Tracing sediment movement on a semi-arid watershed using Rare Earth Elements

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Introduction

Sediment is the most common non-point source pollutant that affects surface water quality and the environment. The movement of soil in watersheds is difficult to quantify because of the existence of multiple sources and sinks of sediments. Identifying these sources and sinks is a complex task, which requires proper sampling, evaluation and modeling techniques. Experimental data, which shows spatial translocation of soil on slope, is rare. At present time there is limited number of reliable field technique capable of tracking soil movement on watershed. One method for obtaining such information is through the use of sediment tagging using appropriate tracer technology. Use of tracers is based on the assumption that tracer concentration is constant across range of particle sizes and area of application.

Tracers used in soil erosion research:
- naturally occurring (210Pb, 7Be, 243Th)
- atomic tests fallout (137Cs)
- deliberately introduced (49Fe, 60Co, metal-labeled particles, magnetic and glass beads, fluorescent coating, etc).

Desired tracer properties:
- strong binding with soil
- sensitivity in analysis
- low background concentration in soil
- non-interfering with sediment transport
- chemical stability
- low uptake by plants
- environmentally safe
- range of tracers with similar properties

In our study a method in which rare earth element (REE) oxides in a powder form were employed to trace sediment movement within watershed was developed.

Objectives

- Assess the applicability of the multiple tracer method in the rangeland setting
- Develop a technique for tracer application on rangeland
- Determine to what degree landscape elements within a small arid watershed act as sources and sinks of sediment

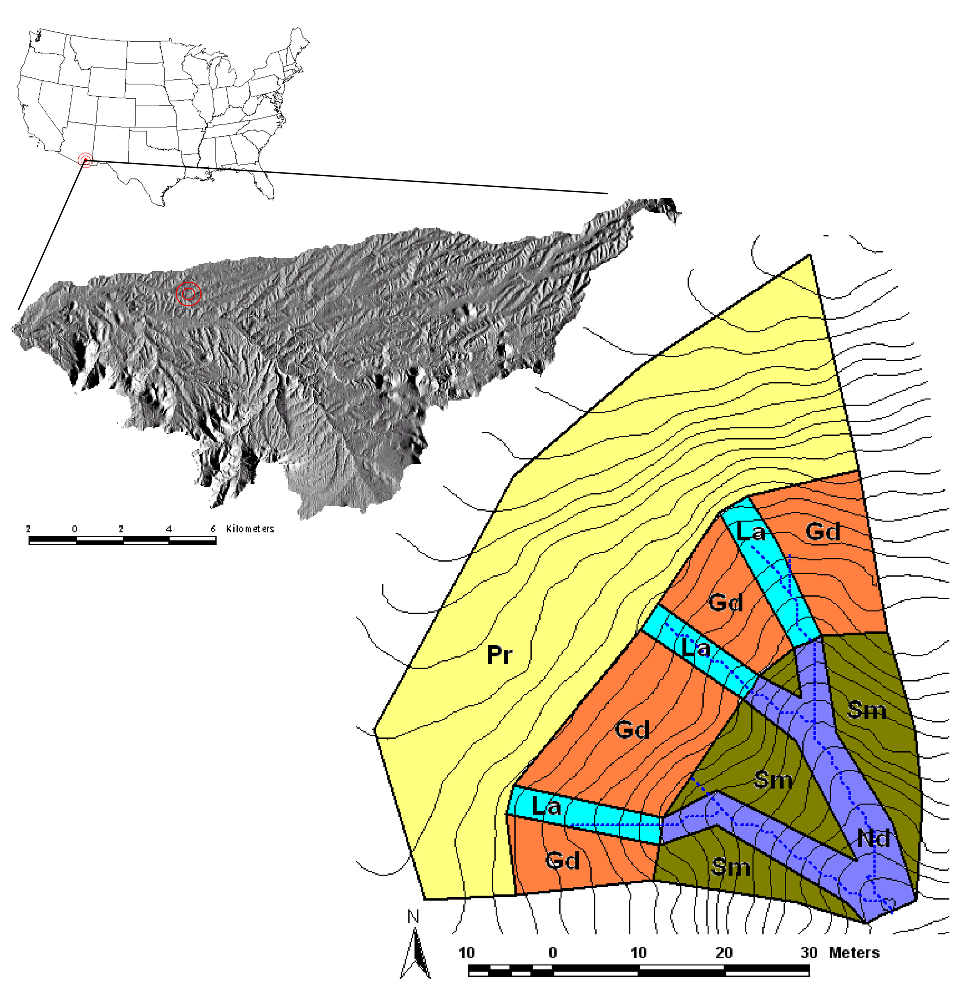

Figure 1. Watershed 106, WGEW.

Methods

Study site: Walnut Gulch Experimental Watershed, San Pedro River basin, AZ (Fig. 1, 2)
Study period: 7/2005 - 9/2005
Rainfall: 292 mm/year
Area: 0.33 ha
Soil: Luckyhills and McNeal, 38.7% gravel, 31.6% sand, 16.2% silt, 13.5% clay
Vegetation: Creosote (*Larrea tridentata* (DC.) Coville) and Whitethorn (*Acacia constricta* Benth.)

Figure 2. Lucky Hill site, Walnut Gulch Experimental Watershed.

Table 1. REE application areas, amounts, and concentrations.

	Unit	REE tracer				
		Upper slope	Middle slope	Lower slope	Upper channel	Lower channel
REE tracer		Pr	Gd	Sm	La	Nd
Mean particle size (D50)	µm	6.93	4.4	5.54	0.96	7.63
Application area	sq. m	1582	744	502	177	286
Fraction of area	%	48.1	22.6	15.3	5.4	8.7
Mass of oxide applied	kg	6.5	2.11	1.52	1.57	2.36
Background concentration	mg/kg	6.07	4.42	4.47	24.39	22.19
Tagged soil concentration	mg/kg	91386	61097	72033	95670	106224

Five rare earth element (REE) oxides were selected as tracers (Table 1). The reasons were:
- good association with soil aggregates (Zhang, 2001)
- insolubility in water
- low natural background level
- low uptake by plants, stable, environmentally safe
- availability of multiple tracers with distinct signature but similar in physical and chemical properties

Watershed was subdivided into five areas (Fig. 1)
- channel: upper and lower
- slope: upper, middle, and lower

Figure 3. Flume on Watershed 103, Walnut Gulch Experimental Watershed.

Data collected
- runoff and sediment yield
- sediment in runoff
- composite surface samples at the end of the experiment

We can assume that the tracers arrive to the outlet in the amount proportional to a) the amount of them applied and b) the amount of soil loss in their corresponding watershed element. Hence, the sediment yield from a watershed section (kg) may be expressed as:

$$s = (m_i / M_i) / \sum(m_i / M_i) \cdot S$$

where *i* is an individual tracer used in the study; Mi and mi are amounts of this tracer applied on and recovered from the watershed respectively; S is a total sediment yield as determined from runoff samples.

Sample analysis
- acid digestion method (Zhang, 2001) modified from USEPA standard method for extractions of metals from environmental samples (USEPA, 1995).
- chemical analysis using Inductively Coupled Plasma-Mass Spectrometer (ICP-MS)

Results and discussion

Sediment yield from the watershed during the experimental period ranged from 0.07 to 0.7 t ha^{-1} per event which covered the range of sediment yields that occurred on the watershed since recording started in 1996. Long term (11 year) sediment yield was well correlated (R^2=0.71) with runoff (Fig. 4).

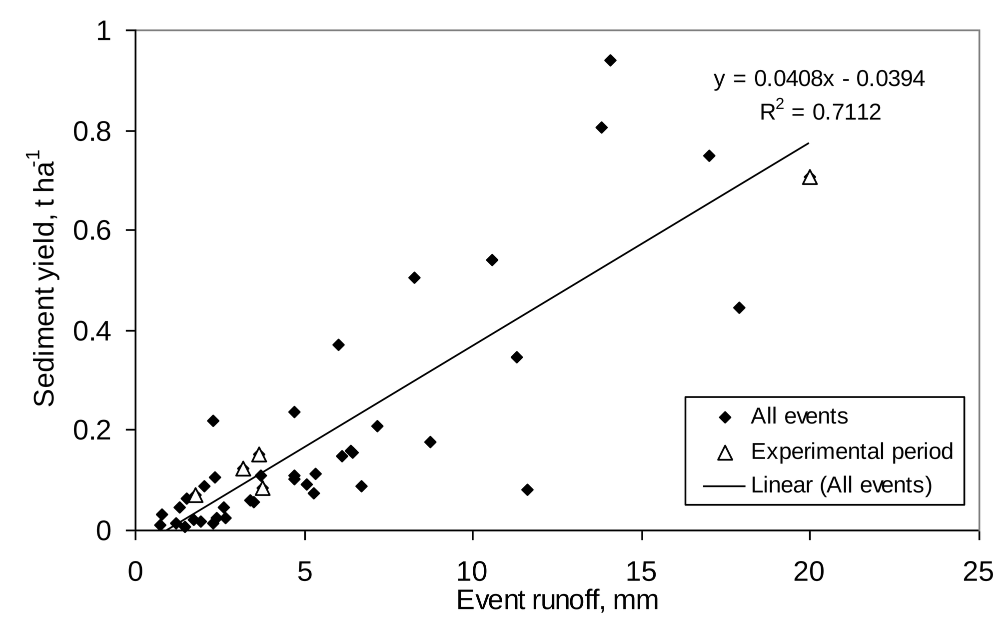

Figure 4. Sediment yield from the watershed during the experimental period and long term (1996 – 2008) data.

The combined sediment yield caused by all storms (Fig. 5) was the greatest on the upper channel (5.7 t ha-1) closely followed by lower channel (4.9 t ha^{-1}). Sediment yield from other locations was moderate (1.2 t ha^{-1} on lower slope) to minimal (0.1 t ha^{-1} on upper slope). Total weighted average sediment yield was 1.6 t ha^{-1}.

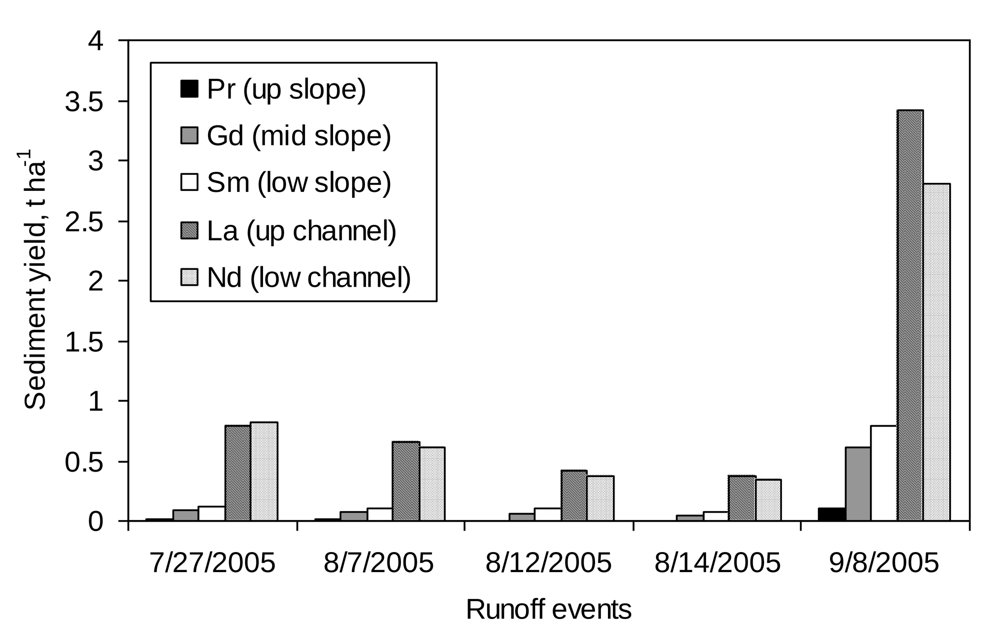

Figure 5. Sediment yield at the watershed outlet from different morphological areas of the watershed during the study period

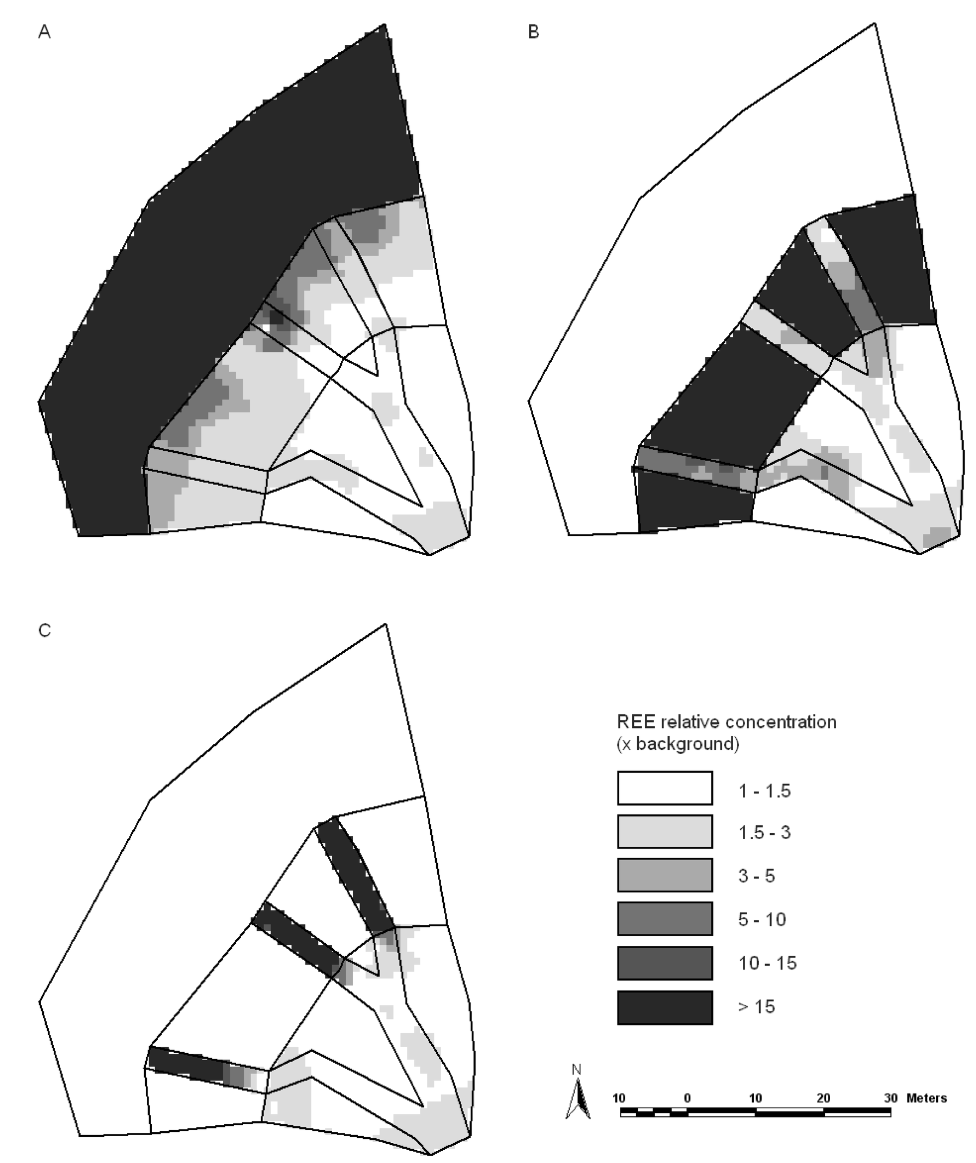

Figure 6. Redistribution and pathways of REE tracers in surface soil from upper slope (A), middle slope (B), and upper channel (C) by the end of the experimental period.

Figure 6 shows details of depositional patterns from upper and middle slopes and upper channel on downslope areas. The flow from the upper slope (Fig. 4A) occurred in a wide frontal pattern and was directed towards middle slope and upper channel. As a result, there was a wide depositional area just below the upper slope, which may indicate that a diffusive erosion process took place. The middle slope, on the other hand, is adjacent to well developed channels. Hence, runoff and sediment move towards the channel over a relatively short distance with little movement occurring in the direction of lower slope. The channel network is well developed which facilitates effective transport of eroded sediments. Once in the channel the sediment moves unobstructed towards the outlet (Fig. 4B). It is plausible that the erosion patterns observed on the watershed are indicative of the long term erosion rates.

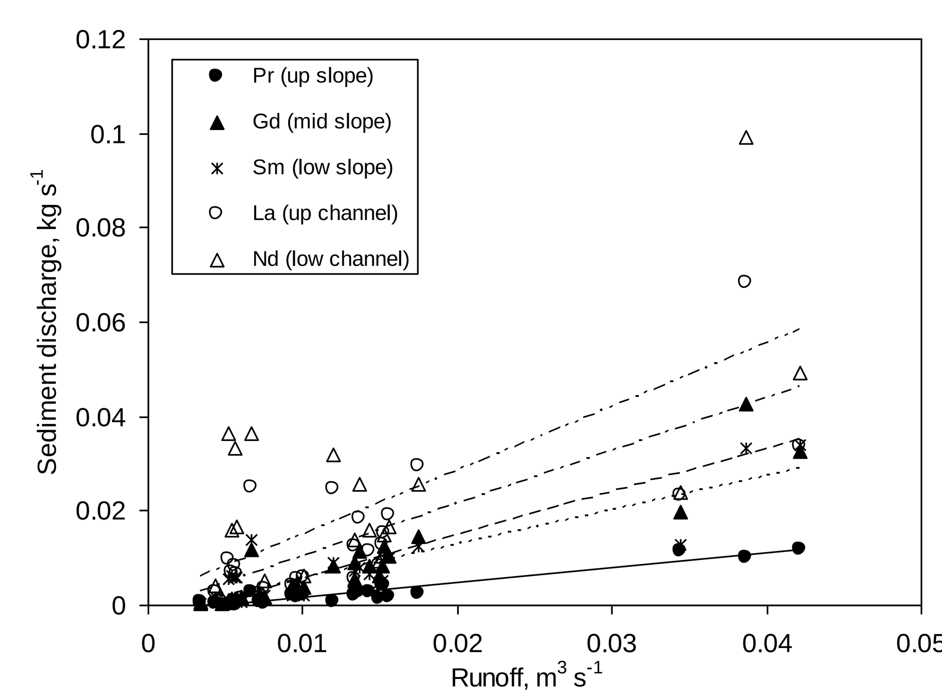

Figure 7. Relationship between runoff and sediment rates from different morphological units of the watershed

Sediment discharge rate was directly linearly related to the runoff rate for all watershed units (Fig. 7) with correlation coefficient ranging between 0.44 (lower channel) and 0.92 (upper slope). The slope coefficient of the regression reflected the morphology and relative position of the watershed units. It was the lowest for upper slope (0.313) and the highest for lower channel (1.348).

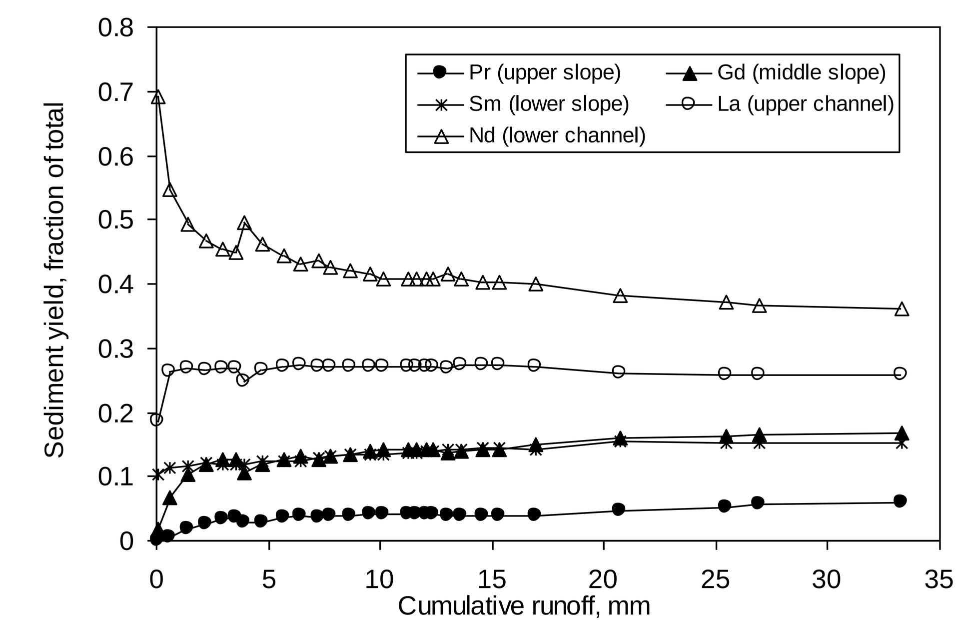

Figure 8. Relative contribution of different areas of the watershed to the total sediment yield during the course of the experiment.

Figure 8 displays the sediment yield dynamics in relation to cumulative runoff from all rainfall events combined. Sediment delivery was characterized by a time lag that varied depending on proximity of the watershed unit to the outlet.
At the beginning of the observation period 70% of the sediment reaching the outlet originated from the lower channel, 20% from the upper channel, and 10% from the lower slope, while the contribution of the middle and upper slope was negligible. Later on the fraction of sediment from each unit approached asymptotic values between 36% (lower channel) and 6% (upper slope).
Relatively low sediment delivery from the upper slope was due to its low erosion rate. At the beginning of the experiment the limiting factors for tagged sediment delivery were both detachment and transitional accumulation. However, by the end of the observation period there was equilibrium in detachment-delivery system. While the upper slope was by far the largest area in the watershed, at equilibrium it contributed the least sediment (per unit area) to the outlet.

Conclusion

- REE have uniform natural background concentration in soil
- While the average sediment yield on the watershed was 1.2 t ha^{-1}, local rates varied between 0.1 ha^{-1} and 5.7 t ha^{-1}
- The surface application of tracer yields satisfactory results and is suitable for short term studies
- Concave landscape elements with steeper slopes experienced the highest net erosion rates, while the upper slope was relatively stable
- Sediment tracing using REE proved to be a useful tool for measuring sediment redistribution in rangeland watershed with coarse soil

References

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