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Use of ^{210}Pb and ^{137}Cs to simultaneously constrain ages and sources of post-dam sediments in the Cordeaux reservoir, Sydney, Australia

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Abstract

Environmental radionuclides can be employed as tracers of sediment movement and delivery to water bodies such as lakes and reservoirs. The chronologies of sediments that have accumulated in the Cordeaux reservoir in Sydney, Australia, were determined by the rate of change of ^{210}Pb$_{ex}$ with depth and indicate slow accretion in the reservoir. The ratio of enrichment of radionuclides in sediment cores to ^{210}Pb$_{ex}$ and ^{137}Cs concentrations in a reference soil sample within the Cordeaux catchment indicates that the dominant source of sediment in the Cordeaux reservoir is surface erosion (detachment and removal of sediment at depths less than 30 cm). However, in the Kembla Creek arm of the reservoir a mixture of sources was detected and includes sheet and rill erosion together with sub-soil contributions. Implications for the utility of these radionuclide sedimentation assessments, especially where samples are limited, are that well-constrained chronologies and sources of soil erosion are facilitated.

Keywords: Sediment chronology; Fallout radionuclides; Sediment source; Sediment yield; Post-dam sedimentation; Soil erosion

1. Introduction

Evaluation and quantification of soil erosion caused by water in the Australian environment have received increased attention during the past three decades mainly because studies utilising radionuclides such as ^{210}Pb and ^{137}Cs generate reasonable age estimates for sediments that allow determination of erosion rates. However, the status of, and potential for, soil erosion in New South Wales (NSW) are still uncertain due to lack of extensive measurements (Department of Environment and Conservation, 2006). This limitation can be attributed to the expensive and time-consuming measurement procedures, which are directly linked to the nature of soil erosion, as well as a combination of logistical, observational and instrumental issues.

In this investigation, soil erosion in a headwater catchment of the Cordeaux reservoir was assessed using sedimentation rates in cores retrieved from the reservoir; identification of erosional processes was another key objective of the study. The relevant water-borne erosional processes include sheet, rill and gully erosion. Sheet erosion occurs when a thin veneer of water moves across the land surface taking soil with it. Rill erosion occurs when prolonged flow concentration creates small distinct channels incised less than 30 cm into the land surface (Humphreys and Mitchell, 1983; Bryan, 2000). Gullies convey ephemeral runoff in channels deeper than 30 cm, commonly with steep sides and headward eroding scarps (Isbell, 1996).

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1.1. Constraining pre-/post-dam sedimentation and the ages of sediments using radionuclides

^{210}Pb, a naturally occurring radionuclide (half-life 22.2 years), is a member of the ^{238}U decay series. The ^{210}Pb content of soils and rocks produced by the in situ decay of ^{226}Ra is referred to as "supported" ^{210}Pb because it is in equilibrium with its parent. However, upward diffusion of a small proportion of the intermediate ^{222}Rn from the soil to the atmosphere leads to subsequent fallout of aerosol associated ^{210}Pb back to the soil surface. This fallout ^{210}Pb is commonly termed "excess" or "unsupported" ^{210}Pb (^{210}Pb$_{ex}$) because it is not in equilibrium with the soil ^{226}Ra.

^{210}Pb-dating is based on a comparison between the levels of unsupported and supported ^{210}Pb. Limitations in applying the technique include the assumption that ^{210}Pb has not been redistributed in the sediment by post-depositional processes such as bioturbation or mass movement. Independent dating of sediment profiles suggests that ^{210}Pb does not diffuse through the sediment column (Gale et al., 1995). Ritchie and McHenry (1990) suggested that ^{210}Pb has a strong affinity for fine sediment particles; thus the aerosol associated ^{210}Pb fallout that reaches soil surfaces could be readily adsorbed onto clays and preferentially removed. However, Wallbrink et al. (1996) demonstrated that this affinity is not significant when sedimentation rates are determined. Whereas the ratio of ^{210}Pb might vary if assessed against different particle size fractions, the total amount, which is used to determine sedimentation rate, remains the same.

The activity of ^{210}Pb$_{ex}$ can be used to reconstruct ages and regressed against sediment depth in cores in order to establish sedimentation rates over the last 100−150 years (Oldfield and Appleby, 1984; Wasson et al., 1987; Olley et al., 2001). Additionally, the ratio of ^{210}Pb$_{ex}$/^{226}Ra can be used to distinguish between sediments that have been buried for a long time (pre-dam sediments) from those recently deposited (post-dam sediments; Wasson et al., 1987; He and Walling, 1997). This ^{210}Pb$_{ex}$/^{226}Ra ratio model can be described as follows: ratio of total ^{210}Pb to ^{226}Ra-supported ^{210}Pb is generally constant with depth in sediments that have not been exposed to recent fallout, whereas ^{210}Pb$_{ex}$ increases up-core in "young" sediments. The point at which the ^{226}Ra-supported and total ^{210}Pb are in equilibrium is called the background level of ^{210}Pb because there is no ^{210}Pb$_{ex}$. Ratios greater than unity correspond to recent input of unsupported ^{210}Pb into the sediment.

The age of sediments can also be determined using ^{137}Cs, a radionuclide deposited worldwide as a result of atmospheric nuclear weapons testing between 1952 and 1964. The first appearance of ^{137}Cs in sediment cores retrieved from water bodies indicates 1954, the year the isotope was first detected in measurable amounts; peak occurrence indicates 1963, the year of maximum fallout (Wasson et al., 1987; Ferro, 1997; Loughran and Elliott, 1996). ^{137}Cs diffuses in sediments and soils, thus does not provide definitive dates; however, combined with ^{210}Pb, ^{137}Cs helps to reduce uncertainties associated with sediment dating.

Significant uncertainties are associated with ^{210}Pb$_{ex}$ and ^{137}Cs dating of sediments, especially where water is highly turbulent, such as at the entrance of streams to lakes, or when bioturbation has caused vertical mixing. These uncertainties must be considered in the calculation and interpretation of the activities of the radionuclides. To minimise the uncertainty and check the integrity of sediment cores, ^{7}Be activities can be determined down the core. ^{7}Be, produced in the atmosphere by cosmic ray spallation of nitrogen and oxygen, is deposited on the Earth's surface through wet and dry deposition (Olsen et al., 1981, 1986; Hancock and Hunter, 1999; Benoit and Rozan, 2001; Kozlowski et al., 2002). ^{7}Be has a half-life of only 53 days, thus high activity serves as a tracer of short-term (<1 year) deposition without mechanical mixing.

1.2. Combining Caesium-137 and Lead-210 to determine sources of erosion

Determination of the sources of soil erosion can be achieved by combining results from analyses of ^{137}Cs and ^{210}Pb. These radionuclides tend to penetrate soils to particular depths. The penetration depth is defined as the depth at which a radionuclide concentration decreases to half the value at the surface (Wallbrink and Murray, 1993). Typically the average penetration depth of ^{137}Cs ranges from 3 to 5 cm. Deposition of measurable amounts of ^{137}Cs in the southern hemisphere ceased in the 1970s suggesting that the current soil inventory is only affected by radioactive decay and soil movement (Wallbrink et al., 2002, 2003). In contrast, ^{210}Pb is constantly being deposited and its penetration depth is typically 1−3 cm. This knowledge can be used to determine the sources of sediments that have been mobilised from hillslopes, thereby inferring the nature of the erosion processes operating.

The principal focus of this paper is to illustrate the use of fallout radionuclides (^{210}Pb and ^{137}Cs) as chronometers and tracers of sediment movement in the Cordeaux reservoir. This is possible because the reservoir sediments represent a sink for the collection and storage of materials from both the atmosphere and terrestrial environments. A link can be identified between atmospherically derived radionuclides and terrestrial systems. This link has facilitated analyses of lake and reservoir deposits to investigate changes in terrestrial environments. In this way, the location, amount and nature of most lake and reservoir sediment can be used to reveal spatial and temporal variations in catchment processes.

2. Study area description, methods and materials

2.1. Study catchment

The Cordeaux catchment is ca. 91.5 km^2 and is situated on the ridge top of the Woronora Plateau, 64 km south west of Sydney (Fig. 1). The catchment drains to an artificial lake, which stores water for supply to Sydney and surrounding townships (SCA, 2002). The lake collects runoff from seven major sub-catchments, namely, Cordeaux, Whale's Tail Bay, Kentish, Goondarin, Kembla, Upper Cordeaux and Sandy Creek sub-catchments (Fig. 1). Channel beds for the streams draining the sub-catchments are predominantly sandstone bedrock, thus down-cutting can be slow (mainly by scouring), although channel