Understanding the Effects of Spatial Scale on Nutrient Dynamics Associated with Overland Flow in Semi-Arid Environments

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Abstract
An experiment was designed to further the empirical understanding of water and dissolved nutrient fluxes from hillslopes in semi-arid shrubland. It was hypothesised that the behaviour of dissolved nutrients might be related to the scale of the contributing hillslope/catchment area and dynamics of the overland flow as has been demonstrated to be the case for soil erosion (Parsons et al. 2004). Data from four hillslope scales and one subcatchment, collected over two monsoon seasons, support this hypothesis and demonstrate that the key controls of average dissolved nutrient loads are flow discharge and plot areas. An implication of these findings is that care must be taken when upscaling results describing nutrient behaviour from small plot experiments, as this behaviour appears to be scale dependent.

Introduction

In the US Southwest, over the last 150 years, a shift in dominance of shrub species over grass species has occurred, resulting in severe erosion and potentially high nutrient losses (Parsons et al. 2003, Schlesinger et al. 1990). Understanding the implications of this shift is therefore of fundamental importance if we are to arrest the currently unsustainable levels of land degradation and nutrient depletion in such environments (Frederickson et al. 1998).

Though some effort has been made to understand the distribution of nutrients within semi-arid soils (Schlesinger et al. 1996; Müller 2004) and the redistribution of nutrients in overland flow from different vegetation types, for example, Parsons et al. (2003; 2005), Schlesinger et al. (1999; 2000), very little work has addressed the dynamics of nutrient fluxes within areas dominated by shrub species at both different spatial and temporal scales under natural rainfall events. As the understanding of nutrient behaviour is currently based upon small scale experiments (see aforementioned papers for examples), but is required at larger scales to meet the needs of recent legislation (Dressing et al. 2003), there is a fundamental requirement to improve understanding at a wider range of scales. Therefore, this paper builds upon recent work reported by Parsons et al. (2004; 2005) who establish the link between hillslope scale and erosion rates in semi-arid environments, postulating that a similar relationship may be found between hillslope scale and nutrient dynamics. Herein we describe the behaviour of dissolved nutrients, primarily (Nitrogen) that are associated with the flow discharge and aforementioned erosion rates to provide a more holistic eco-geomorphic understanding of the off-site effects of intense rainfall and subsequent overland flow. It has been shown that as hillslope length increases and runoff coefficients decrease sediment yield from interrill areas initially increases (up until approximately seven metres downslope) and then decreases (Parsons et al. 2004; 2005). Thus, it is an objective of this paper to test whether such spatial scaling behaviour is also true of nutrient loads via interpretation of field data collected during 14 natural rainfall events over two monsoon seasons in the semi-arid Southwest of the USA.

Methods

The field site is part of the Lucky Hills catchment within the Walnut Gulch Experimental Watershed, southern Arizona, USA (Renard et al. 1993). Vegetation cover is predominantly woody shrub of the species *Larrea tridentata* and *Acacia constricta* (Weltz et al. 1994) which have succeeded the grassland community over the last 100-150 years (Renard et al. 1993). Soil types are Lucky Hills-McNeal sandy loams (Ustochreptic Calciorthids) which typically contain large proportions of rock fragments and have developed a distinct stone pavement across much of the catchment (Simanton et al. 1994) which has resulted in increased runoff rates and high levels of erosion throughout the catchment (Ritchie et al. 2005). Rainfall is monsoonal, typically falling as high intensity, short duration events between July and September with mean annual rainfall of 356 mm (Nichols et al. 2002).

Plots were constructed to monitor soil erosion at four locations within the catchment (Parsons et al. 2005). These were designed as pairs of small (ca. $2m^2$) control plots and larger plots: Laurel, Abbott, Dud and Wise, (21.01 m^2, 115.94 m^2, 56.84 m^2 and 302.19 m^2, with lengths of 4.12 m, 14.48 m, 18.95 and 27.78 m) which were also instrumented to monitor intra-event behaviour of rainfall, flow and nutrient fluxes on a one-minute timestep (see Figure 1 for an example). In addition, a $1500m^2$ first-order subcatchment (Cleese) was instrumented to monitor the same variables at a larger spatial scale to include the effects of concentrated (rill) flow as well as unconcentrated (interrill) flow within the investigation.

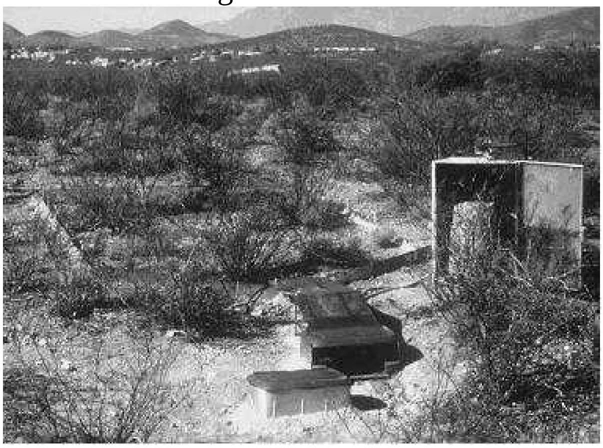

Figure 1. The Laurel hillslope plot (21.02 m^2)

Details of the plot construction are given in Parsons et al. (2005). A flume was located at the base of each plot to concentrate flow, allow measurement of flow depth and permit the extraction of pump samples for nutrient analysis. Samples were collected when the intake was completely submerged, at flow depths of 10-20mm. Depending upon event timing, samples were removed from the field site for filtering as soon as was practical and always within four hours of the end of each event. On return to the laboratory 30ml sub-samples of the one litre pump samples were taken and filtered through pre-rinsed 0.45µ Millipore HA filters into polypropylene sample bottles. These samples were then analysed for Ammonium (NH_4-N) and Nitrate (NO_3-N) using standard methods on a Traacs 800 Autoanalyser. Total inorganic N was taken as the sum of NH_4-N + NO_3-N. Each sample was then subjected to a persulfate digestion (D'Elia et al. 1977) and reanalysed. The difference between the digested and undigested concentrations was assumed to represent dissolved organic forms of N (DON).

Rainfall intensity was recorded using a tipping-bucket raingauge at each plot recording intensity on a one-minute timestep. Events were monitored over the 2001 and 2002 monsoon seasons. Though a total of seven rainfall events over the five sites occurred during this time (i.e. 35 plot-events), only 14 plot-events yielded high quality water, sediment and nutrient data.

Schlesinger et al. (1996) indicate that the pattern of vegetation within a study area exerts a strong control on the spatial distribution and redistribution of the nutrients by overland flow within that area. Consequently, surface cover afforded by vegetation (as well as stone pavement and fine particles) was kept as constant as was practical when plot location was determined (Table 1). Other variables such as soil type, and plot gradient were also kept as constant as possible though despite these efforts, some variation between plots is inevitable (Table 1). As this variability is by no means consistent between plots (Parsons et al. 2005), however, it is argued that it does not unduly bias the analysis of plot characteristics on nutrient behaviour.

Variable	Laurel	Abbott	Dud	Wise	Cleese
Mean pavement cover (%)	55.34	56.67	57.35	56.87	26.27
Mean fines cover (%)	24	14.1	21.7	16.5	48.77
Mean vegetation cover (%)	20.7	29.8	21.05	26.6	24.94
Gradient (degrees)	8.15	5.8	10.4	6.6	8*

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* Represents gradient of main channel

Table 1. Variables describing plot characteristics, modified from Parsons et al. (2005)

Results

To investigate the relationship between nutrient behaviour, hillslope characteristics and discharge an analysis of all 14 events from five spatial scales was performed. In the first instance this work focussed on a regression analysis of nutrient loads (mg m^2 min^{-1}) against plot areas. Figure 2 illustrates the relationship between instantaneous TN loads from all events and plot area. A wide range of TN load is evident from all plot sizes with large standard deviations (0.43, 0.54, 0.48, 0.39, 0.23 mg m^2 min^{-1}) around the means (0.79, 0.45, 0.49, 0.20, 0.31 mg m^2 min^{-1}) with increasing plot area and weak, positive relationships with plot area (r^2 = 0.13). When described by the median loads (to reduce bias towards any extreme values) Figure 2 shows a trend of increasing TN loads with plot area until approximately 56m^2 (corresponding with a slope length of 14.475 m) with a subsequent decrease in loads as plot areas increase up to 1500m^2.

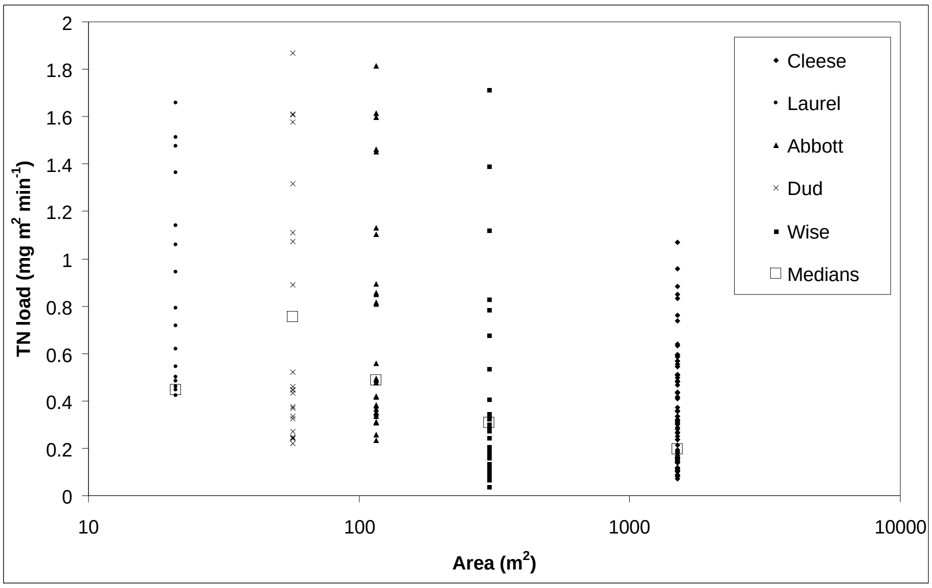

Figure 2 Instantaneous TN loads (mg m^2 min^{-1}) and median values as a function of area (m^2)

To consider the influence of overland flow upon nutrient behaviour instantaneous nutrient loads were plotted against instantaneous discharge for all events (Figure 3). Though there is some evidence for a very weak positive relationship between instantaneous loads and discharges, there is a high degree of variability within the dataset, particularly for low discharges, those less than 300 l min^{-1} producing TN loads of between 0.03 and 1.87 mg m^2 min^{-1}. However, if the influence of discharge on nutrient loads at each separate spatial scale is considered, Figure 3 shows the linear best fit lines that describe the discharge/load relationships at each scale, much stronger relationships are found as plot areas increase (r^2 = 0.82, 0.89, 0.89, 0.97, 0.54 respectively), suggesting that the relationship between nutrient yields and discharges identified by previous authors (Schlesinger et al. 2000), may in fact be scale dependent, as the slope of the best fit line decreases with an increase in scale. Thus the data collected here demonstrate a weak general increase in TN load with increasing discharge, though the rate at which this increase occurs is significantly reduced as plot size increases.

Discussion

Schlesinger et al. (2000) monitored nutrient yields from small (2m^2) plots under natural rainfall events and used these results in combination with atmospheric deposition data, to calculate net gains/losses of N to/from the landscape in units of kg ha^{-1} yr^{-1}. Results showed that losses of dissolved nutrients in runoff were potentially significant (0.43 kg ha^{-1} yr^{-1}) if extrapolated to the landscape scale. However, data presented here suggest that the relationship between the size of plot where observations are made and the magnitude of those observations may be more complex than has previously been assumed. In fact a positive relationship between plot/catchment area and nutrient loads (normalised by unit area) is evident across the range of plot sizes from 21 – 1500 m^2, a result that brings into question the approach of upscaling results from such small plots to the landscape scale, an area of work that requires much care, (Wainwright et al. 2000). A key finding of this work is that extrapolation of results from small spatial scale experiments using either simulated or natural rainfall events may be less meaningful if only one spatial scale of observation is used. Parsons et al. (2004) have demonstrated that for soil erosion it is the explicit consideration of hillslope length, that allows scaleable predictions of sediment yields to be made,

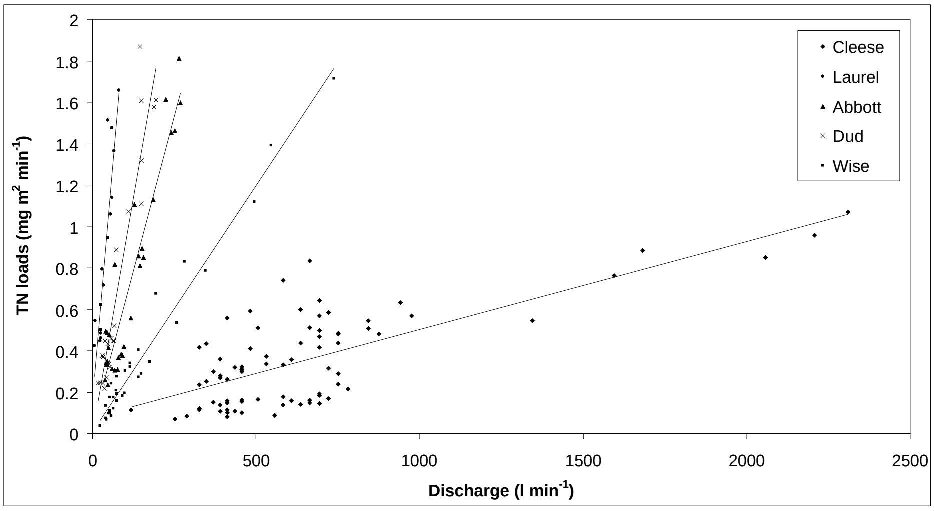

Figure 3 Instantaneous TN load (mg m^2 min^{-1}) as a function of instantaneous discharge (l min^{-1}).

herein it is suggested that a similar approach is taken to upscaling understanding of nutrient yields, with direct consideration of plot/catchment areas being made in order to provide larger scale estimates of dissolved nutrient losses in overland flow that do not underestimate potential losses by ignoring the effect of spatial scale observed here.

Conclusion

Observations show that event-based nutrient concentrations are initially high and decline through events, indicating that nutrient exhaustion occurs, in a system that can be described as supply limited. Nutrient loads are strongly controlled by event hydrology, so that even when concentrations are at their highest (typically on the rising limb of the hydrograph), dissolved loads are low, only reaching their peak when discharge increases. As desert soils tend to be low in nutrients and in this case have suffered from accelerated erosion over the last 100-150 years, such behaviour is understandable and agrees with the existing datasets that describe event dynamics at single spatial scales from rainfall simulation experiments. In addition these data show that there is a scale dependence in nutrient behaviour, such that dissolved loads increase with increasing plot size, a conclusion which suggests that upscaling observations from small plot experiments may provide underestimates of nutrient loads from the larger catchment scale.

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