Tracing Sediment Movement on a Semiarid Watershed using Rare Earth Elements

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A multi-tracer method employing rare earth elements (REE) was used to determine sediment yield and to track sediment movement in a small semiarid watershed. A 0.33-ha watershed near Tombstone, AZ was divided into five morphological units, each tagged with one of five REE oxides. Relative contribution of each unit to the total sediment yield was determined by collecting runoff and sediment, and the spatial redistribution of sediment was determined from sampling the soil surface. Average sediment yield was 1.0 Mg ha^{-1} yr^{-1} from the entire watershed, but varied between 0.1 Mg ha^{-1} yr^{-1} from the upper slope to 5.0 Mg ha^{-1} yr^{-1} from the lower channel. Little re-deposition occurred in the channels indicating an effective transport system. The erosion pattern and rates were in agreement with the current morphology of the watershed, which has a well-developed channel network.

Abbreviations: DEM, digital elevation model; ICP–MS, Inductively Coupled Plasma Mass Spectrometer; LC, lower channel; LS, lower slope; MS, middle slope; REE, rare earth element; RHEM, Rangeland Hydrology and Erosion Model; RTK GPS, real time kinematic global positioning system; UC, upper channel; US, upper slope; USLE, Universal Soil Loss Equation; USDA-ARS, United States Department of Agriculture-Agricultural Research Service; WEPP, water erosion prediction project; WGEW, Walnut Gulch Experimental Watershed.

Advancing our understanding of hydrological processes taking place on arid rangelands necessitates development of new tools capable of monitoring and modeling them. Development of erosion modeling tools such as Water Erosion Prediction Project (WEPP; Flanagan and Nearing, 1995) and Rangeland Hydrology and Erosion Model (RHEM) aimed specifically at rangelands (Wei et al., 2007) requires new sets of field data to be obtained, namely, data that can show the fate of sediment eroded from specific source areas within watersheds. Among the most common approaches to studying spatial distribution of erosion and pollution sources is the use of soil tracers.

Tracing techniques have been developed and applied to quantify and map erosion and sedimentation. Various soil chemical and physical properties, such as mineral magnesium (Caitcheon, 1998; Motha et al., 2002; Parsons et al., 1993), particle shape and color (Krein et al., 2003), grain distribution of sediments (Kurashige and Fusejima, 1997), naturally occurring radionuclides (Wallbrink and Murray, 1996; Walling et al., 2003; Wilson et al., 2003; Zapata, 2003), as well as man-made substances such as radioactive fallout (Ritchie and McHenry, 1990), fly ash (Gennadiev et al., 2002; Olson et al., 2006), and magnetic and other particles (Ventura et al., 2002), have been used as sediment tracers. A combination of several physical and chemical properties of sediments, which is called the fingerprinting technique, has also been utilized (Collins and Walling, 2002; Krause et al., 2003; Rhoton et al., 2008).

Single tracer techniques have performed well in providing data on the spatial distribution of erosion and deposition in a study area. However, the use of multiple tracers have an advantage over a single tracer in that it may provide information on sediment redistribution. In addition to measuring the net gain at a given point on a watershed, multiple tracers can be used to identify the relative contribution of several upslope sources to the deposited sediment at a specific point downslope. Likewise, in areas of net soil loss (erosion), the fate of the lost sediment can be followed: where the sediment was re-deposited downslope and how much exited the watershed.

Rare earth elements, or the lanthanides, is group of elements with periodic numbers 57 through 71. Lanthanide's trivalent state and ionic radii ranging between 0.861Å (Lu^{3+}) and 1.03Å (La^{3+}), similar to that of Ca^{2+}, allow easy adsorption on to clays when they are applied in the form of oxides. Rare earth elements possess a range of characteristics desirable for tracers, such as low background concentration in soils (Markert, 1987), good soil binding properties (Mahler et al., 1998; Zhang et al., 2001), sensitivity to analysis, no interference with soil movement, chemical stability, negligible biological uptake and low toxicity (Wyttenbach et al., 1998), and the availability of a range of elements (Lu through La) with similar properties.

Rare earth element oxides have been used as tracers in environmental science (Krezoski, 1989) and geology (Mahler et al., 1998). Recently this technique has made its way to soil erosion research both in the laboratory under simulated rainfall (Polyakov and Nearing, 2004; Zhang et al., 2003) and on the

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field in short-term (Li et al., 2006; Matisoff et al., 2001; Polyakov et al., 2004; Tian et al., 1994) and long-term studies (Kimoto et al., 2006b). However, the method has not been tested in a semiarid rangeland environment, where mechanical incorporation of the tracer into the top soil layer may not be possible. In addition, coarse gravely soil of the U.S. Southwest region presented an additional challenge, which requires special methods to be employed to account for variations in soil particle-size specific adsorption (Kimoto et al., 2006a).

The objectives of this study were (i) to adapt the REE multiple marker tracer method in the rangeland setting with undisturbed soil that would allow evaluation of spatial and temporal soil erosion distribution, and (ii) to assess the sediment movement and yield on a small rangeland watershed in southern Arizona.

MATERIALS AND METHODS

Description of the Experimental Site

The study was conducted on Watershed 106 (31° 44' 31" N; 110° 3' 13" W) in the Walnut Gulch Experimental Watershed (WGEW) that is located within the upper San Pedro River basin in southern Arizona, USA. Walnut Gulch is an ephemeral tributary to San Pedro River. The WGEW has a total area of 148 km^2 and supports an array of land uses, among which are cattle grazing, mining, limited urbanization, and recreation. The geology of the area is represented primarily by fan deposits with igneous-intrusive and volcanic rocks in the southeastern and southern parts of the WGEW. This study was conducted on the alluvial fan deposits. The alluvium is very deep and consists of clastic materials ranging from clay and silts to boulder conglomerates.

The climate of the area is semiarid with highly spatially and temporally varying precipitation dominated by the North American Monsoon. The mean annual precipitation from1963 through 2004 at Watershed 106 was 292 mm, with 60% of the total occurring in July, August, and September during the monsoon season. Monsoon storms are typically characterized as short-duration, high intensity, localized rainfall events. Mean annual temperature is 17.7°C.

Watershed 106 is located at 1361 m above sea level, has an area of 0.33 ha and average slope of 8.8%. It is covered with shrub, dominated by Creosote (*Larrea tridentata* [DC.] Coville) and Whitethorn (*Acacia constricta* Benth.). Luckyhills (coarse-loamy, mixed, superactive, thermic Ustic Haplocalcids) and McNeal (fine-loamy, mixed, superactive, thermic Ustic Calciargids) from Luckyhills-McNeal complex (very gravely sandy loam) are the two soil series identified on Watershed 106 (USDA, 2003). The soil consists of approximately 39% gravel, 32% sand, 16% silt, and 13% clay (Kimoto et al., 2006a). The organic C content of the soil surface (0–2.5 cm) ranges from 0 to 1.0%, calcium carbonate content ranges from 0 to 4%, and the pH ranges between 7.4 and 8.4.

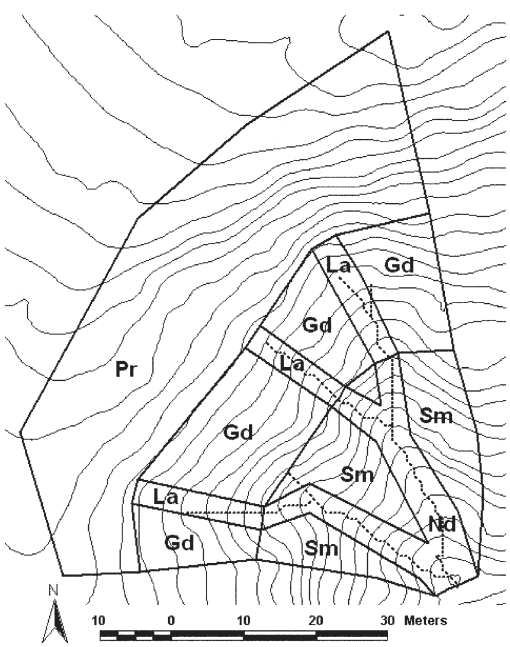

Fig. 1. Topography and location of channels on the experimental watershed. The elementary morphological units are delineated by polygons and labeled with the corresponding REE name: upper slope (US), middle slope (MS), lower slope (LS), upper channel (UC), and lower channel (LC). Contour intervals are 0.2 m.

Tracer Preparation and Application

The watershed was divided into five morphological units: upper slope (US), middle slope (MS), lower slope (LS), upper channel (UC), and lower channel (LC) (Fig. 1). This division reflected the relationship between topography and erosion process. Considerations for the division were the flow accumulation pattern, slope length, gradient and aspect, and observations in the field such as existing rills, depositional areas, etc. Five REE oxides (La_2O_3, Pr_6O_{11}, Sm_2O_3, Gd_2O_3, and Nd_2O_3) were used as the tracers. A different tracer element was assigned to each of the morphological units.

The tracers were applied on the study area in a soil mixture (Table 1) in June 2004. A leaching experiment on the same soil by Kimoto et al. (2006a) showed that after tagging the soil with REE oxides their distribution among various particle-size classes was non-uniform. To prepare the tracer mixture, soil collected on the watershed was air-dried, passed through a 4-mm sieve and subdivided into three groups (<0.088, 0.088–0.3, and 0.3–4.0 mm), based on laboratory chemical binding results (Kimoto et al., 2006a). Then, soil of various size classes were thoroughly mixed with the REE oxide powders in the amount needed to achieve the same concentration in all three groups, to address the issue of size specific binding preferences (Kimoto et al., 2006a). Then the mixture was wetted and air-dried again. The wetting and drying cycle was meant to better associate the REE powder and soil aggregates. The ratio of soil to REE oxides in the application mixture was 10:1. The REE concentrations in the soil on the watershed were targeted to be approximately 100 times of the background concentrations, assuming an arbitrary incorporation depth of 0.5 cm. The REE and soil mixture was spread on the watershed by hand as evenly as possible by marking off small areas on the order of approximately 30 to 100 m^2 with string and subdividing the amount of tracer to be applied on each marked off area. The entire area was then sprayed with water taking care that no runoff was generated to better associate the tagged material with the soil and to reduce potential dust removal by wind. In addition, before the first runoff occurred more than a year after the treatment, there were 64 rainfall events with a total of 192 mm of precipitation that did not generate runoff. This sequence of wetting, raindrop impact and drying ensured that loose soil mixture spread on the surface become consolidated and resembled the undisturbed soil.

Data Collection and Analysis

Precipitation and runoff data as well as sediment samples in runoff and surface soil samples were collected during the course of the experiment. Precipitation was measured using a high resolution (0.25 mm, 1 min) rain gauge located on the eastern edge of the watershed.

The watershed is equipped with an H-Flume with a depth-integrated pump sampler (Nearing et al., 2007; Nichols et al., 2008). Runoff samples collected during individual runoff events were used to determine the total sediment yield from the watershed as well as relative sediment contribution from each morphological unit to total sediment yield. Runoff samples were collected during each runoff event at 3- to 10-min intervals depending on the flow duration.

Table 1. Rare earth elements application areas, amounts, and concentrations.

		Watershed unit				
	Unit	Upper slope	Middle slope	Lower slope	Upper channel	Lower channel
REE tracer		Pr	Gd	Sm	La	Nd
Mean particle size (D50)†	μm	6.93	4.40	5.54	0.96	7.63
Application area	m^2	1582	744	502	177	286
Fraction of area	%	48.0	22.6	15.3	5.4	8.7
Mass of oxide applied	kg	6.50	2.11	1.52	1.57	2.36
Background concentration	mg kg^{-1}	6.07	4.42	4.47	24.39	22.19
Tagged soil concentration	mg kg^{-1}	91386	61097	72033	95670	106224
Target concentration‡	mg kg^{-1}	632.15	432.60	460.95	1347.53	1253.70
Measured concentration	mg kg^{-1}	702.97	469.98	554.10	1306.79	1348.65

† (Polyakov, 2002).

‡ Target concentration determined assuming uniform mixing to a depth of 0.5 cm.

Soil surface samples were used to identify sediment sources and pathways on the watershed. Surface sample locations were randomly distributed over the watershed, except the upper slope, where no samples were collected. The reason for this is that redistribution of a tracer within its area of application could not be detected by surface sampling in a short-term study (Polyakov et al., 2004). A small change in Pr concentration due to erosion would be well within the variability range of the tagged soil and be masked by Pr already present there. In contrast, on lower areas where Pr was not applied a small increase in its concentration against low natural background (6 ppm) would be readily detected. A total of 61 sampling locations were identified using RTK GPS and marked with flags. Combined samples were collected using metal probe 19 mm in diameter. Each combined sample consisted of 30 subsamples taken randomly within a distance of 2 m from the flag to a depth of 1.5 cm. Surface samples were collected following the end of monsoon season on 19 Sept. 2005.

Soil and sediment samples were air-dried, thoroughly mixed, and ground. Subsamples of 2 g were then taken for acid digestion and analysis by Inductively Coupled Plasma Mass Spectrometer (ICP–MS). Acid digestion was performed using the extraction procedure modified by Zhang et al.(2001) from the USEPA standard method for extractions of metals from environmental samples (USEPA, 1995). Two grams of soil sample was placed into a 50-mL flask. Ten milliliters of concentrated HNO_3 (70% by weight) was added, and the mixture refluxed for 2 h in a water bath at 85°C. After cooling to <70°C, 10 mL of H_2O_2 (30%) was slowly added to remove organically bound REE. The solution was then heated to 85°C until effervescence subsided. Five milliliters of concentrated HCl (36% by weight) was added, and the solution again refluxed for 2 h in a water bath at 85°C. After a 24-h waiting period at room temperature, the solution was filtered through Whatman filter Paper # 5, and eluted with 5 mL of deionized water (18 MΩ cm^{-1}). The solution was then filtered througsh a 0.45-μm membrane. The analysis was performed on ICP–MS model ELAN DRC-II by PerkinElmer at the Arizona Laboratory for Emerging Contaminants, University of Arizona, Tucson. Samples were diluted 100,000-fold in 1% (v/v) nitric acid.

The watershed was surveyed using RTK GPS collecting 426 elevation points. This data was used to create 1-m DEM of the watershed and compute nine topographic attributes (Table 2). Sediment transport index, topographic wetness index, and stream power index were calculated as defined by Moore et al. (1993). Tracer concentration at the sampling locations downslope from their respective area of application was correlated with topographic attributes at the same locations.

Table 2. Description of topographic attributes.

Topographic attribute	Units	Definition
Gradient	%	Slope between horizontal plane and soil surface
Flow path length	m	Maximum distance of water flow to a point
Sediment transport index	dimensionless	Characterizes the effect of topography on soil loss, analogous to LS factor in USLE, but applicable to 3D landscape
Topographic wetness index	dimensionless	The ratio between the catchment area and slope to reflect flow accumulation.
Profile curvature	deg m^{-1}	Down slope curvature of slope segment
Plan curvature	deg m^{-1}	Across slope curvature of slope segment
Mean curvature	deg m^{-1}	Combined curvature of slope segment
Stream power index	kg s^{-3}	Time rate energy expenditure per unit contour width
Specific catchment area	m^2 m^{-1}	Upslope area draining across unit contour width

RESULTS AND DISCUSSION

Storm Characteristics and Soil Loss

More than 80 rainfall events with total precipitation of 333.6 mm occurred during the observation period from June 2004 through September 2005. Among the rainfall events, only five (107 mm) produced measurable runoff (32.4 mm or 30% of precipitation) and sediment yield (1.2 Mg ha^{-1}), and all of these occurred during the 2005 monsoon season. No runoff producing events occurred in 2004. The historical average precipitation (1964–2008) at the location for the monsoon season (July, August, and September) was 187 mm.

The runoff events were a result of short duration, high intensity storms (Table 3). The four smaller storms of the five represented 24-h return frequencies of <1 yr, but the storm of 8 Sept. 2005 storm had a return frequency of approximately 4 yr. The September 8 event, though representing only 12% of the total rainfall, produced 61% (20 mm) of the total runoff and generated 62% (243 kg) of total sediment yield. To put this storm into context, the average annual sediment delivery for this watershed for the 11-yr period from 1995 through 2005 was 272 kg yr^{-1} (Nearing et al., 2007). Sediment delivery rate at the flume outlet during an individual event was highly variable with the peak occurring at approximately 1/3 into the duration of runoff.

Sediment yield from the watershed during the experimental period ranged from 0.07 to 0.7 Mg ha^{-1} per event, which

Table 3. Rainfall evens and their characteristics during the study period.

Rainfall event	Precipitation			Runoff			Sediment yield
	total	peak	duration	total	peak	duration	
	mm	mm h^{-1}	min	mm	mm h^{-1}	min	kg
7/27/2005	24.5	68.6	148	3.7	15.0	43	52.17
8/07/2005	11.4	83.8	41	3.2	18.4	33	42.01
8/12/2005	17.9	83.8	183	3.7	15.6	78	28.80
8/14/2005	14.7	38.1	192	1.8	7.8	77	24.06
9/08/2005	38.7	144.8	76	20.0	76.4	79	243.15
Total	107.2			32.4			390.19

fairly well covered the range of magnitudes of sediment yields that occurred on the watershed from 1996 through 2008 (Fig. 2). Sediment yields for events over the 13-yr period, including the five events from the study period, were well-correlated (R^2 = 0.71) with runoff (Fig. 2).

The runoff samples provided information on total sediment yield and concentration of REEs in the sediment. Using this information it was possible to determine the contribution of the five different watershed topographic units to the total sediment yield. The soil loss from an individual watershed unit could not be calculated directly based on tracer concentration in the sediment recovered at the outlet because the tracers were not incorporated into the depth of the soil as was done in previous studies (Polyakov et al., 2004). However, we can assume that the tracers arrive to the outlet in the amount proportional to (i) the amount of them applied and (ii) the amount of soil loss in their corresponding watershed unit. Hence, the sediment yield from a watershed unit (kg) may be expressed as:

$$s = (m_i/M_i)/\sum(m_i/M_i)S \quad [1]$$

where i is an individual tracer used in the study; M_i and m_i are amounts of this tracer applied on the watershed and recovered from the runoff respectively; S is a total sediment yield as determined from runoff samples. Equation [1] does not account for the sediment detached and redeposited before reaching the outlet. However, it may eliminate or reduce the error associated with tracer enrichment assuming that all REEs had the same enrichment coefficient.

Sediment yield from individual topographic unit of the watershed during the study as determined from Eq. [1] and presented in Fig. 3 demonstrates a large spatial variation. The combined sediment yield caused by all storms was the greatest on the upper channel (5.0 Mg ha^{-1}) closely followed by lower channel (4.3 Mg ha^{-1}). Sediment yield from slopes was moderate (1.0 Mg ha^{-1} on lower slope) to minimal (0.1 Mg ha^{-1} on upper slope). Total average sediment yield was 1.0 Mg ha^{-1}.

There are several possible explanations for such differences. First, the channels have a larger gradient (13.0%) compared with the slopes (8.1%), and more importantly, greater flow accumulation. Second, the variable erosion pattern could be linked to the concept of partial runoff contribution. Lane and Kidwell (2003), using several methods and a herbicide tracer study on a watershed in a similar semiarid conditions, suggested that only 45 to 60%, of the drainage area was contributing runoff at the watershed outlet. These non-contributing areas are mostly located on slopes with low gradient on the watershed edges, which in our case was the upper slope.

Sediment Source Distribution

The watershed under investigation was a rangeland; hence the tracers could not be incorporated into the soil, and were applied on the surface. Because of this the budget for every watershed element could not be explicitly calculated (Polyakov et al., 2004). However the analysis of the surface samples enables assessment of relative sediment distribution and pathways over the watershed.

The coefficient of variation of background concentrations of different REEs in our study was relatively uniform and ranged from 17.3% for Pr to 19.7% for Gd (Table 1). Thus a 40% increase in REE concentration in surface samples could be interpreted as being caused by sedimentation (at α = 0.05).

Figure 4 show details of depositional patterns from upper and middle slopes and upper channel on downslope areas. It appears from Fig. 4A that the flow from the upper slope occurred in a wide frontal pattern and was directed toward 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. A relatively small amount of Pr (the upper slope tracer) was found in the lower channel and in the sediment leaving the watershed. A possible explanation for

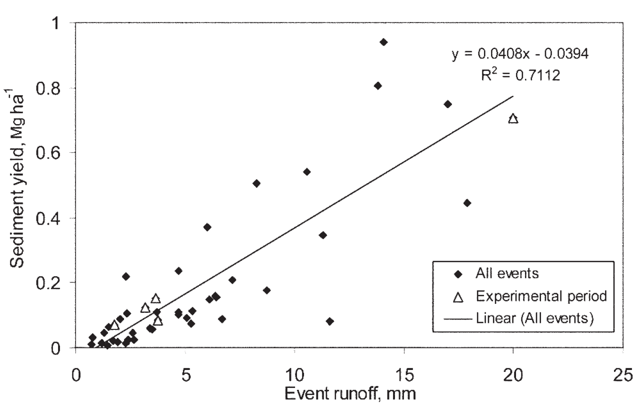

Fig. 2. Sediment yield from the watershed during the experimental period and long term (1996– 2008) data.

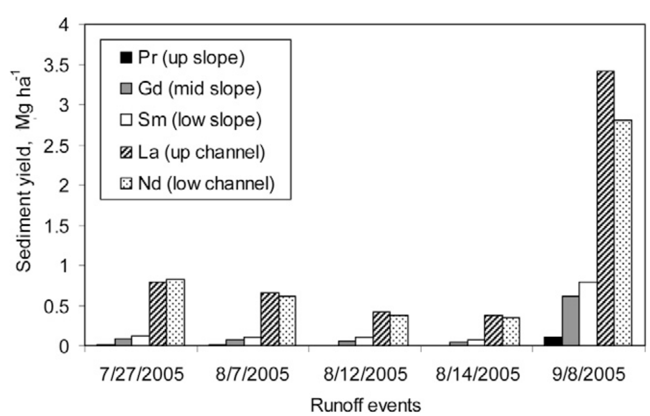

Fig. 3. Sediment yield at the watershed outlet from different morphological areas of the watershed during the study period.

such behavior is that the area between upper and middle slope is poorly channelized. The watershed is in a degraded condition where shrubs are essentially lone plants separated by relatively wide spaces with low vegetative cover, which facilitates sheet flow and diffusive erosion process.

The middle slope, on the other hand, is adjacent to well-developed channels. Hence, runoff and sediment move toward the channel over a relatively short distance with little movement occurring in the direction of lower slope. The channel network is well developed and has an average gradient of 13.0%. This facilitates effective transport of eroded sediments. Once in the channel the sediment moves unobstructed toward the outlet (Fig. 4b). The deposition in the channel occurred either close to the source or at the lower most section of the channel where the channel bed is stabilized by the flume structure.

None of the nine topographic attributes (Table 2) was a good predictor of tracer concentration on the soil surface. However, for Pr (applied on the upper slope) the best predictor was flow path length (R^2 = 0.15), while for Gd (applied on the middle slope) the best predictor was the topographic wetness index (R^2 = 0.26). Both relationships were significant at 95% confidence level. This corresponds well with the observations described earlier. Sediment from the upper slope moving in sheet flow over a relatively flat surface creates a uniform front with concentration gradient being a function of the distance from the source. The middle slope, on the other hand, is adjacent to the well-defined channel network. The sediment that originates from the middle slope enters the channel almost immediately and is transported a relatively long distance in concentrated flow. Hence, topographic wetness index, which is a function of slope and flow contributing area, was a better predictor of tracer redistribution than other topographic attributes.

Concave areas with convergent flow and decreasing slope are generally characterized by a relatively high sediment retention rates (Montgomery et al., 1997) and often become a sediment sink. This is observed on Fig. 4(a-c) near the flume, where a three- to five-fold increase over the background REE concentration coincided with the slope gradient decrease and concave form of relief.

Sediment Transport Dynamics

Sediment discharge rate was directly linearly related to the runoff rate (Fig. 5) for all watershed units with correlation coefficient ranging between 0.44 (lower channel) and 0.92 (upper slope). It should be pointed out that the runoff rate reported was the total watershed rate at the outlet, and not the rate from an individual morphological unit. The slope parameter of the linear relationship reflected the morphology and relative position of the watershed units. It was the lowest for upper slope (0.313) and the highest for lower slope (1.348).

Figure 6 displays the sediment yield dynamics in relation to cumulative runoff from all rainfall events combined. The first runoff sample collected during the observation period reveled that 70% of the sediment reaching the outlet originated from the lower channel, 20% from the upper channel, and 10% from the lower slope of the watershed. The contribution of the middle and upper slope was negligible. Later on the fraction of sediment from individual morphological units approached asymptotic values between 36% (lower channel) and 6% (upper slope). This indicates that there was a transport lag in delivering tagged sediment from various morphological units to the outlet. This lag was greater for units located far from the outlet and smaller for adjacent units. The fraction that an individual unit contributed to the total sediment yield became relatively constant after a sufficient amount of cumulative runoff has occurred.

We believe that the disproportionally low sediment delivery from the upper slope was due to its low erosion rate. It took approximately 20 m^3 of runoff (Fig. 6) to accumulate transitional sediment tagged with REE on the flow path to the outlet. During this time the delivery of tagged sediments at the flume was low but increasing. The limiting factors for sediment delivery were both detachment and transitional accumulation. However, by the end of the observation period there was equilibrium in detachment-delivery system and the detachment was the limiting factor. Note that while the upper slope was by far the largest area in the watershed (Table 1), at equilibrium it contributed the least sediment to the outlet (Fig. 6).

The movement of sediment over the landscape can be represented as a continuous flow from the source to the outlet where

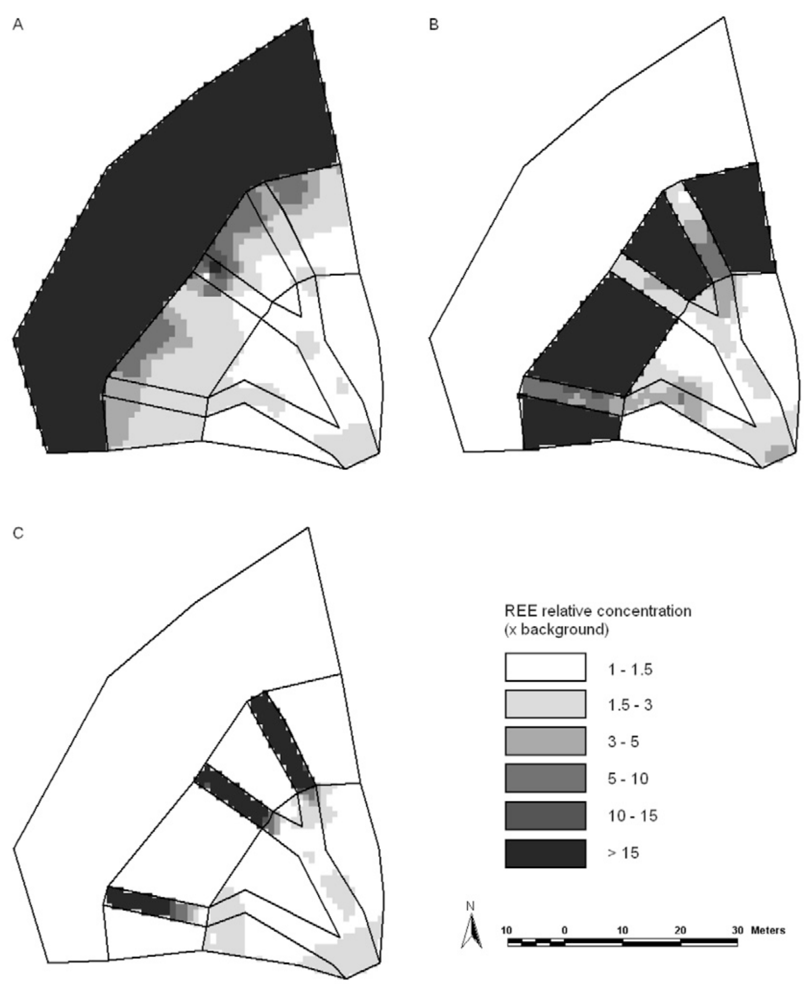

Fig. 4. Redistribution and pathways of rare earth element tracers in surface soil from upper slope (A), middle slope (B), and upper channel (C) by the end of the experimental period.

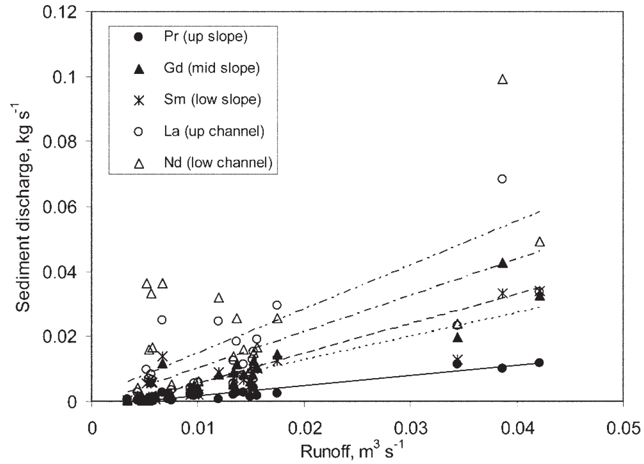

Fig. 5. Relationship between runoff and sediment rates from different morphological units of the watershed.

at any given time some amount of sediment is in transition or temporarily re-deposited. In our particular experiment this would apply only to non-channelized areas. In channels, or areas adjacent to them this might not be true because there was little or no deposition found in the channels. It can be argued that the amount of sediment in transition is relatively constant, that is, a steady-state condition exists at a long-term scale (multiple events). This amount of sediment in transition is greater if the source is farther from the outlet, and smaller if the source is adjacent to the outlet.

CONCLUSION AND IMPLICATIONS

Sediment tracing using REE proved to be a useful tool for measuring sediment redistribution in rangeland watershed with coarse soil. Surface application of tracer yields satisfactory results and is suitable for short-term studies. In addition, it may be the only option on undisturbed watersheds. The secondary benefit of the method was cost and time saving comparing with tracer incorporation, which might become important for larger watershed studies.

It was found that upper and middle channels of the watershed were eroding at a much greater rate compared with slopes. This will ultimately result in deepening and expansion of the channel system. During the observed period the upper channel experienced higher sediment loss (5.0 Mg ha^{-1}) than the lower channel (4.3 Mg ha^{-1}). This is likely due to the lower channel having a fixed base level (the flume structure) which limits its deepening, at least in its lower part. The upper channel, on the other hand, can deepen and develop head cuts. It is plausible that the erosion patterns observed on this watershed are indicative of the long-term erosion rates. The channels are well defined, and nick points indicate that the channel network is evolving. Minimal deposition in the lower channel indicates that the watershed has an efficient transport system.

However, the proposed technique is not without its limitations. Ideally the method would require mixing of the tracer into the soil profile. This is not possible on uncultivated rangeland watershed without severe disturbance of the system and therefore the full potential of the method may not be realized. An even greater limitation is that erosion on areas with incisions such as rills and nick points may be underestimated, because the eroded depth will almost certainly exceed the application depth of the tracer.

Another potential source of error is the contamination of downslope areas with tagged sediments from upslope areas. Although the REE technique allows identification of the original sediment source area, it is not capable of differentiating sediment directly transported from the original positions and re-entrained sediment from re-deposited locations. The adverse effect of contamination, however, will be offset over time by the continuous process of re-deposition and re-entrainment of soil particles, which maintain a quasi-equilibrium state. While the cumulative amount of soil reaching the outlet increases with every storm event, the amount of sediment in transition (temporarily redeposited) should remain relatively stable.

Surface application of tracers also limits the time during which it is possible to reliably trace sediment movement. During the monsoon season when the study was conducted, between 2.6% (Pr, upper slope) and 18.9% (Nd, lower slope) of applied tracers was recovered at the flume. Considering that the observed sediment loss (390 kg) was close to a long term yearly average (272 kg) the tracer application method that was used can only be utilized in short-term studies. As the tracer is washed away from the surface this measurement technique will increasingly misrepresent relative soil loss.

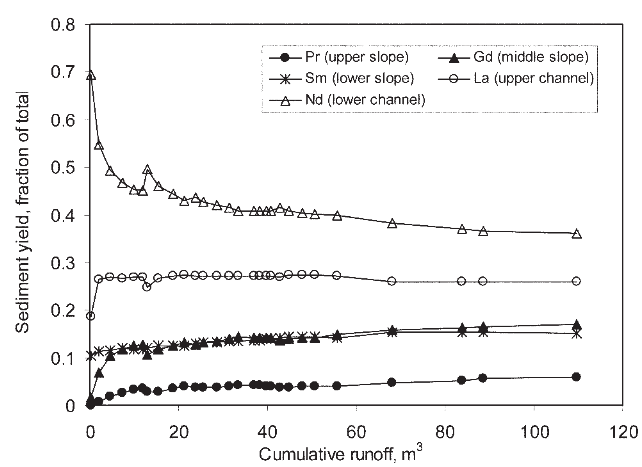

Fig. 6. Relative contribution of different areas of the watershed to the total sediment yield during the course of the experiment.

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