Determining erosion and sedimentation chronology on semi-arid catchments using radioisotopes

Polyakov*, V., M. Nichols, M. Nearing
USDA-ARS

Introduction

Sediment stored in landscape depressions, ponds and lakes contain record of erosion rates on contributing watershed evolving under natural and anthropogenic disturbances. Accurate sediment chronologies are critical for interpreting these records.

Some of the most common tools for dating recent (0-150 years) sediment deposits are ^{210}Pb and ^{137}Cs. In many cases these radionuclides have proved to be a reliable method, particularly in environments with uniform sediment accumulation rates (Appleby, 2008; Ritchie and McHenry, 1990). The method has also been used on sites with non-uniform accumulation, however in such case an appropriate dating model needs to be selected based on a set of restricting assumptions. The lack of control measurements of sedimentation for validation purposes makes the task particularly challenging.

Semi-arid environment is defined by high magnitude, low frequency rainfalls that produce highly variable soil erosion rates. In the southwestern United States stock ponds are commonly constructed on rangelands to harvest water for irrigation, livestock, and flood control. These ponds present unique opportunity for measuring sediment accumulation and erosion rates on contributing watersheds.

Stock ponds chosen for this study have been regularly monitored by topographic surveys for over 50 years. For the first time sediment accumulation rates determined from fallout isotopes have been verified by direct volumetric measurements.

Objectives

- Estimate historic soil erosion and sedimentation rates on selected semi-arid watersheds.
- Determine the effect of management and hydrologic regime on sedimentation and erosion processes.
- Investigate the applicability of ^{210}Pb and ^{137}Cs method for sedimentation chronology in semi-arid environment.

Methods

Location

Three watersheds at Walnut Gulch Experimental Watershed, Tombstone, AZ, USA
(31° 43' N; 110° 04' W)
Geology: alluvium
Elevation: 1400 m
Rainfall: 276 mm y^{-1}
Vegetation: whitethorn acacia, creosote bush, tarbush, black grama, curly mesquite

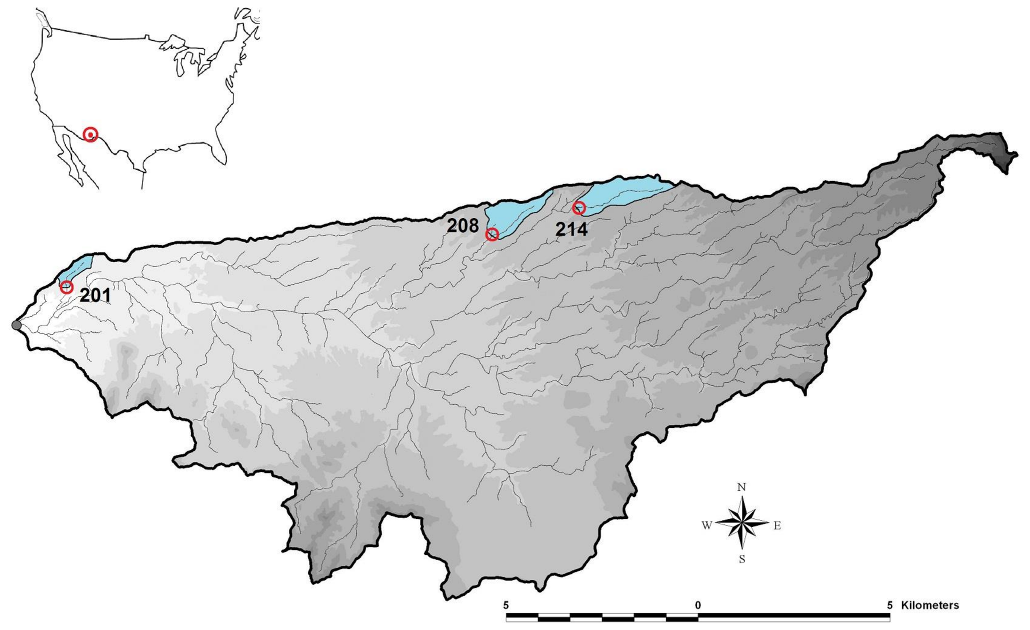

Figure 1. Location of three experimental watersheds on WGEW, Arizona, USA

Watersheds and stock ponds

- Each watershed drains into a stock pond excavated across drainage channels and separated by earthen dam with spillway
- Water level monitored using stilling well equipped with float and water level recorder
- Sediment accumulation was measured through periodic topographic surveys of the surface of each stock pond when the ponds were dry
- Three automated rain gages in close proximity to ponds
- Continuous grazing
- Brush removal on watershed 201 (June, 1971), seeded to *Bouteioua curtipendula* and *gracilis*.

Figure 2. Watershed 208.

Table 1. Watershed and stock ponds characteristics (Nichols, 2006)

Stock pond / watershed ID	201	208	214
Watershed area, ha	44.0	92.2	150.5
Average channel slope	0.021	0.026	0.019
Soil texture	Very gravelly sandy loam	Gravelly fine sandy loam	Very gravelly loam
Sediment record start	1967	1973	1957
Average runoff, mm y^{-1}	11.0	13.4	16.8
Pond capacity in 2004, m^3	5300	7600	17900
Sediment accumulation (2006), m^3	870	1090	11015
Trap efficiency, %	90.5	76.1	92.2
Sediment yield (survey), $m^3\ ha^{-1}\ y^{-1}$	0.6	0.5	1.7
Average mass accumulated, t y^{-1}	34	43	285

Figure 3. Stock pond #208 and location of the sampled profiles.

Sampling and isotope analysis

- Core samples were collected in May-July 2014 to the depth of 1.5 to 3 m at 15 cm depth increments.
- Profiles were spaced 5 m apart in a cross sections across middle of the pond
- The samples were ground, weighed, and placed into 170 ml air-tight jars for incubation to establish ^{226}Ra – ^{210}Pb equilibrium
- ^{137}Cs and ^{210}Pb activity was measured using gamma spectrometry system consisting of shielded HPG detectors coupled with MCA
- Activity of ^{137}Cs and ^{210}Pb (total) was determined from the 661.6 keV and 46.7 keV photopeaks. Excess ^{210}Pb was calculated through ^{214}Pb (351.9 keV)
- The samples were counted until <5% peak area uncertainty
- Sample activity was corrected for self-attenuation due to density variation (Quindos et al., 2006).

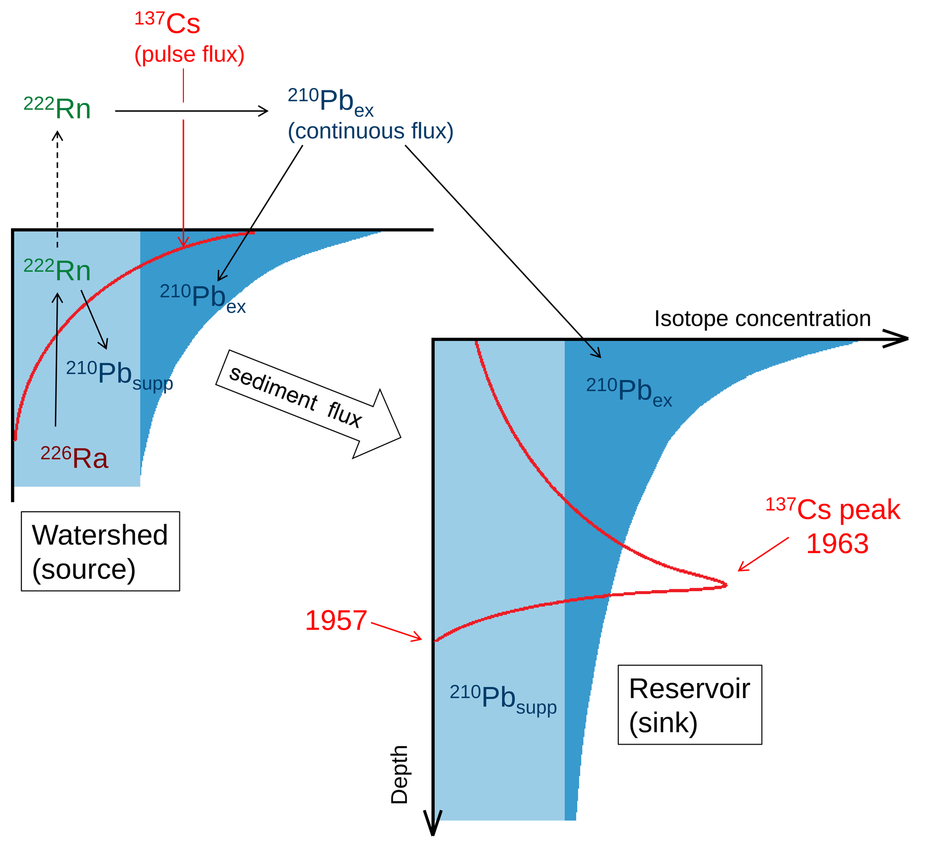

Figure 3. ^{210}Pb and ^{137}Cs fluxes, decay, and landscape redistribution.

The CRS (constant rate of supply) model

- The rate of deposition of $^{210}Pb_{ex}$ from atmosphere is constant
- $^{210}Pb_{ex}$ is quickly adsorbed to particulate matter
- The initial concentration in any sediment layer varies in inverse proportion to the sedimentation rate
- Non-monotonic variation of the $^{210}Pb_{ex}$ concentration versus depth

The age of sediments at depth i :

$$t_i = \frac{1}{\lambda}\ln\left(\frac{A(0)}{A_i}\right)$$

where λ is radioactive decay constant (0.03114 y^{-1}), *A(0)* and A_i are unsupported ^{210}Pb inventories at depth *0* and *i*.

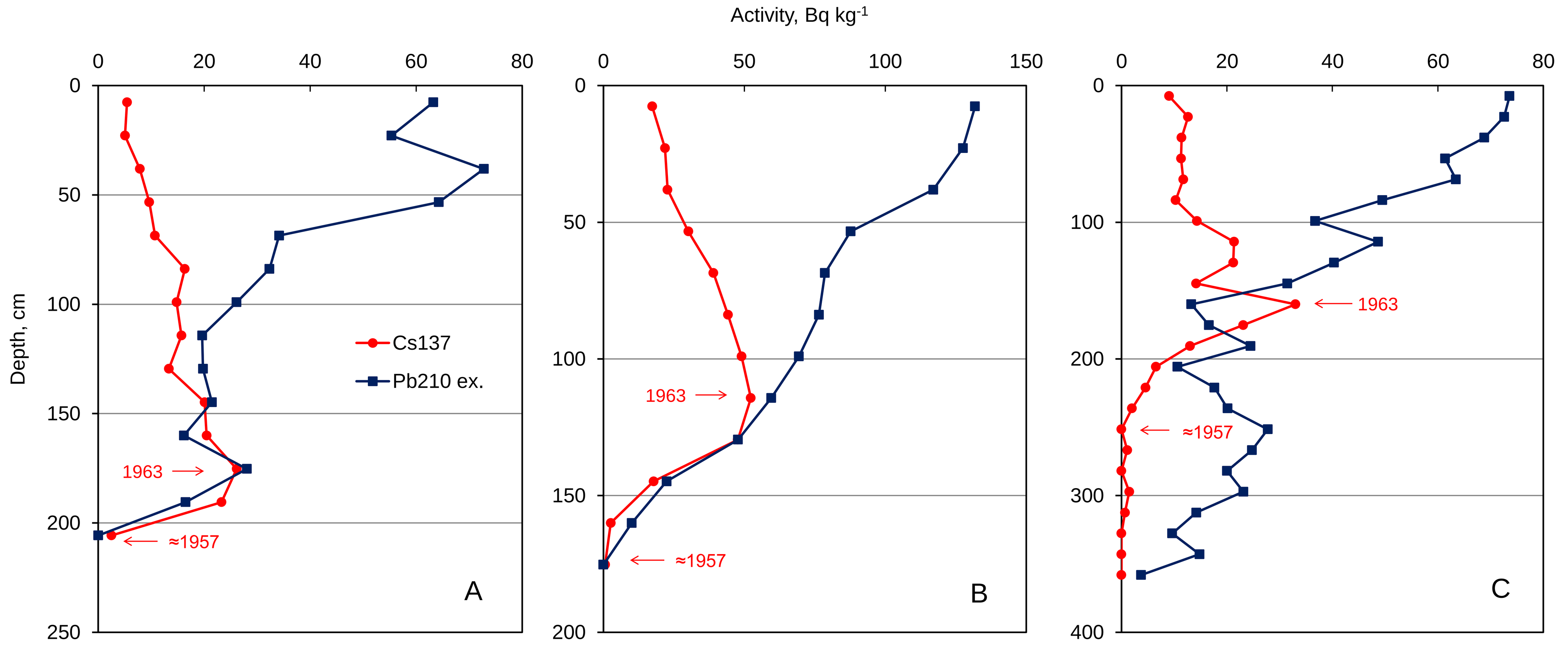

Figure 4. $^{210}Pb_{ex}$ and ^{137}Cs activity in selected profiles on ponds 201 (A), 208 (B), and 214 (C). 1957 and 1963 are the beginning and peak of nuclear test fallout.

Correction for incomplete inventory

If the core length is too short or sediment layer too recent, the total ^{210}Pb concentration will not reach the base ($^{210}Pb_{supp}$) value. Underestimation of *A(0)* causes overestimation of t_i, particularly at greater depth.

^{137}Cs peak concentration at 1963 was used as a reference depth.

Inventory below the reference depth:

$$A_i = \frac{\Delta A}{e^{t_i\lambda} - 1}$$

where *ΔA* is $^{210}Pb_{ex}$ inventory above depth *i*.

Results

The activities of unsupported ^{210}Pb show deviations from the exponential decay line (Fig. 4) resulting from physical or biological mixing of the layers of sediment and/or variation in sedimentation rate which cause either dilution or concentration. High activities indicate low accumulation rates and vice versa.

The overall non-monotonic ^{210}Pb concentration pattern suggested the use of constant rate of supply model (CRS) for sediment dating.

^{137}Cs peaks were clearly identifiable in all profiles at 125-175 cm depth that corresponds to radiometric age of ~50 years.

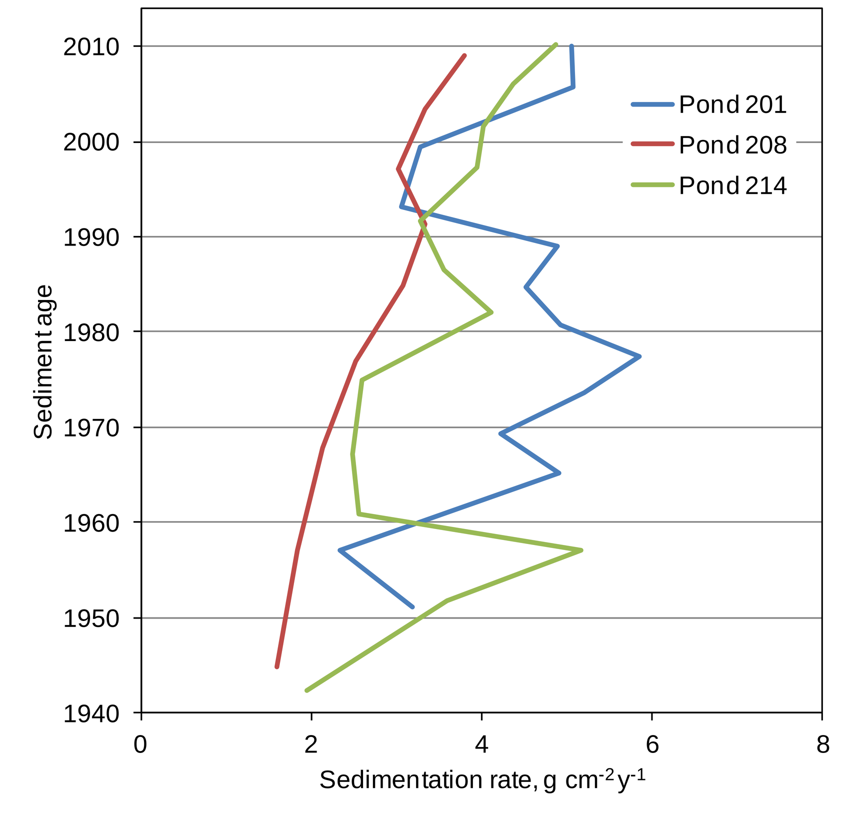

Figure 5. Pond sedimentation rate at selected profiles determined from ^{210}Pb with total inventory correction using known age marker (^{137}Cs).

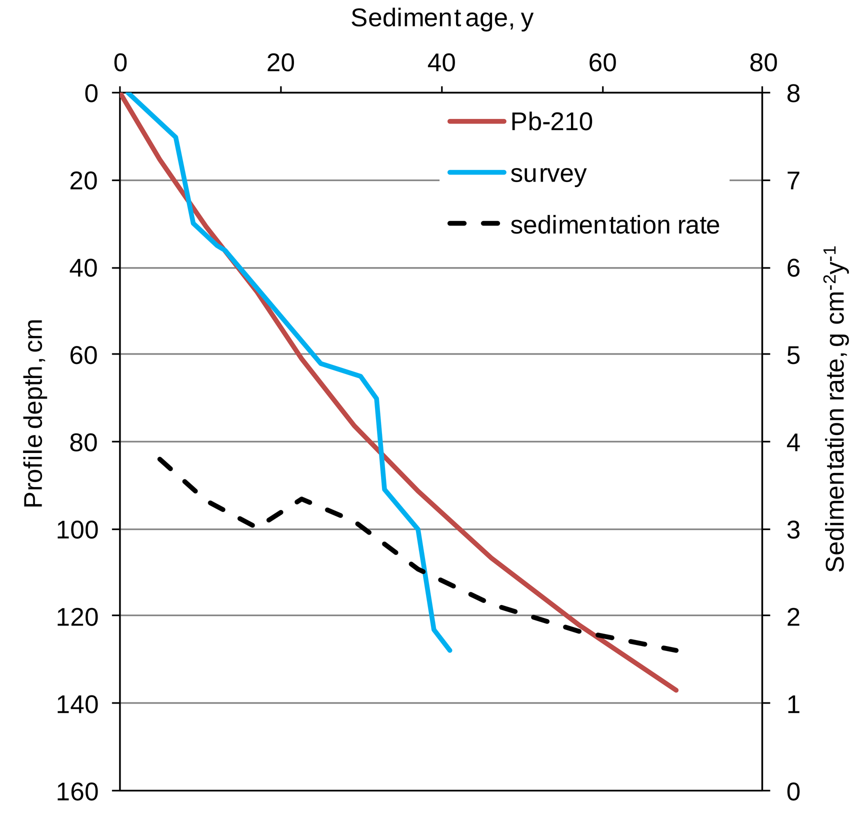

Figure 6. Comparison of sediment age in pond 208 between direct survey measurements and the ^{210}Pb method.

CRS model without correction for incomplete inventory overestimated sediment age for older deposits.
Greater sedimentation rates were observed in the middle of the pond, and smaller towards their periphery.
Mass sedimentation rate increased with decreasing age in most cores.

Table 2. Sedimentation and erosion rates on three watersheds estimated from ^{210}Pb profiles.

Stock pond / watershed ID	201	208	214
Pond sedimentation rate, cm y^{-1}			
average	3.4	2.2	3
min	2.3 (1956-65)	1.2 (1944-56)	1.6 (1942-51)
max	4.6 (1977-80)	3.1 (2010-14)	4.0 (1956-60)
Watershed erosion rate, t $ha^{-1}\ y^{-1}$	1.1	0.5	1.5

Conclusions

- This is the first ^{210}Pb and ^{137}Cs analysis of cores from ponds in arid environment backed by direct repetitive measurements of sedimentation.
- A constant rate of supply (CRS) model was used to assess ^{210}Pb data from 3 sites (18 cores). Mean sedimentation rates for these sites ranged from 1.2 to 4.6 cm y^{-1}.
- Long term sedimentation rates calculated from ^{210}Pb were in good agreement with those directly measured by survey.
- Due to the nature of accumulation in artificial ponds (incomplete profile) ^{210}Pb method requires a time marker for total inventory correction. ^{137}Cs is a reliable tool for this purpose.

References

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* USDA-ARS Southwest Watershed Research Center, 2000 E Allen Rd., Tucson, AZ 85719
ph: (520) 647-2996, e-mail: viktor.polyakov@ars.usda.gov