistical detection of this effect, despite their being indication of this interaction as shown in Figure 1.

The dominant process of mobilisation appears to be dissolution of source phosphorus, with >90% of P being present as DRP. This is supported by the low percentage of particulate P (PP); 10 and 5 % of total P in runoff from the small and large plots respectively. In runoff from pasture plots, Sharpley and Kleinman (2003) reported higher particulate P concentrations from larger rainfall simulation plots (10 m long) than small plots (2 m long) due to the higher runoff rates on the larger plots being able to transport more particulate matter. However, in both cases they were using simulated rainfall at moderate intensities that presumably mobilised some sediment that was more effectively transported from the larger plots. The composition of runoff P that we observed under both simulated conditions is consistent with data collected over several years from runoff generated by natural rainfall on the large plots where DRP was >85 % of total P (data not presented). Similarly Nash and Murdoch (1997) observed high percentages of P present as DRP (>85%) in runoff from a small sub-catchment of several hectares being used for grazing of dairy cows. Although there was a difference in the percentage of P present as particulate P % between the two methods, i.e. 5 vs. 10 %, the difference is small, suggesting that despite the high intensity and associated high kinetic energy of rainfall used in the small plots which delivered higher PP, the process of mobilisation has not been greatly altered, i.e. dissolution of P is still the dominant process under high intensity rainfall simulation. However, these processes of mobilisation may change depending on ground cover and runoff volumes. For example, Fleming et al. (1998) observed particulate P making a large contribution (up to 50 %) to runoff P export when pasture cover was poor and runoff rates were high from a sub-catchment of 2.5 ha.

Concentrations of P in discrete runoff samples taken within events for both methods showed no effect of time of sampling, flow rate or volume of runoff on runoff P concentration, despite the high runoff rates from small plots being an order of magnitude higher than those from the large plots. This suggests that the mobilisation of P is not limited by source factors; rather that it is a rate limited process. The transfer of P from soil to solution is generally regarded as being diffusion limited (Sparks 1985) and is most likely to be especially so in situations such as this where runoff is flowing over an essentially stable soil surface.

The differences in the soil P-runoff P regressions between T_1 and T_2 are most likely associated with the relatively short equilibration time of fertiliser with the soil associated with T_1 runoff event, i.e. 30 days. Nash et al. (2000) observed little decrease in runoff P concentration beyond 20 days post-fertiliser

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application, presumably as a result of an achievement of pseudo-equilibrium between the newly added fertiliser P and the existing soil P. Further investigation of the relationship between time since application and soil P, and soil P and runoff P at a range of times after fertiliser application is required.

Conclusions

Rainfall simulation using small plots and high intensities underestimates the concentration of P in runoff. However, it does provide useful relative estimates of soil fertility effects on runoff P. The processes of mobilisation of P may not be affected by the method of measurement. In both cases, P appears to be mobilised as a result of dissolution of P sources and subsequently P is transferred predominantly in dissolved (0.45 µm) forms. Rainfall simulation may be used in the prediction of runoff P concentrations at scales broader than plot providing the effect of the short residence times and high runoff rates from simulations are considered. It may also be necessary to consider the effect of hydrological issues such as variable contributing areas.

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