



Sediment tracing and dating techniques employed at CSIRO Land and Water

Gary Hancock and Tim Pietsch

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Cover Photographs:

Description: Left: the Latrobe River at Sale during bank full discharge. Right. Core collection using a CSIRO-made drop hammer device.

Photographer: Gary Hancock

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EXECUTIVE SUMMARY

This document summarises sediment tracing and dating techniques used in the Canberra laboratory of CSIRO Land and Water. The techniques address environmental issues involving sediment transport and the document is designed to inform managers of the capabilities of the techniques currently being employed by CSIRO. The document also aims to provide sufficient scientific and technical information such that managers are able to assess their research requirements.

The CSIRO methods have been developed over a period of approximately 20 years, some independently and others in collaboration with international researchers. The techniques are specifically aimed at addressing the problems associated with typical Australian river catchments; that is, the erosion, transport and deposition of highly weathered clay-rich sediment through large river catchments, many of which have been highly altered as a result of European settlement.

The document is divided into three sections – one on sediment tracing and the other on sediment dating. In each section the aims, basic methods and an example of its application are given. More detail on these applications can be found in section 3 which summarises studies undertaken by CSIRO and provides references.

In section 1 the concept of sediment tracing is defined and the different approaches described. The first, spatial tracing, involves the measurement of many physical properties (mostly tracer element contentions) of the soil and sediment, and aims to identify distinct spatial sources of sediment within a catchment. After selecting the tracers providing the best discrimination a mixing model is applied to obtain the best estimate of the proportions of the various sources to the mix.

The second tracing approach aims to identify the erosion process delivering sediment to the streamlines. This technique utilises surface tracers, these mainly being fallout nuclides (^{210}Pb , ^{137}Cs , Pu and ^7Be) which have become firmly attached to hillslope topsoil. By contrast, subsoil sources (gullies and channel bank) contain little or no surface tracer. Surface tracers therefore provide unique information on the contribution of topsoil eroded from hillslopes to river sediment. Other applications of topsoil tracers include assessments of the redistribution of topsoil on hillslopes caused by bushfires and anthropogenic activities (logging etc.).

Section 2 of the document considers the applications of sediment dating to issues relating to catchment management. A common aim of sediment core dating is the determination of sedimentation rates for the pre-European and post-European settlement periods, thus allowing a comparison of the extent of disturbance of the catchment from its natural state.

Two approaches to dating are discussed: excess $^{210}\text{Pb}/^{137}\text{Cs}/\text{Pu}$ dating (applicable to the last 100 years), and optical (OSL) dating (applicable to 0-100,000 years). Excess ^{210}Pb geochronology requires the modelling of a series of measurements (usually 10 or more) spanning the detectable excess ^{210}Pb region of the core profile. Measurements of ^{137}Cs and Pu are used to validate the ^{210}Pb chronology and to increase confidence in the period 1950-1970. OSL dating can provide “stand alone” dates for individual depth segments of the core, but requires the presence of a minimum number of quartz and/or feldspar grains. Recent advances in the technique has allowed young sediment (<200 years) to be dated with an uncertainty of less than 10 years. Importantly, OSL dating can span the period of European settlement 150-200 years ago, a time frame few other techniques can cover.

Section 3 provides Tables describing the catchment management questions best answered by the various techniques. Table 3 summarises studies undertaken by CSIRO over the last 10 years. A list of references to these studies is given.

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1. INTRODUCTION

1.1. What this document describes

The following document summarises the tracing and dating techniques used in the Canberra laboratory of CSIRO Land and Water. The methods have been developed over a period of approximately 20 years, some independently and others in collaboration with international researchers. The techniques are specifically aimed at addressing the problems associated with typical Australian river catchments; that is, the erosion, transport and deposition of highly weathered clay-rich sediment through large river catchments, many of which have been highly altered as a result of European settlement.

The document is divided into three sections – the first on sediment tracing and the second on sediment dating. In each section the aims, basic methods and an example of its application are given. More detail on these applications can be found in section 3 which summarises studies undertaken by CSIRO and provides references. A description of the analysis methods associated with this document can be found at <http://www.clw.csiro.au/services/radionuclide/> (radionuclide analysis) and <http://www.clw.csiro.au/services/osl/> (OSL dating).

2. SEDIMENT TRACING

2.1. Why trace and date sediment?

A major concern for catchment management authorities, land-care groups and city councils has been the degradation of the health of waterways and estuaries as a result of human activity in river catchments. Land-use changes associated with urban and rural development have often led to increased sediment delivery to rivers, with subsequent water quality degradation. The application of tracing and dating techniques to determine the spatial source of sediments and the timing and nature of major erosion processes offer a direct method of targeting soil conservation and reparation works. The techniques can be particularly powerful when they are used in conjunction with catchment modelling of sediment sources (e.g. SedNet) and in-stream monitoring of water quality such that catchment topography, rainfall and land-use, together with stream network parameters and sediment flux measurements are incorporated. The three linked approaches, tracing and dating, modelling and instream monitoring build confidence in the construction of sediment budgets.

Determination of the sedimentation history of a catchment by dating sediment cores at strategic locations in the river system offers a method of verifying these budgets, as well as providing a way of assessing the historical effect of recent land-use changes on sediment delivery. By comparing recent sedimentation rates with pre-European settlement rates, the degree of disturbance of the catchment is assessed, an important factor when attempting to return catchments to something approaching their 'natural' state. Greater understanding of the dynamics of sediment movement within river catchments can also be achieved through investigation of intermediate deposition stores, with this approach particularly useful in locations where sediment generated by recent erosion has not yet reached the end of the catchment (e.g. Rustomji and Pietsch, 2007).

2.2. The concept of sediment tracing

A sediment tracer is defined as a physical characteristic of the sediment that behaves conservatively during sediment transport; i.e. it remains attached to sediment particles despite particle abrasion and exposure to water. Ideally, the tracer should be distinctive enough that it allows discrimination between different sediment sources.

The suspended sediment load transported by a river will usually represent a mixture of sediment derived from different regions and erosion pathways within the contributing catchments. It is seldom the case that a single tracer can provide unambiguous discrimination of potential sources; most tracer applications require a suite of tracers (physical and/or chemical characteristics associated with a particular sediment source) to determine a characteristic signature or 'fingerprint' for each source. The source fingerprints are then compared with equivalent values of the transported end-member; these end-members being suspended sediment downstream of the catchments, or sediment deposited in a 'sink' of interest. The best estimate of the contributions of each of the sources is then apportioned. Major sediment sources identified using this approach include soils associated with distinct geological zones, differentiation of surface and subsurface soils, topsoil losses from uncultivated land-uses (forest/pasture), and channel bank erosion.

It is emphasised that tracing generally only gives the relative proportions (%) of the various erosion sources. To obtain a sediment budget requires estimates of sediment yield using other techniques, such as instream monitoring, catchment modelling or sediment core chronologies.

In general, sediment tracing techniques can be divided into two categories – spatial sourcing and erosion process tracing. These are described separately below.

2.3. Spatial source tracing

Spatial sourcing of sediment uses a combination of tracers that distinguish an area or region of the catchment. The tracers commonly used at CSIRO include major and trace element geochemistry, isotopic signatures and mineral magnetic properties. However other tracers are routinely used elsewhere, including sediment/soil colour, clay mineralogy and, more recently, compound specific resins and fatty acids to determine land-use contributions.

At CSIRO, a combination of major and trace element measurements is made in an attempt to distinguish soils originating from geologically distinct catchments. These elements are determined using techniques such X-ray fluorescence (XRF), ICP optical emission spectrometry (ICPOES) and ICP mass spectrometry (ICPMS), and Laser Ablation ICPMS activation. The methods can be used individually, or in combination to maximise the number of useful elements available as tracers. Major elements measured include Si, Al, Fe, Ca, Mg, Na, K, Ti, P, Mn. Trace elements measured include the less abundant transition elements, rare earth elements and other heavy metals. This list is often supplemented by lithogenic and fallout radionuclides (uranium and thorium series

nuclides and ^{137}Cs) determined using the CSIRO Land Water Gamma Spectrometry facility in Canberra.

The application of these tracers involves a 2-step process whereby tracers are first examined such that only those that clearly differentiate potential source materials are selected for use. The selected tracers are then applied to multivariate mixing models to apportion a given sediment mixture between those sources. The best estimate of the relative contribution from each tributary is obtained by minimizing the difference between the measured tracer value in the sediment mixture, and that calculated using a range of different proportions of the various sources.

An example of the application of geochemical source tracing is provided by Hancock et al., (2007), whereby the contribution of subsoil originating from the foothills region north-east of Bairnsdale to the load of sediment delivered to the Gippsland Lakes by the Mitchell River is determined. The area is prone to a form of subsoil erosion ('tunnel' erosion) that is particularly difficult to detect by aerial surveillance. The discrimination shown by some of the tracers is shown in Figure 1. This example consists of just two sediment sources, 'subsoil' sources from the foothills north of Bairnsdale, and 'upper Mitchell sediment' (sediment delivered from the Mitchell 'uplands' to the north). The resultant mixture is represented by 'Lower Mitchell sediment', collected downstream of Bairnsdale. When all the tracers are integrated into the mixing model the model predicts that 11 ± 4 % of Lower Mitchell sediment is derived from subsoil sources (Table 1). When coupled with catchment modelling and instream monitoring of suspended sediment loads a subsoil sediment yield of 7.5 t/yr is calculated.

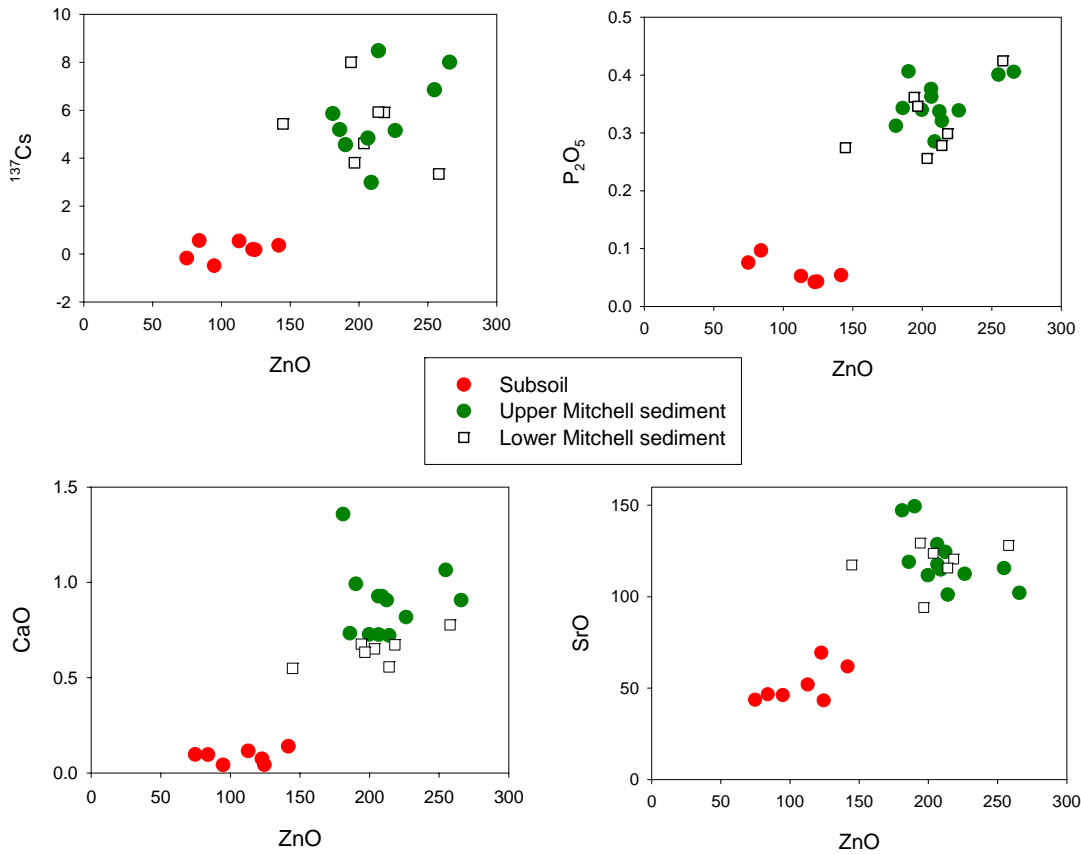


Figure 1: Plots of various geochemical and surface tracers for subsoil (tunnel) soil and sediment in the upper and lower Mitchell River.

Table 1: Mean values of tracer used to determine tunnel subsoil contribution to Lower Mitchell River sediment. Values in brackets represent the standard error. R gives the best estimate of the proportions of the two source terms.

	CaO	P_2O_5	ZnO	SrO	^{137}Cs	LOI	R
Subsoils	0.09 (0.01)	0.06 (0.01)	110 (9)	53 (4)	0.0 (0.1)	7.7 (0.4)	0.11
Upper Mitchell sediment	0.89 (0.05)	0.35 (0.02)	215 (11)	121 (7)	5.2 (0.6)	16.6 (0.7)	0.89
Lower Mitchell sediment	0.64 (0.03)	0.32 (0.02)	204 (13)	118 (4)	4.6 (0.4)	14.8 (0.9)	

2.4. Erosion process tracing

Erosion process tracing is generally not catchment specific, but identifies the process leading to sediment mobilization, such as sheet erosion of topsoil, gully erosion of subsoil, and channel bank collapse. This technique relies heavily on the fallout tracers ^{137}Cs , ^{210}Pb , ^7Be and plutonium to distinguish topsoil and subsoil. These tracers (described below) are deposited from the atmosphere mainly in association with rainfall and strongly bind to fine-grained particles in soil. In doing so they label a thin layer of topsoil over the earth's surface. Due to their different half-lives and deposition histories each nuclide provides unique information on the source of the sediment and the processes controlling its erosion. Fallout tracers ^{137}Cs , ^{210}Pb and ^7Be are determined simultaneously by gamma spectrometry. Plutonium is measured by alpha spectrometry.

2.4.1. ^{137}Cs and Pu

Caesium-137 and isotopes of plutonium are anthropogenic products of atmospheric nuclear weapons tests that commenced in the early 1950s. ^{137}Cs is most commonly used as a tracer, although recent measurements in the Herbert catchment (Everett et al., in press) indicate that Pu may have distinct advantages, especially in tropical regions. Once deposited ^{137}Cs and Pu became tightly bound to fine soil particles, particularly clays. Over the last 50 years there has been some downward migration of these particles, such that ^{137}Cs and Pu are now concentrated mainly in the upper 10 cm of the soil profile (Figure 2). Thus high activities of ^{137}Cs and Pu are typically seen in undisturbed topsoil in forested regions and some pastures with a history of low intensity grazing. Due to mixing of the soil during cultivation the depth distribution of ^{137}Cs and Pu in cultivated soils is much deeper (~30 cm) than uncultivated, and the ^{137}Cs and Pu activities in cultivated soils are correspondingly lower than undisturbed soils. In subsoils recently exposed by erosion ^{137}Cs and Pu are virtually absent.

2.4.2. ^{210}Pb excess

Fallout ^{210}Pb (half-life 22 yr), also known as 'excess' ^{210}Pb ($^{210}\text{Pb}_{\text{ex}}$) is a naturally-occurring nuclide generated from the decay of ^{222}Rn in the atmosphere. It is continually precipitated on the soil surface by rainfall and is usually determined from the 'excess' of ^{210}Pb activity over its parent ^{226}Ra . These three nuclides (^{226}Ra , ^{222}Rn and ^{210}Pb) are all members of the uranium decay series. Maximum concentrations of $^{210}\text{Pb}_{\text{ex}}$ in soils are usually found at the surface, decreasing approximately exponentially with soil depth and reaching typically undetectable levels at depths of ~10 cm (Figure 2).

2.4.3. ^7Be

Be-7 (half-life 53 days) is also naturally-occurring and is created in the atmosphere by the reaction of cosmic rays with nitrogen and oxygen. Being short-lived it provides information on different time-scales to ^{210}Pb and ^{137}Cs , ^7Be being mainly applied to the tracing of sediment eroded during single rainfall events and deposition-resuspension cycles. Other applications include assessment of the depth of hillslope erosion during a single rainfall event.

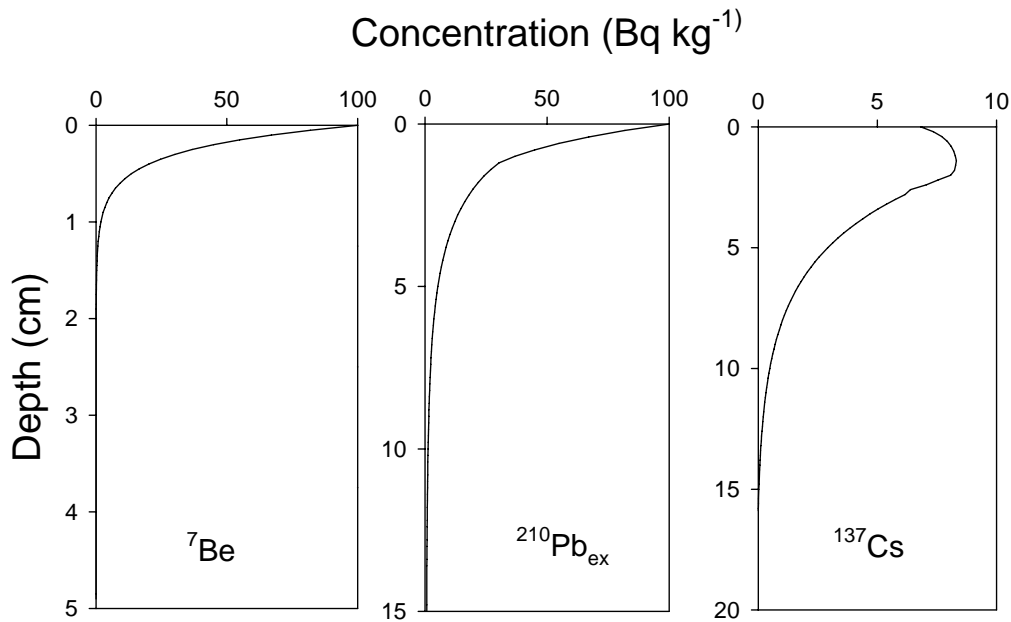


Figure 2: Hillslope depth profiles of fallout tracers. Note the different depth scales. ^7Be is only seen in the upper 1 cm of soil whereas excess $^{210}\text{Pb}_{\text{ex}}$ and ^{137}Cs are mainly held in the upper 5 cm and 10 cm respectively.

2.5. Application of topsoil tracers to sediment source determination

The tracing method involves comparing the ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ concentrations in samples collected from the erosion sources (uncultivated and cultivated soils, channel banks and erosion gullies) with concentrations in samples collected from deposited river sediments downstream. In its simplest application, these tracers can distinguish surface and sub-surface mixtures.

Figure 3 shows some of the combinations of ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ activities that define various erosion processes. A combination of high ^{137}Cs and high $^{210}\text{Pb}_{\text{ex}}$ activities indicates sheet erosion of topsoil. Conversely low activities of both nuclides indicate a subsoil source, such as gully or channel bank collapse. Detectable ^{137}Cs in the absence of $^{210}\text{Pb}_{\text{ex}}$ can indicate cultivation, and in the case of even higher ^{137}Cs , rill formation. High $^{210}\text{Pb}_{\text{ex}}$ in absence of ^{137}Cs can indicate erosion of subsoil sources exposed since the cessation of ^{137}Cs fallout (i.e. the last 30 years).

Although there is often more than one combination of sources providing a solution for a given measurement of ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$, information given by other topsoil tracers can help disentangle sources. For example, organic carbon and total P (P_2O_5) are known to associate with A-horizon soils, especially in fertilised pastures and cultivated soils (Figure 4). Another approach is to directly compare tracer activities with those predicted

by catchment modelling. Such an approach allows a check on model outputs and adjustments to some model parameters which may be considered uncertain. This integrative approach can provide improved model-based estimates of sediment flux and erosion mapping (e.g. Hancock et al., 2007; Rustomji et al., 2007).

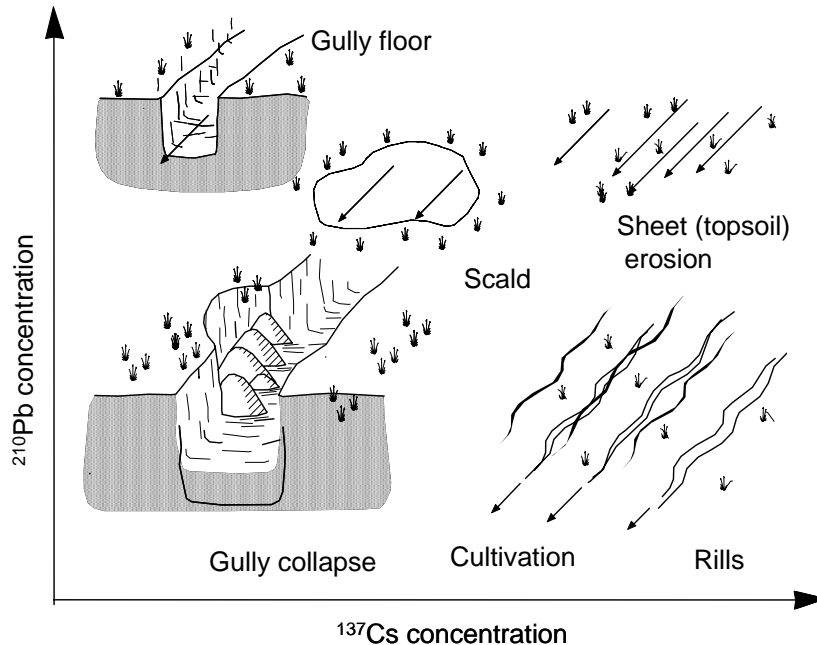


Figure 3: Schematic showing ^{137}Cs and excess ^{210}Pb activities and their relationship to various erosion processes.

The addition of ^7Be to the suite of topsoil tracers opens the possibility of examining erosion and transport processes operating over a single high flow event. Since the half-life of ^7Be (53 days) is comparable to or shorter than the return time for major rainfall events most of the ^7Be attached to sediment is likely to have been delivered during the flow event being traced. A sediment transport process identifiable using a combination of ^{137}Cs , $^{210}\text{Pb}_{\text{ex}}$ and ^7Be is that of the interaction of freshly eroded ^7Be -rich sediment with that of low activity ^7Be -dead' bed sediment. Deposition of freshly eroded sediment during transport through the river network combined with remobilisation of bed sediment will lead to a decrease in ^7Be activity of the suspended sediment, but not necessarily that of ^{137}Cs or $^{210}\text{Pb}_{\text{ex}}$. Such a process can be discriminated from channel bank erosion because all tracers will be low in channel bank sediment.

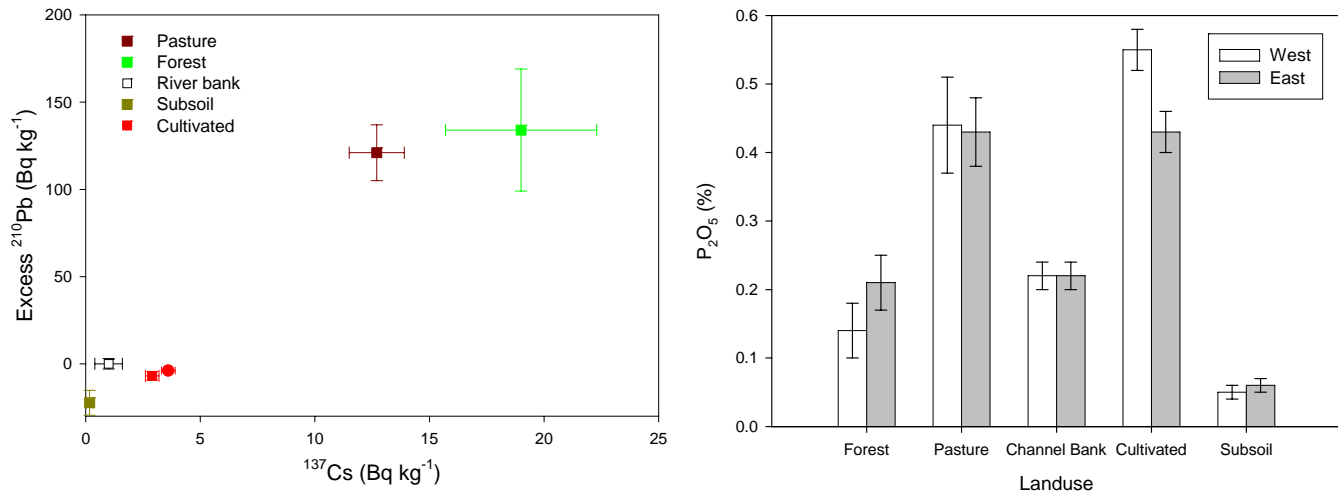


Figure 4: Measurements of topsoil tracers ^{137}Cs , excess ^{210}Pb and P_2O_5 in various soil sources in Gippsland.

2.6. Application of topsoil tracers to hillslope soil redistribution

Fallout tracers can also be used to assess recent sediment redistribution on hillslopes (Wallbrink *et al.*, 2002). Inventory budgets of ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ provide information on a time-scale of decades, whereas ^7Be provides an estimate on a time-scale of a few months (Blake *et al.*, 1999). This is particularly useful when assessing the effects of rapid and catastrophic events (such as bushfires or clearing) on sediment erosion (English *et al.*, 2005; Wallbrink *et al.* 2005). The method utilizes measurements of fallout tracer inventories determined from soil profiles collected from various sites on the hillslope. These activity inventories measured are compared to reference site inventories which are considered to represent the ‘undisturbed’ condition. Inventories higher than the reference sites indicate sites of deposition; likewise sites of erosion show reduced inventories. Once again the different half-lives of the tracer provide redistribution information over different time frames.

2.7. Problems and limitations

One of the major problems complicating sediment tracing is the depletion or enrichment of tracer properties during erosion and transport of the sediment. This sometimes involves non-conservative processes, such as physical and chemical alteration of the tracer properties, but a more direct concern is the variation of sediment particle size which occurs as a result of the size selective nature of fluvial transport. The erosion of soil inevitably favours the transport of finer particles of bulk soil, with the size distribution of the sediment end-member depending on the energy of river flow and the deposition environment. Variability of tracer properties with the particle size of sediment occurs for a variety of reasons. Soil mineralogy changes greatly with particle size, with clay minerals dominating the very fine <2 μm fraction and quartz and feldspar minerals dominating material >63 μm . In addition, tracers bound to the surface of sediment grains, such as is the case for fallout radionuclides and tracer elements bound to the Fe-

oxide coating of grains, will show a concentration dependency linked to the surface area (and hence size) of the sediment grain.

Thus all tracing applications must address the issue of particle size variability during transport. One method of doing this is to isolate a size fraction of interest such that concentration variation of the tracers within that size fraction is considered minimal. This approach has been taken by CSIRO researchers, most commonly using the <10 µm fraction. The reason for focussing on the fine sediment fractions is two-fold; first, the fine fraction < ~20 µm is the fraction most readily transported, and second, it is the fraction which often presents the most environmental concerns. These concerns include water column turbidity and the fact that fine particles deliver a large proportion of the riverine load of particle-bound nutrients and other pollutants.

2.8. Sample collection protocols

Although there is no generally applicable methodology for the characterisation of catchment sediment sources and sinks most studies focus on obtaining representative samples from potential sediment sources. This involves integrating sample collection over as large an area as possible. At CSIRO Land and Water the erosion source characterisation involves the collection of up to 50 grabs from up to 5 separate locations. These grabs are combined into a single sample. The number of source samples measured for tracer values generally involves the consideration of statistical variability and analysis cost. Typically 6-10 samples are collected and measured to characterise each erosion source, this number being considered the minimum required to obtain a reasonable estimate of catchment variability (and hence source term uncertainty). Where other tracer studies have been undertaken in nearby regions with similar rainfall patterns tracer data can be combined to provide improved estimates of the tracer concentration of the various sediment source terms.

Mixing of sediment sources during transport means that less sediment sink samples (stream and end-member sediments) are required to obtain a representative estimate of tracer values. Only where sediment is considered to be inhomogeneous in regard to mixing of sources, such as an estuary or embayment with multiple input sources, is there a need to measure multiple samples.

Sample collection involves targetting eroding or erodible sources. The upper 10-20 mm of exposed or loose hillslope topsoil is sampled. Likewise, actively eroding channel banks are also chosen. Attempts are made to characterise all geologically distinct provinces. When sampling stream sediment high flow deposits are preferred, these often having been deposited as overbank material, sometimes deposited in overbank depressions or even perched in trees.

3. DATING OF SEDIMENT CORES

3.1. Determining the history of catchment disturbance

The reconstruction of the history of recent human impacts on the aquatic environment has attracted increasing interest over the last few decades. Environmental changes arising from industrialisation, urbanisation and catchment disturbance are often recorded in undisturbed sediments in lakes, reservoirs, estuaries, in-channel benches and peat bogs. Determining a chronology is essential to the evaluation of these sediment records. Measurements of ^{210}Pb in conjunction with fallout ^{137}Cs is the most common approach to determining a sediment chronology spanning the 'modern' period (last 100 years). Both these nuclides are measured simultaneously by gamma spectrometry.

At CSIRO Land and Water we often complement ^{137}Cs measurements with measurements of Pu isotopes (see below) in order to improve ^{210}Pb geochronology. We also recommend the use of optical dating (optically stimulated luminescence, or OSL) where it is important to obtain accurate dates prior to ~1940. OSL not only offers the opportunity of providing corroboration of ^{210}Pb dating, an important requirement, but can also span the period pre- and post-European settlement (last 200 years and beyond). The period from 100 to 250 years BP (before present) is notoriously difficult to date using traditional dating techniques (^{210}Pb and radiocarbon), yet it is often the period of most interest because it spans the period of European settlement and the accompanying changes in landscape function and sediment erosion. OSL is therefore one of the very few methods that can provide 'base-line' or 'natural state' information on catchment erosion rates. Together, ^{210}Pb and ^{137}Cs (Pu) geochronology and OSL dating offer a powerful method for determining the degree of alteration a catchment has been subjected to by recent land-use changes. Such information is an important consideration when deriving catchment remediation targets.

3.2. ^{210}Pb geochronology

Lead-210 (half-life 22.3 y) occurs as a member of the ^{238}U decay series, and is naturally present in all rocks, soils and sediments. 'Excess' ^{210}Pb occurs in soils and sediments as a result of the decay of naturally occurring radioactive radon gas (^{222}Rn) in the atmosphere. Radon emanates into the atmosphere from rocks and soils on the earth's surface and decays to form ^{210}Pb . Atmospheric ^{210}Pb then rapidly attaches itself to dust particles and aerosols, and is eventually removed from the atmosphere by dry deposition or rainfall. This 'fallout' ^{210}Pb is presumed constant on a time scale of months to years, and leads to 'excess' ^{210}Pb in sediment and soils, the 'excess' pertaining to the elevation of ^{210}Pb concentrations above that normally present in soil.

In determining a chronology, excess ^{210}Pb activity of sediment is assumed to decay exponentially with time once it is isolated from the atmosphere by burial. Because of the assumptions used in the modelling of the decay profiles, ^{210}Pb geochronology is most successful where the sediment accumulation rates are not highly variable.

An example of a core chronology derived from ^{210}Pb measurements is given in Figure 5. The excess ^{210}Pb activity (log scale) decreases with depth (Figure 5 (a)) more or less exponentially, indicating periods of constant sediment accumulation. Validation of the chronology derived from the ^{210}Pb profile (Figure 5 (b)) is given by agreement of the ^{210}Pb geochronology with known events in the catchment. This validation often includes ^{137}Cs and Pu measurements, but can also include high levels of charcoal associated with recorded fires, and the occurrence of outbreaks of exotic pollen.

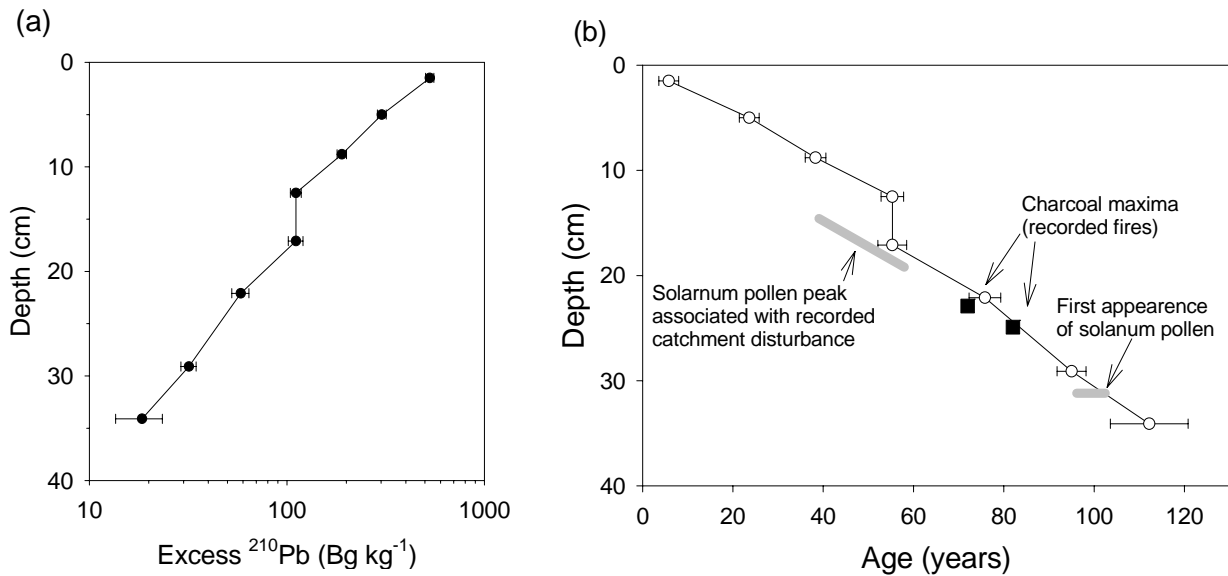


Figure 5: Depth profiles of (a) excess ^{210}Pb activity, and (b) the sediment age as determined from the ^{210}Pb activity of a core from Lake Barrine (Walker *et al.*, 2000). Other proxy age indicators are shown.

3.3. Chronology using ^{137}Cs and Pu

An important aid to the chronological interpretation of core profiles is provided by measurements of the artificial fallout radionuclides, ^{137}Cs and Pu isotopes. As described above, these nuclides appear in sediments and soils as a result of atmospheric testing of atomic weapons in the 1950s to 1970s. Due to its ease of measurement by gamma spectrometry ^{137}Cs is the radionuclide most commonly employed. However, recent work has shown that Pu has many advantages in the Australian landscape. In the Southern Hemisphere, where fallout activity was much lower than north of the equator, the application of ^{137}Cs is mostly limited to identifying the 1955 time horizon corresponding to the first detectable appearance of ^{137}Cs . The peak in ^{137}Cs activity associated with maximum fallout levels in 1964, often used in the Northern Hemisphere is seldom seen in the south. Pu isotopes, however, can provide dated time horizons associated with the first appearance of $^{239+240}\text{Pu}$ (~1954), the $^{239+240}\text{Pu}$ fallout peak (1964), and the 1968 peak in the $^{238}\text{Pu}/^{239+240}\text{Pu}$ ratio corresponding to the disintegration of the SNAP-9A satellite (Figure 6). In some cases the shift in the $^{238}\text{Pu}/^{239+240}\text{Pu}$ ratio corresponding to the early (~1952) nuclear weapons tests in the Pacific can be seen. These time horizons

provide high resolution chronology during the period 1950-1980, and, most importantly, can provide validation of the ^{210}Pb chronology.

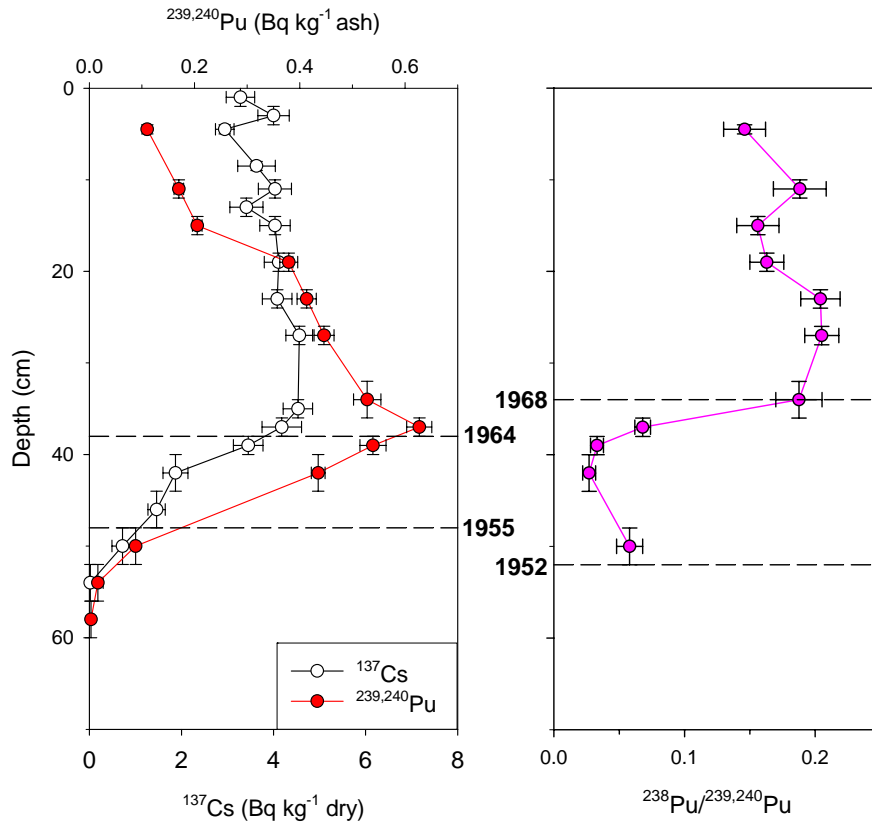


Figure 6: Time horizons determined using ^{137}Cs and Pu isotopes in a sediment core from Lake King (Gippsland Lakes).

3.4. Relating catchment disturbance to core chronology

The resolution of $^{210}\text{Pb}/^{137}\text{Cs}/\text{Pu}$ geochronology is such that under favourable circumstances discrete sedimentation events can be accurately dated with an uncertainty of ± 2 to 3 years. Employment of an appropriate model describing ^{210}Pb accumulation is critical, and providing the model assumptions hold, a history of sediment accumulation and catchment erosion can be elucidated. Figure 7 shows an age profile derived from ^{210}Pb data for a lagoon in the Bundeena catchment (Mooney *et al.*, 2001). Also shown is the sediment accumulation rate derived from the same data. The profile indicates a period of rapid accumulation corresponding to European settlement of the catchment. Similar trends have been observed in profiles of sediments in lakes and reservoirs whose catchments have undergone disturbance by human activities such as ploughing, cattle and sheep farming, forestry, urbanisation and mining.

Periods of rapid accumulation are often associated with changes in the physical and geochemical characteristics of sediment. By establishing a chronology of a sediment

profile the effects of specific land use changes in the catchment can be related to documented events, and sediment sources subsequently identified.

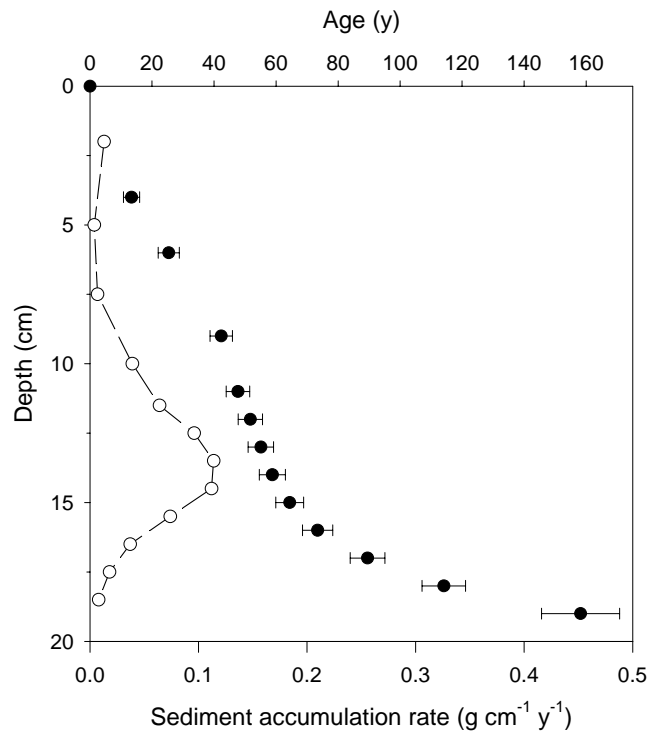


Figure 7: Sediment age (closed circles) and accumulation rate (open circles) in a core from Jibbon Lagoon, as determined from the ²¹⁰Pb profile (Mooney *et al.*, 2001).

3.5. Optically stimulated luminescence

Optically stimulated luminescence (OSL) is a sediment dating technique which can provide ‘stand-alone’ dating of a sediment profile as well as being able to complement and validate ²¹⁰Pb geochronology. As noted above, it is capable of spanning the pre-and post European settlement time period (last 150-250 years). However, it can also provide contemporary information on sediment transport. Recent advances in instrumentation (Bøtter-Jensen *et al.*, 2000) and analysis methods (Olley *et al.*, 2004) have expanded the variety of applicable depositional environments such that OSL dating can now accurately date fluvial and alluvial material with <10 years of accumulated dose (see examples below, and see sister document, Pietsch, 2007).

The OSL technique utilises the ability of natural crystals such as quartz or feldspar to accumulate a population of electrons which become *trapped* in natural defects within the crystal. The electrons originate from atoms in the crystal which are ionised by natural radiation emanating from the surrounding sediment. The size of the trapped electron population provides a measure of the radiation dose received by the crystal since it was last re-set to zero, an event which results from exposure to sunlight during transport. Determination of the concentration of radionuclides within the deposit allows calculation of the dose rate; that is, the rate at which the dose accrued. In combination,

measurements of the dose and the dose rate enable calculation of the age, or more precisely, the time elapsed since the last exposure to sunlight sufficient to fully bleach the accumulated dose:

$$\frac{Dose}{Dose\ Rate} = Age$$

Clearly optical dating requires specific sample collection, manipulation procedures and analysis procedures such that exposure of the sample to light is eliminated. CSIRO Land and Water have developed specialised sampling equipment and laboratory facilities to accomplish this (see Pietsch, 2007).

3.6. Reliability of OSL dates

The reliability of OSL dating on time scales of hundreds to thousands of years is well known. It is now proposed that, by using single grain analysis, reliable dating of sediment grains can occur on a time frame of decades. Figure 8 shows a plot of ^{137}Cs and OSL age for a range of samples taken from in-channel benches in the Daly River. The fact that all OSL ages in sections where ^{137}Cs is present are less than 50 years shows the accuracy of the method (generally ± 5 to 10 years). Thus OSL has the ability to provide information on sediment transport and deposition over time scales relevant to current land management practice.

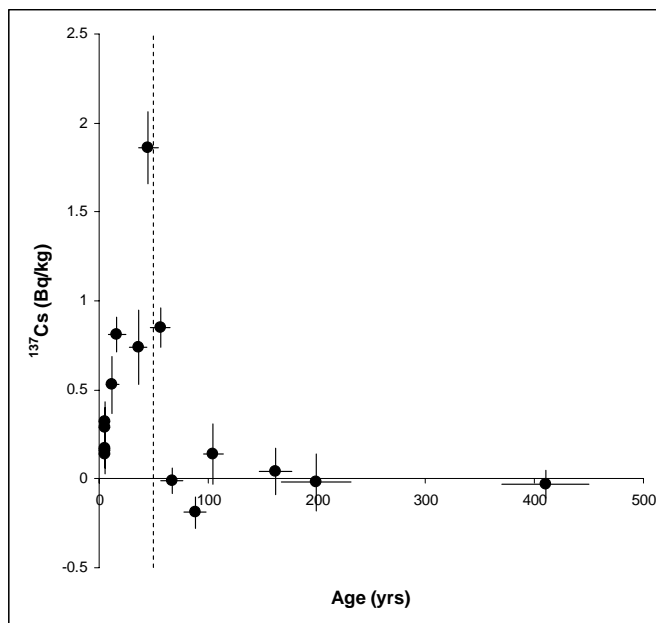


Figure 8: The relationship between ^{137}Cs and OSL age for core depth sections from the Daly River. The dashed line shows AD 1956. The fact that no ^{137}Cs is seen in samples with OSL dates earlier than 1956 show the accuracy of the OSL technique (from Wasson *et al.*, 2007).

3.7. Examples of the application of OSL

Figures 9 and 10 provide examples where OSL dating has been used to indicate the nature and rate of recent sediment deposition, and by inference, erosion. In the first example, an investigation into deposition on in-channel benches in the Daly River, (Figure 9), sand deposition is shown to have dominated sediment delivery in the last ~20 years. This conclusion is consistent with observations by local residents that sand transport has recently become commonplace. However, the OSL dating in combination with the geomorphology evidence indicates that this trend is not necessarily a new development, with a period of sand deposition having commenced below 100 cm (OSL age 199 ± 32 years), well before modification of the catchment by Europeans in the late 1800s. Thus, the current phase of sand transport is not unique and cannot be solely attributed to grazing and/or clearing.

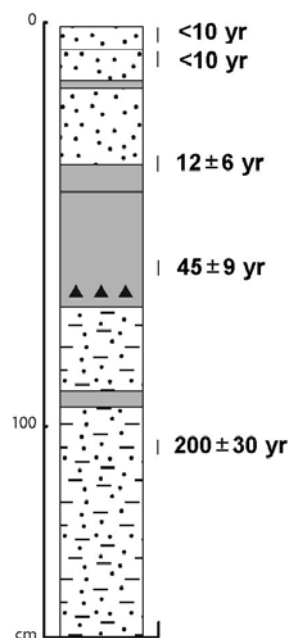


Figure 9: OSL ages for a sediment deposition bench in the Daly River. Rapid deposition of sand (dots on white background) is seen in the last ~20 years, as well as an equivalent sand episode at ~100 cm depth and below. OSL dating indicates the latter event occurred prior to major landuse change in the catchment (from Wasson *et al.*, 2007).

In contrast, the second example of a depositional floodplain from the Mulwaree River in southeastern Australia (Figure 10) clearly shows that the depositional period that immediately followed settlement has no comparison in the preceding ~10,000 years. The sequence highlights the extent of post European aggradation and illustrates the broad dating range of OSL dating.

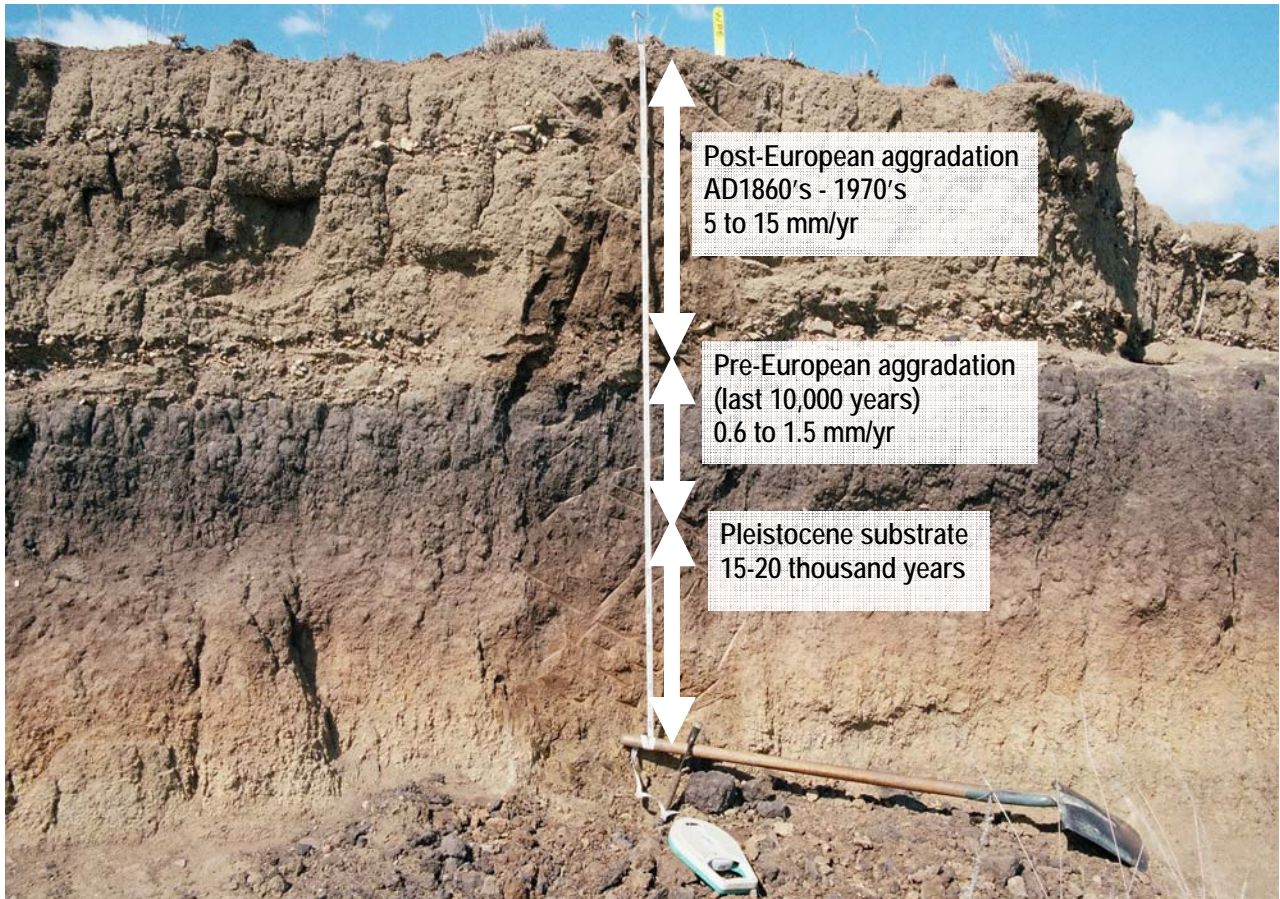


Figure 10: A deposition bench from the Mulwaree River dated by OSL.

4. APPLICATION OF TRACING AND DATING METHODS

4.1. Which method should I employ?

To aid in the selection of an appropriate method for a particular sediment-related problem some of the common applications where tracing and dating techniques have been utilised are listed in Table 2. Generalised outcomes are given.

Table2: Common applications where tracing and dating techniques have been utilised

Application	Purpose	Methods	Outcomes
Sediment sourcing	<ul style="list-style-type: none"> • Effective targeting of erosion mitigation works • Assessing the proportional contribution to sediment fluxes of various land-uses and sub-catchments 	<ul style="list-style-type: none"> • Erosion process tracing • Spatial tracing 	<ul style="list-style-type: none"> • Determination of erosion processes delivering sediment to river. • Determination of spatial source (river sub-catchment) delivering sediment to river.
Catchment budgets	<ul style="list-style-type: none"> • Determining end-of-catchment sediment and nutrient budgets to estuaries and other water bodies 	<ul style="list-style-type: none"> • Sediment core analysis ($^{210}\text{Pb}/^{137}\text{Cs}$, OSL) • Catchment modelling (+ tracers) 	<ul style="list-style-type: none"> • An assessment of current and past sediment fluxes to the receiving water body or estuary. • Catchment sediment yield.
Hillslope soil mobilisation	<ul style="list-style-type: none"> • Estimating hillslope soil redistribution and losses resulting from land disturbance 	<ul style="list-style-type: none"> • ^{210}Pb, ^{137}Cs, ^7Be inventories 	<ul style="list-style-type: none"> • Better estimates of hillslope soil losses for catchment modelling (SedNet) parametisation and for hillslope erosion mitigation works.
Channel bank migration	<ul style="list-style-type: none"> • Determining channel bank stability • Determining the contribution of bank erosion to sediment fluxes 	<ul style="list-style-type: none"> • OSL (bank migration) • ^7Be, ^{137}Cs (erosion source tracing) 	<ul style="list-style-type: none"> • Natural and post European channel bank migration rates. • The extent that channel banks are a sediment source.
Comparing pre and post European sedimentation	<ul style="list-style-type: none"> • Estimation of sediment fluxes associated the “natural” or undisturbed state of the catchment 	<ul style="list-style-type: none"> • Sediment core analysis (^{210}Pb, ^{137}Cs, Pu, OSL) 	<ul style="list-style-type: none"> • Effect of land-use change after European settlement on sediment delivery at point of core collection.

4.2. Tracing and dating studies Undertaken by CSIRO

Table 3 details studies undertaken by CSIRO Land and Water and collaborators over the last 10 years. Reference details are given at the end of this document.

Table 3: Studies undertaken by CSIRO Land and Water and collaborators over the last 10 years

Study catchment	Outcomes	References
Brisbane River (south Queensland)	<ul style="list-style-type: none"> ▪ Moreton Bay accumulation rates estimated ▪ Sources of sediment to Moreton Bay determined, both spatially and by erosion process 	Hancock (2001) Caitcheon et al., (2001) Wallbrink (2004)
Torrens River (Adelaide Hills)	<ul style="list-style-type: none"> ▪ Reservoir accumulation rates measured ▪ Sources of sediment to Kangaroo Creek Dam determined 	Tibby et al.,(2007)
Western Port (Southern Victoria)	<ul style="list-style-type: none"> ▪ Sources of sediment to Westernport determined, ▪ Fate of particles mobilised within the embayment determined 	Hancock et al., (2001) Wallbrink et al., (2003a)
Gippsland Lakes (south-east Victoria)	<ul style="list-style-type: none"> ▪ Sources of sediment to Gippsland Lakes determined by integration of tracer measurements and SedNet modelling. ▪ Sediment accumulation rates within Lake Wellington estimated, both pre and post-European settlement 	Hancock and Pietsch (2006) Hancock et al., (2007)
Darling-Barwon River (western NSW)	<ul style="list-style-type: none"> ▪ Spatial sediment sources to the Darling River determined using major element geochemistry 	Olley and Caitcheon (2000a)
Namoi River (central NSW)	<ul style="list-style-type: none"> ▪ Diffuse sediment sources to the Namoi River determined (erosion process, land-use) 	Wallbrink et al., (2003b)
Maroochy River (Queensland)	<ul style="list-style-type: none"> ▪ Sources of sediment to the Maroochy estuary determined, including erosion process (subsoil/bank erosion) and spatial sources. 	Caitcheon et al. (2006)
Lake Burragorang (west of Sydney)	<ul style="list-style-type: none"> ▪ Spatial and erosion process sources determined ▪ Sediment budgets constructed using geochemical tracers, spatial modelling and in-stream monitoring ▪ Influence of bushfires on sediment delivery estimated 	Caitcheon et al., (2007) Rustomji et al. (submitted) Wilkinson et al., (2006)
Murrumbidgee River (southern NSW)	<ul style="list-style-type: none"> ▪ Erosion sources determined by land-use (cultivated and uncultivated) and erosion process (channel bank contribution) 	Wallbrink et al., (1998)
Hume reservoir (Murray, River, NSW/Vic)	<ul style="list-style-type: none"> ▪ The pilot study determined the major sediment source to the reservoir (The Murray River) ▪ The major erosion process delivering this sediment was determined (gully and bank erosion) . ▪ Sedimentation rates in the reservoir were determined 	Olley and Caitcheon (2000b)
Fitzroy River (Rockhampton, Queensland)	<ul style="list-style-type: none"> ▪ Spatial sediment sources to Fitzroy estuary determined using geochemical tracers 	Douglas et al., (2003)
Ovens river (northern Victoria)	<ul style="list-style-type: none"> ▪ A combination of SedNet modelling, in-stream monitoring and geochemical tracer measurements were used to determine erosion process sources 	DeRose et al., (2005).
Herbert River (north Queensland)	<ul style="list-style-type: none"> ▪ A combination of SedNet modelling, fallout tracer measurements and in-stream monitoring were used to determine erosion process sources 	Bartley et al., 2005 Additional work in progress
Bowen River (north Queensland)		In progress
Daly River (north NT)		In progress
Logan-Albert (south Queensland)		In progress

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