

^{210}Pb and ^{137}Cs Dating of Remote Lake Sediments in Adirondack Park, New York

Abdul J. Khan^{1*}, Tanveer Ahmad^{1,2}

¹Wadsworth Center, New York State Department of Health, Albany, NY, USA

²General Electric Vernova, Schenectady, NY, USA

Email: *abduljabbar.khan@health.ny.gov

How to cite this paper: Khan, A. J., & Ahmad, T. (2026). ^{210}Pb and ^{137}Cs Dating of Remote Lake Sediments in Adirondack Park, New York. *Journal of Geoscience and Environment Protection*, 14, 285-311. <https://doi.org/10.4236/gep.2026.1410012>

Received: September 17, 2026

Accepted: October 27, 2026

Published: October 30, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

This study establishes sediment chronologies for West Pine Pond (WP), a remote soft-water lake in the Adirondack Park region of New York, using natural ^{210}Pb and anthropogenic ^{137}Cs as geochronological tracers. Four sediment cores were analyzed by gamma spectrometry, and age-depth relationships were developed using the Constant Initial Concentration (CIC), Constant Flux-Constant Sedimentation (CF-CS), and Constant Rate of Supply (CRS) models. Unsupported ^{210}Pb ($^{210}\text{Pb}_{\text{unsup}}$) profiles showed well-defined declines with depth, and three of the four cores contained distinct ^{137}Cs fallout maxima associated with the 1963 atmospheric nuclear-testing peak, providing independent chronological validation. Mass accumulation rates ranged from 0.0106 to 0.0177 g $\text{cm}^{-2} \text{yr}^{-1}$, while linear sedimentation rates ranged from 0.18 to 0.20 cm yr^{-1} , indicating relatively stable long-term deposition. The CIC model showed the closest overall agreement with the ^{137}Cs marker horizon in the three cores with identifiable ^{137}Cs maxima, whereas the CF-CS model showed the closest overall agreement with the ^{137}Cs marker horizon in the three cores with identifiable ^{137}Cs maxima, whereas the CRS model revealed substantial depth-dependent variability in sediment accumulation among the four cores. Unsupported ^{210}Pb inventories ranged from 28.56 to 44.16 dpm cm^{-2} , with corresponding fluxes of 0.89 - 1.38 $\text{dpm cm}^{-2} \text{yr}^{-1}$. The resulting chronologies preserve approximately 150 years of environmental history and demonstrate the value of combining multiple ^{210}Pb dating models with independent ^{137}Cs validation for reconstructing long-term sedimentation and environmental change in lacustrine systems.

Keywords

^{210}Pb Dating, ^{137}Cs , Adirondack Mountains, CIC, CF-CS, CRS, Sediment Focusing

1. Introduction

Over the past 150 years, there has been a significant increase in human activities, including construction, agriculture, mining, and the consumption of fossil fuels. As awareness of the impact of these activities on human and environmental systems grows, establishing accurate timelines of ecological change has become increasingly important. Chronologies derived from sediment core profiles typically utilize the activities of radionuclides deposited and stratified within the physical environment. One of the most widely used radionuclides for establishing chronologies over approximately the past 150 years is ^{210}Pb . The ^{210}Pb radiometric dating technique is among the most widely employed methods for dating sediments deposited within the last 100 to 150 years across lacustrine, estuarine, marsh, and marine environments. The technique was first applied to lake sediments by Krishnaswamy et al. (1971), following its initial development for dating ice cores by Goldberg (1963). Since then, ^{210}Pb dating has become an essential tool for determining sediment chronologies, bottom core ages, and sedimentation rates.

In addition to establishing sediment accumulation histories, ^{210}Pb dating has played a crucial role in studies of erosion rates, accelerated eutrophication, atmospheric circulation patterns, the residence time of tropospheric aerosols, and air-sea exchange processes (Goldberg, 1963; Krishnaswamy et al., 1971; Nozaki et al., 1978; Sanak et al., 1981; Appleby, 2004; Turner & Delorme, 1996; Erten, 1997).

^{210}Pb is a naturally occurring radionuclide from the ^{238}U decay series, commonly found in the Earth's crust. It decays through various intermediates to reach stable ^{206}Pb . One significant intermediate is ^{226}Ra ($t_{1/2} = 1600$ years), which transforms into noble gas ^{222}Rn (half-life = 3.825 days). Because ^{222}Rn is gaseous, it can escape from the soil into the atmosphere, disturbing the initial secular equilibrium with ^{238}U . Once in the air, ^{222}Rn decays and eventually forms ^{210}Pb through short-lived progeny. Atmospheric ^{210}Pb has a half-life of 22.26 years and quickly adheres to aerosol particles. These ^{210}Pb bearing aerosols typically reside in the troposphere for less than a week (Goldberg, 1963; Benninger et al., 1975; Nozaki et al., 1978; Lewis, 1977). Through dry and, especially, wet deposition, which accounts for approximately 90% of atmospheric input (Binford et al., 1993), ^{210}Pb is deposited onto the Earth's surface. In aquatic systems like lakes, ^{210}Pb becomes part of the bottom sediments (Benninger et al., 1975). Research indicates that dissolved ^{210}Pb in river water is efficiently removed by adsorption onto suspended particles (Benninger et al., 1975; Benninger, 1978; Krishnaswami et al., 1978; Durham & Joshi, 1980). The ^{210}Pb originating from atmospheric ^{222}Rn decay is known as unsupported ^{210}Pb ($^{210}\text{Pb}_{\text{unsup}}$), because its activity is not sustained by in-situ ^{238}U decay. Conversely, ^{210}Pb produced within sediment from the decay of sediment-bound ^{226}Ra is called supported ^{210}Pb ($^{210}\text{Pb}_{\text{sup}}$). $^{210}\text{Pb}_{\text{unsup}}$ reaches lake sediments mainly through direct atmospheric deposition and, to a lesser extent, via particle transport from inflowing rivers and catchment runoff. However, studies consistently show that catchment contributions are minor compared to direct atmospheric input, with most of the $^{210}\text{Pb}_{\text{unsup}}$ retained in soils and not reaching lake sediments (Krishnaswamy et al.,

1971; Benninger et al., 1975; Benninger, 1978; Lewis, 1977).

The total ^{210}Pb activity ($^{210}\text{Pb}_{\text{tot}}$) measured in sediment samples includes both supported and unsupported fractions. The $^{210}\text{Pb}_{\text{sup}}$ activity, typically expressed in disintegrations per minute per gram (DPM g^{-1}) of dry sediment, is assumed to stay relatively constant over time due to secular equilibrium with its parent ^{226}Ra . The $^{210}\text{Pb}_{\text{unsup}}$ activity is determined by subtracting the supported component from the total activity. If $^{210}\text{Pb}_{\text{unsup}}$ does not significantly migrate after deposition, its activity decreases with depth in sediment cores due to radioactive decay. This decay profile serves as the foundation of ^{210}Pb -based dating methods. Determining the age of sediment layers is crucial for understanding the timescales of geochemical processes and the impacts of human activities. Moreover, sedimentation rates derived from ^{210}Pb dating are essential for environmental remediation efforts, land-use planning, and comprehending the physical and chemical dynamics within aquatic systems. Lakes, serving as repositories for eroded particles from their catchments, preserve sediment records that enable the reconstruction of historical erosion and deposition events. The Adirondack region, marked by cold, snowy winters and cool, wet summers, offers a unique environment for studying such processes. Precipitation is distributed evenly throughout the year, while temperature, frost-free season length, and other meteorological variables like wind speed and cloud deposition fluctuate with elevation. These climatic factors affect the deposition of ^{210}Pb into lake systems.

Climate change has significantly impacted the Adirondack region. A study on lake ice in the area reported rapid changes between 1975 and 2007, with ice cover durations decreasing by up to 21 days, primarily due to delayed freeze-up and, to a lesser extent, earlier breakup (Beier et al., 2012). The Adirondack Mountains have been extensively affected by acidic atmospheric deposition and associated watershed biogeochemical changes over the past century. Previous regional investigations have documented long-term declines in sulfate and nitrate deposition, changes in surface-water chemistry, and evidence of partial ecological recovery in Adirondack lakes following reductions in atmospheric emissions (NYSERDA, 2015; Driscoll et al., 2007). Because sediment records preserve signals of these environmental changes, the development of accurate sediment chronologies using radionuclides such as ^{210}Pb and ^{137}Cs is essential for reconstructing temporal variations in sediment accumulation and environmental processes within Adirondack Lake ecosystems. These changes are expected to alter growing seasons, vegetation patterns, and runoff dynamics, which can affect ^{210}Pb deposition and cycling. Furthermore, the region's watersheds are biogeochemically sensitive, particularly to atmospheric inputs of sulfate, nitrate, and radionuclides like ^{210}Pb . Acid deposition from sulfur and nitrogen oxides has historically impacted the region, although emissions have declined significantly since the passage of the U.S. Clean Air Act Amendments of 1990. However, the behavior and fate of ^{210}Pb under these evolving conditions remain poorly studied. This investigation is part of a broader research initiative aimed at monitoring historical atmospheric deposition of elemental carbon and trace elements across

lake sediments from the Midwest to the Adirondack Park region (Husain et al., 2008; Sarkar et al., 2015). As part of this study, four sediment cores from West Pine Pond (WP), a high-altitude, remote lake in the Adirondack Park, were dated, and sedimentation rates were calculated. The sediment chronologies were constructed using three commonly applied ^{210}Pb dating models: the Constant Initial Concentration (CIC), Constant Flux-Constant Sedimentation (CF-CS), and Constant Rate of Supply (CRS) models (Abril-Hernández, 2023; Ruiz-Fernández et al., 2020; Hunter et al., 2023). To validate the ^{210}Pb derived age models, profiles of ^{137}Cs , an independent tracer of atmospheric fallout, were also analyzed (Heldal et al., 2021).

Recent advances in ^{210}Pb sediment dating have emphasized the importance of selecting appropriate models to account for non-ideal depositional conditions and spatial heterogeneity. A comprehensive review by Abril-Hernández (2025) highlights the development of numerous models and the growing recognition of model-dependent uncertainties in sediment chronologies. Furthermore, recent studies have demonstrated that traditional models such as CIC and CRS may not adequately capture sediment dynamics in systems with variable porosity or episodic deposition, prompting the development of alternative approaches and model validation strategies (Anderson et al., 2024). These developments underscore the need for multi-model comparison and independent validation using tracers such as ^{137}Cs , as applied in the present study.

While ^{210}Pb dating has been widely applied to lake sediments, relatively few studies have combined multi-core analysis, multi-model comparison, and independent validation using ^{137}Cs within a single lacustrine system to evaluate both chronological accuracy and spatial variability in sedimentation processes. This study addresses this gap by integrating multi-model comparison with independent chronological validation and environmental interpretation, providing a more comprehensive framework for assessing sediment chronologies in complex depositional environments.

2. Experimental

Sediment cores were collected from West Pine Pond (WP), a remote lake in the Adirondack Park region of upstate New York. The Adirondack Park covers approximately 6 million hectares and is predominantly forested, with mountainous terrain and more than 3,000 lakes and ponds. It encompasses the largest wilderness area east of the Mississippi River (Lorey & Driscoll, 1999; Adirondack Lakes Survey Corporation). Many lakes in this region are located at relatively high elevations and are remote from major roads and highways. West Pine Pond (approximately 44°20' N, 74°25' W) has a surface area of 25.5 ha and a catchment area of 235 ha, with a mean water depth of approximately 5.5 m.

Four sediment cores (WP-1, WP-2, WP-3, and WP-5) were collected in September 2005 from the deep depositional region of the lake at a water depth of approximately 13 m. The geographic coordinates of the individual coring stations, recorded using a Global Positioning System (GPS), were 44°20.2830' N, 74°25.5830'

W (WP-1); 44°20.2730' N, 74°25.5830' W (WP-2); 44°20.2790' N, 74°25.5790' W (WP-3); and 44°20.2810' N, 74°25.5790' W (WP-5). The four stations were closely spaced within the deep depositional basin, with approximate inter-core distances ranging from 3.7 to 18.5 m.

Coring was conducted from a rowboat using a gravity-driven coring device fitted with removable plastic tubes having an internal diameter of 5.12 cm. The recovered sediment cores were approximately 55 cm long, and the sediment-water interface was retained intact during core recovery, preserving the uppermost sediment layer. Immediately after recovery, the cores were sectioned in the field to minimize physical disturbance and post-collection redistribution of sediment. The cores were sliced horizontally into sections with thicknesses that were multiples of 0.125 inch (3.18 mm). Each sediment section was transferred to a clean, pre-weighed plastic cup (5 cm internal diameter) with a lid and maintained at 4°C during transport to the laboratory. Upon arrival at the laboratory, the samples were refrigerated at 4°C and subsequently freeze-dried using a LABCONCO freeze dryer (Model 7753020) prior to radionuclide analysis.

3. Measurement of ^{210}Pb and ^{137}Cs Activities

Freeze-dried sediment samples were homogenized to create a fine powder. Approximately 0.4 - 3 g of sediment from each slice was accurately weighed, and the activity of 46.5 keV γ -ray from ^{210}Pb was measured using a non-destructive well-type high-purity germanium detector (HPGe) manufactured by Canberra Inc. (Meriden, CT). The well dimensions were 20 mm in diameter and 40 mm in length. The detector provided high efficiency and low background for low-energy γ radiation (20 - 400 keV). It has a resolution of 1.21 keV and 2.18 keV (FWHM) at γ -ray energies of 59.5 keV and 1332.5 keV from ^{241}Am and ^{60}Co , respectively. The detector is shielded from background radiation by a 6-inch (15.24 cm) thick Pb container and is positioned inside a room constructed of 6-inch-thick steel plates from pre-World War II iron. Teflon tubes (outer diameter: 19 mm; length: 110 mm) with screw caps were employed to count the γ -rays of ^{210}Pb , filled with sediments up to the 5 ml marking. A latex protective cover was wrapped around the tubes to shield the detector from contamination. Details of this detector have been provided elsewhere (Parekh et al., 2003, 2004).

An independent verification of the ages derived from ^{210}Pb was provided by measurements of ^{137}Cs radioisotope ($t_{1/2} = 30.17$ yr) activity (Appleby, 2000, 2004; Turner & Delorme, 1996). Unlike naturally occurring ^{210}Pb , ^{137}Cs is an artificial radioisotope that was introduced into the atmosphere from nuclear weapons testing and, in some regions such as Russia, Norway, Sweden, and parts of Central Europe, from the 1986 Chernobyl reactor accident (Taylor et al., 1988; Erten, 1997). Because the source of ^{137}Cs differs from that of ^{210}Pb , ^{137}Cs can serve as an independent chronological marker for verifying dates obtained from ^{210}Pb dating. Global fallout of ^{137}Cs increased after 1954, reaching a maximum in the Northern Hemisphere in 1963 (Figure 1), and subsequently declined following the 1963

Partial Test Ban Treaty (Appleby, 2000; Carroll et al., 1999). However, studies have shown that due to the post-depositional mobility of ^{137}Cs , the record of this radionuclide in the sediment column can become degraded (Appleby et al., 1991). The activity of 661.7 keV γ -rays of ^{137}Cs was measured using a high-efficiency, p-type, closed-end HPGe detector in a 2-inch plastic jar. The spectrometers were calibrated with NIST-traceable ^{210}Pb and ^{137}Cs standards in the same matrix as the analyzed sample. The counting time varied from 1000 to 4000 minutes.

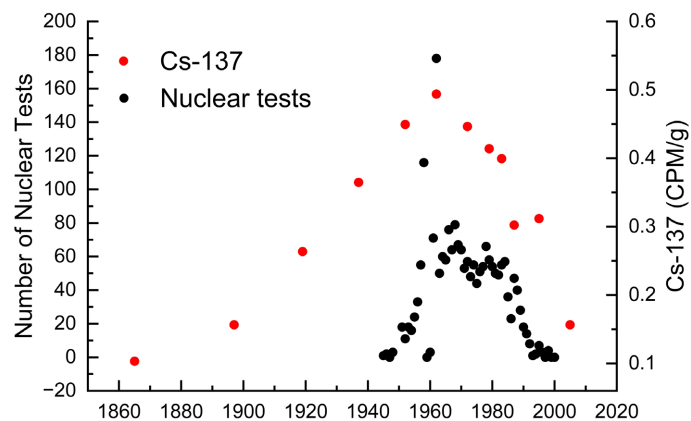


Figure 1. ^{137}Cs deposition in lake sediments due to global nuclear testing.

4. ^{210}Pb Activity Processing and Quality Control

Total ^{210}Pb activity was determined from the 46.5-keV gamma-ray photopeak and expressed on a dry-sediment mass basis (dpm g^{-1}). Supported ^{210}Pb ($^{210}\text{Pb}_{\text{sup}}$) was determined separately for each core from the deepest sediment intervals in which the measured total ^{210}Pb activity approached a relatively constant asymptotic value, indicating that the unsupported component had become negligible. The activities of these deep intervals were averaged to obtain a core-specific supported ^{210}Pb activity, and the associated uncertainty was determined from the uncertainties and variability of the measurements included in the average. The resulting $^{210}\text{Pb}_{\text{sup}}$ activities were 0.90, 1.36, 0.93, and 1.11 dpm g^{-1} for WP-1, WP-2, WP-3, and WP-5, respectively.

Unsupported ^{210}Pb activity ($^{210}\text{Pb}_{\text{unSUP}}$) for each sediment interval was calculated by subtracting the corresponding core-specific supported activity from the measured total ^{210}Pb activity:

$$^{210}\text{Pb}_{\text{unSUP}} = ^{210}\text{Pb}_{\text{tot}} - ^{210}\text{Pb}_{\text{sup}}$$

Sediment intervals were included in the ^{210}Pb chronology while measurable $^{210}\text{Pb}_{\text{unSUP}}$ remained distinguishable from the supported component within the measurement uncertainty. At greater depths, where total ^{210}Pb activity approached the supported value, the sediment was below the practical ^{210}Pb dating horizon.

For gamma-spectrometric quality control, freeze-dried and homogenized sediment samples were measured in Teflon tubes using the well-type HPGe detector described above. Sample geometry was maintained consistently with the calibra-

tion geometry, and detector efficiency calibration was performed using NIST-traceable standards (Semkow et al., 2015). Because attenuation of the low-energy 46.5-keV gamma ray is sensitive to sample composition, density, and counting geometry, density-dependent attenuation/self-absorption corrections were determined using the GESPECOR Monte Carlo software (Sima et al., 2001). The sample-specific density and measurement geometry were incorporated into the GESPECOR calculations to correct the 46.5-keV counting efficiency for differences between calibration standards and sediment samples.

Detector background was characterized using a 4000 min background measurement under the same counting configuration. Background counts in the 46.5-keV region were incorporated into the net-peak activity and detection-limit calculations. Minimum detectable activities (MDA) were determined using the detection-limit procedure described elsewhere (Currie, 1968), incorporating the measured background, counting time, detector efficiency, ^{210}Pb gamma-ray emission probability, and dry sample mass. Samples were counted for 1000 - 4000 min, with longer counting times used where necessary to improve counting statistics for low-activity sediment intervals. The combined use of controlled counting geometry, NIST-traceable efficiency calibration, GESPECOR density/self-absorption correction, long-duration background measurements, and MDA evaluation provided quality control for the low-energy ^{210}Pb measurements.

The $^{210}\text{Pb}_{\text{unsup}}$ profile was evaluated only over sediment intervals for which the activity was above the minimum detectable activity (MDA). The practical dating horizon was defined as the depth at which $^{210}\text{Pb}_{\text{unsup}}$ activity decreased below the MDA. Sediment intervals below this horizon were not used for age determination, and no extrapolation of $^{210}\text{Pb}_{\text{unsup}}$ activity or additional residual unsupported ^{210}Pb inventory was assigned below the measured horizon.

5. Age Determination Using ^{210}Pb Dating

Three commonly used ^{210}Pb dating models for sediment cores are the Constant Initial Concentration (CIC), Constant Flux-Constant Sedimentation (CF-CS), and Constant Rate of Supply (CRS) models. In this paper, we provide a summary of each. The details of these models can be found in Appleby (2001). Although all three models are based on key assumptions, the optimal model will differ depending on the environment and the expected constancy of ^{210}Pb influx to sediments, as well as the mass accumulation rate:

- 1) ^{210}Pb is removed from the atmosphere and the water column and is quickly sequestered into sediments.
- 2) Once deposited, the ^{210}Pb in the sediment is immobile.
- 3) The sedimentation process will be uninterrupted.

5.1. Constant Initial Concentration (CIC) Model

The CIC model assumes a constant initial $^{210}\text{Pb}_{\text{unsup}}$ activity of sediments at the time of deposition, so each layer of sediments in a core will have the same initial

$^{210}\text{Pb}_{\text{unsup}}$ activity, $C(0)$, at the sediment-water interface, regardless of the variability in the sedimentation rate (Robbins, 1978; Appleby & Oldfield 1983; Binford, 1990; Binford et al., 1993). The age (t) of sediment at any depth x (cm) is then given by (Appleby & Oldfield 1983).

$$C(x) = C(0)\exp(-\lambda t) \quad (1)$$

where $C(x)$ = activity of $^{210}\text{Pb}_{\text{unsup}}$ per gram of dried sediment at any depth x (cm) below the sediment-water interface (DPM g^{-1}), $C(0)$ = activity of the $^{210}\text{Pb}_{\text{unsup}}$ per gram of dried sediment at the sediment/water interface (DPM g^{-1}), and λ = ^{210}Pb decay constant (0.03114 yr^{-1}). Equation (1) can also be written as

$$C(x) = C(0)\exp\left\{-\lambda\left(\frac{x}{\omega}\right)\right\} \quad (2)$$

where ω = mean linear sedimentation rate (cm yr^{-1}). The log-linear plot's least-squares regression slope, $-\lambda/\omega$, in Equation (2) will give the mean sedimentation rate ω for the core. The age t_i of any sediment slice in a column can be found using the relation.

$$t_i = \frac{x_i}{\omega} \quad (3)$$

where x_i is the thickness of a particular slice in cm.

The sedimentation rate (ω), obtained from Equation (2) represents a core-averaged linear sedimentation rate and is not an inherent assumption of the general CIC model. The CIC ages reported at successive depths were calculated using this mean-rate approximation. Consequently, sediment intervals of equal thickness have equal age increments. The resulting CIC chronology therefore represents a smoothed, long-term age-depth relationship for comparison among the individual cores and with the independent ^{137}Cs fallout record. Depth-dependent variations in sediment accumulation are evaluated separately using the CRS model.

5.2. Constant Flux—Constant Sedimentation (CF-CS) Model

The CF-CS model assumes that both the flux of $^{210}\text{Pb}_{\text{unsup}}$ into the sediments and the sediment accumulation rate remain constant over time (Appleby & Oldfield, 1983; Appleby, 1993). In the CF-CS model, the $^{210}\text{Pb}_{\text{unsup}}$ activity is plotted against the cumulative dry mass of the sediment, or mass depth, rather than against depth, as in the CIC model, to account for the sediments' post-depositional compaction. As expressed by Appleby (2001),

$$C(m) = C(0)\exp\left\{-\lambda\left(\frac{m}{r}\right)\right\} \quad (4)$$

where $C(m)$ is the $^{210}\text{Pb}_{\text{unsup}}$ activity of dry sediment at cumulative mass depth m (dpm g^{-1}), $C(0)$ is the initial $^{210}\text{Pb}_{\text{unsup}}$ activity at the sediment-water interface (dpm g^{-1}), λ is the ^{210}Pb decay constant (0.03114 yr^{-1}), r is the dry-mass sediment accumulation rate ($\text{g cm}^{-2} \text{ yr}^{-1}$), and m is cumulative dry mass depth (g cm^{-2}). For each sediment slice, dry bulk density, ρ_i (g cm^{-3}), was calculated from the freeze-dried sed-

iment mass and the original volume of the sediment slice before freeze-drying:

$$\rho_i = M_i^d / V_i \quad (5)$$

where M_i^d is the freeze-dried sediment mass (g) of slice i and V_i is the original volume (cm^3) of that sediment slice. The original slice volume was calculated from the internal cross-sectional area of the 5.12 cm diameter coring tube and the original thickness of the sediment interval:

$$V_i = \pi \left(\frac{D}{2} \right)^2 \Delta x_i \quad (6)$$

where D is the internal diameter of the coring tube (5.12 cm) and Δx_i is the thickness (cm) of sediment slice i .

The dry sediment mass per unit area represented by an individual slice (Δm_i) is given by.

$$\Delta m_i = \rho_i \times \Delta x_i \quad (7)$$

where Δx_i = thickness of any slice i (cm), and ρ_i = dry bulk density of any slice i (g cm^{-3}). When $^{210}\text{Pb}_{\text{unsup}}$ activity, $C(m)$, in Equation (4) is plotted on a logarithmic-linear scale against the cumulative dry mass depth, the resulting profile will be a linear plot. The plot's least-squares regression slope, $-\lambda/r$, will give the mean mass accumulation rate r ($\text{g cm}^{-2} \text{ yr}^{-1}$) for the core. The age t_i of any sediment slice is calculated using the relationship.

$$t_i = \frac{m_i}{r} \quad (8)$$

Accordingly, the CF-CS-derived mass accumulation rates reported in this study are based entirely on dry sediment mass and are expressed in $\text{g cm}^{-2} \text{ yr}^{-1}$.

5.3. Constant Rate of Supply (CRS) Model

The CRS model assumes constant fallout of $^{210}\text{Pb}_{\text{unsup}}$ from the atmosphere into the lake (or water body), resulting in the constant rate of supply of $^{210}\text{Pb}_{\text{unsup}}$ to the sediments per unit time, irrespective of any changes in the sedimentation rate (Goldberg, 1963; Appleby & Oldfield, 1978; Robbins, 1978; Appleby & Oldfield, 1983). By accounting for dilution of ^{210}Pb activity associated with variations in sediment accumulation rate, the CRS model accommodates changes in sediment accumulation through time (Appleby & Oldfield, 1978; Binford, 1990), this model considers the variability in the ^{210}Pb depth profiles, whereby changes in the sediment accumulation rate (predominantly due to the changes in the surface runoff) have altered ^{210}Pb from its initial concentration. Age (t) of sediment at any depth x (cm), is given by (Appleby, 2001)

$$A(x) = A(0) \exp(-\lambda t) \quad (9)$$

where $A(x)$ = cumulative $^{210}\text{Pb}_{\text{unsup}}$ inventory beneath sediment of depth x (DPM cm^{-2}), $A(0)$ = total inventory of the $^{210}\text{Pb}_{\text{unsup}}$ in the sediment column (DPM cm^{-2}). $A(x)$ and $A(0)$ can be found through numerical integration using equations from Appleby (2001) and Miguel et al. (2003):

$$A(x) = \sum_i^{\infty} C(x)_i m_i, \text{ and} \quad (10)$$

$$A(0) = \sum_0^{\infty} C(x)_i m_i \quad (11)$$

The varying sediment accumulation rate r ($\text{g cm}^{-2} \text{yr}^{-1}$) at each stage of sediment accumulation (or sediment slice) is given by

$$r = \frac{\lambda A(x)}{C(x)} \quad (12)$$

The net $^{210}\text{Pb}_{\text{unsup}}$ flux (P) in $\text{DPM cm}^{-2} \text{yr}^{-1}$ of $^{210}\text{Pb}_{\text{unsup}}$ to the sediments is given by (Binford et al., 1993)

$$P = A(0)\lambda \quad (13)$$

Appleby & Oldfield (1983) pointed out that the CIC and CRS models are mathematically practicable for calculating ^{210}Pb dates under varying sediment accumulation rates.

The uncertainties associated with the parameters and derived ages in these models arise from both analytical measurements and model assumptions. A detailed mathematical treatment of uncertainty propagation for each model is presented in Appendix A.

6. Analytical Precision and Uncertainty Treatment

Measurement uncertainties in ^{210}Pb and ^{137}Cs activities were derived primarily from counting statistics, with additional contributions associated with background subtraction, detector-efficiency calibration, sample geometry, and density-dependent corrections. These measurement uncertainties provide the analytical basis for assessing the precision of the radionuclide activity profiles used in the sediment chronology calculations.

Uncertainty in model-derived ages and sediment accumulation rates depends not only on the analytical uncertainty of the measured ^{210}Pb activities but also on the assumptions and mathematical formulation of the individual dating models. In the CIC and CF-CS approaches, uncertainty is associated with the regression parameters used to determine the mean sedimentation or mass accumulation rate. CRS-derived quantities are additionally sensitive to uncertainties in the cumulative unsupported ^{210}Pb inventory because the chronology is calculated from the fraction of total inventory remaining beneath a given sediment horizon.

A mathematical framework for propagation of measurement uncertainties through the CIC, CF-CS, and CRS calculations is provided in **Appendix A**. The framework identifies the principal sources of uncertainty and their propagation into model-derived quantities.

7. Results and Discussion

7.1. ^{210}Pb Activity Profiles and Supported Activity

The core-specific supported ^{210}Pb ($^{210}\text{Pb}_{\text{sup}}$) activities and other summary parame-

ters for sediment cores WP-1, WP-2, WP-3, and WP-5 are summarized in **Table 1**, while the sediment chronologies derived using the CIC, CF-CS, and CRS models are presented in **Tables 2-5**. The model-derived ages and accumulation rates are not reported with individual confidence intervals. Therefore, comparisons among the three dating models are based primarily on their age-depth relationships, underlying model assumptions, and independent validation using the ^{137}Cs fallout record, rather than on formal statistical comparisons of overlapping confidence intervals.

Table 1. Summary of ^{210}Pb parameters and sediment accumulation characteristics for the four West Pine Pond sediment cores.

Core	$^{210}\text{Pb}_{\text{sup}}$ (dpm g ⁻¹)	Surface activity C (0) (dpm g ⁻¹)	$^{210}\text{Pb}_{\text{unsup}}$ Inventory* (dpm cm ⁻²)	Focusing factor	$^{210}\text{Pb}_{\text{unsup}}$ Flux (dpm cm ⁻² yr ⁻¹)	Sedimentation rate (cm yr ⁻¹)	Mass accumulation rate (g cm ⁻² yr ⁻¹)
WP-1	0.9	157.74	28.56	0.84	0.89	0.19	0.0108
WP-2	1.36	189.97	36.82	1.08	1.15	0.18	0.0138
WP-3	0.93	237.74	44.16	1.29	1.38	0.20	0.0177
WP-5	1.11	149.19	36.25	1.06	1.13	0.18	0.0106
—	1.08 ± 0.21	183 ± 40.10	36.45 ± 6.37	—	1.13 ± 0.20	0.19 ± 0.01	0.0132 ± 0.0033

*Expected atmospheric $^{210}\text{Pb}_{\text{unsup}}$ inventory value = 34.14 dpm cm⁻² (Kada & Heit, 1992).

Table 2. Sediment chronologies for core WP-1 calculated using the CIC, CF-CS, and CRS models.

Sample	Depth (cm)	Section (g cm ⁻²)	CIC Interval (yr)	CIC Date	CIC Mid-point Calendar Year	CF-CS Interval (yr)	CF-CS Date	CF-CS Mid-point Calendar Year	CRS Interval (yr)	CRS Date	CRS Mid-point Calendar Year
WP-1-1	1.27	0.03	6.6	1999-2005	2002	3.2	2002-2005	2003	6.7	1999-2005	2002
WP-1-2	2.54	0.08	6.6	1992-1998	1995	4.5	1998-2001	2000	8.1	1991-1998	1994
WP-1-3	3.81	0.14	6.6	1986-1991	1988	5.4	1992-1997	1995	4.8	1986-1990	1988
WP-1-4	5.08	0.20	6.6	1979-1985	1982	5.4	1987-1991	1989	4.5	1981-1985	1983
WP-1-5	6.35	0.26	6.6	1972-1978	1975	6.0	1981-1986	1983	4.5	1977-1980	1979
WP-1-6	8.89	0.38	13.2	1959-1971	1965	10.7	1970-1980	1975	8.8	1968-1976	1972
WP-1-7	11.43	0.51	13.2	1946-1958	1952	11.8	1958-1969	1964	10.6	1957-1967	1962
WP-1-8	13.97	0.65	13.2	1933-1945	1939	13.2	1945-1957	1951	18.3	1939-1956	1948
WP-1-9	16.51	0.79	13.2	1919-1932	1925	13.2	1932-1944	1938	24.1	1915-1938	1927
WP-1-10	19.05	0.93	13.2	1906-1918	1912	14.5	1918-1931	1924	17.7	1897-1914	1906
WP-1-11	21.59	1.12	13.2	1893-1905	1899	15.5	1902-1917	1909	22.7	1875-1896	1885
WP-1-12*	24.13	1.29	13.2	1880-1892	1886	15.7	1886-1901	1894	18.8	1856-1874	1865

*Below this depth, total ^{210}Pb activity approaches the supported ^{210}Pb level, defining the practical ^{210}Pb dating horizon.

Table 3. Sediment chronologies for core WP-2 calculated using the CIC, CF-CS, and CRS models.

Sample	Depth (cm)	Section (g cm ⁻²)	CIC Interval (yr)	CIC Date	CIC Mid-point Calendar Year	CF-CS Interval (yr)	CF-CS Date	CF-CS Mid-point Calendar Year	CRS Interval (yr)	CRS Date	CRS Mid-point Calendar Year
WP-2-1	1.27	0.04	7.0	1998-2005	2001	2.7	2003-2005	2004	6.8	1999-2005	2002
WP-2-2	2.54	0.09	7.0	1991-1997	1994	3.5	1999-2002	2001	7.7	1991-1998	1994
WP-2-3	3.81	0.15	7.0	1984-1990	1987	4.2	1995-1998	1997	3.9	1987-1990	1989
WP-2-4	5.08	0.21	7.0	1977-1983	1980	4.4	1991-1994	1992	2.9	1984-1986	1985
WP-2-5	6.35	0.27	7.0	1970-1976	1973	4.7	1986-1990	1988	3.9	1980-1983	1982
WP-2-6	8.89	0.41	14.0	1956-1969	1963	9.5	1976-1985	1981	7.6	1973-1979	1976
WP-2-7	11.43	0.54	14.0	1942-1955	1949	9.5	1967-1975	1971	8.8	1964-1972	1968
WP-2-8	13.97	0.68	14.0	1928-1941	1935	10.4	1957-1966	1961	10.4	1953-1963	1958
WP-2-9	16.51	0.84	14.0	1914-1927	1921	11.3	1945-1956	1950	15.2	1938-1952	1945
WP-2-10	19.05	1.00	14.0	1900-1913	1907	11.3	1934-1944	1939	16.6	1922-1937	1929
WP-2-11	21.59	1.17	14.0	1886-1899	1893	11.8	1922-1933	1928	14.4	1907-1921	1914
WP-2-12*	24.13	1.33	14.0	1872-1885	1879	11.7	1910-1921	1916	16.0	1891-1906	1899

*Below this depth, total ²¹⁰Pb activity approaches the supported ²¹⁰Pb level, defining the practical ²¹⁰Pb dating horizon.

Table 4. Sediment chronologies for core WP-3 calculated using the CIC, CF-CS, and CRS models.

Sample	Depth (cm)	Section (g cm ⁻²)	CIC Interval (yr)	CIC Date	CIC Mid-point Calendar Year	CF-CS Interval (yr)	CF-CS Date	CF-CS Mid-point Calendar Year	CRS Interval (yr)	CRS Date	CRS Mid-point Calendar Year
WP-3-1	1.27	0.02	6.4	1999-2005	2002	1.6	2004-2005	2004	3.5	2002-2005	2003
WP-3-2	2.54	0.05	6.4	1993-1998	1995	2.8	2001-2003	2002	7.3	1995-2001	1998
WP-3-3	3.81	0.10	6.4	1986-1992	1989	3.8	1997-2000	1999	9.9	1985-1994	1989
WP-3-4	5.08	0.15	6.4	1980-1985	1983	4.8	1992-1996	1994	3.3	1982-1984	1983
WP-3-5	6.35	0.22	6.4	1974-1979	1976	5.4	1987-1991	1989	3.7	1978-1981	1979
WP-3-6	8.89	0.34	12.8	1961-1973	1967	10.4	1977-1986	1981	7.7	1970-1977	1974
WP-3-7	11.43	0.47	12.8	1948-1960	1954	11.0	1966-1976	1971	9.6	1961-1969	1965
WP-3-8	13.97	0.61	12.8	1935-1947	1941	12.3	1953-1965	1959	9.9	1951-1960	1955
WP-3-9	16.51	0.76	12.8	1923-1934	1928	12.8	1940-1952	1946	15.0	1936-1950	1943
WP-3-10	19.05	0.92	12.8	1910-1922	1916	13.8	1927-1939	1933	17.9	1918-1935	1926
WP-3-11	21.59	1.10	12.8	1897-1909	1903	14.9	1912-1926	1919	24.5	1893-1917	1905
WP-3-12	24.13	1.26	12.8	1884-1896	1890	14.2	1898-1911	1904	29.0	1864-1892	1878
WP-3-13*	26.67	1.43	12.8	1871-1883	1877	14.1	1883-1897	1890	20.6	1844-1863	1853

* Below this depth, total ²¹⁰Pb activity approaches the supported ²¹⁰Pb level, defining the practical ²¹⁰Pb dating horizon.

Table 5. Sediment chronologies for core WP-5 calculated using the CIC, CF-CS, and CRS models.

Sample	Depth (cm)	Section (g cm ⁻²)	CIC Interval (yr)	CIC Date	CIC Mid-point Calendar Year	CF-CS Interval (yr)	CF-CS Date	CF-CS Mid-point Calendar Year	CRS Interval (yr)	CRS Date	CRS Mid-point Calendar Year
WP-5-1	1.27	0.03	7.1	1998-2005	2001	2.4	2003-2005	2004	3.6	2002-2005	2003
WP-5-2	2.54	0.06	7.1	1991-1997	1994	3.2	2000-2002	2001	8.0	1994-2001	1997
WP-5-3	3.81	0.10	7.1	1984-1990	1987	3.4	1997-1999	1998	7.5	1986-1993	1990
WP-5-4	5.08	0.15	7.1	1977-1983	1980	4.8	1992-1996	1994	4.6	1982-1985	1984
WP-5-5	6.35	0.21	7.1	1970-1976	1973	5.4	1986-1991	1989	3.7	1978-1981	1979
WP-5-6	8.89	0.33	14.2	1956-1969	1962	10.9	1975-1985	1980	9.4	1969-1977	1973
WP-5-7	11.43	0.46	14.2	1942-1955	1948	11.8	1964-1974	1969	11.4	1957-1968	1963
WP-5-8	13.97	0.60	14.2	1927-1941	1934	12.4	1951-1963	1957	16.9	1940-1956	1948
WP-5-9	16.51	0.74	14.2	1913-1926	1920	13.3	1938-1950	1944	24.3	1916-1939	1928
WP-5-10	19.05	0.91	14.2	1899-1912	1906	14.8	1923-1937	1930	6.0	1910-1915	1913
WP-5-11	21.59	1.08	14.2	1885-1898	1891	15.4	1908-1922	1915	12.2	1898-1909	1904
WP-5-12*	24.13	1.25	14.2	1871-1884	1877	15.5	1892-1907	1899	15.7	1882-1897	1890

* Below this depth, total ²¹⁰Pb activity approaches the supported ²¹⁰Pb level, defining the practical ²¹⁰Pb dating horizon.

Supported ²¹⁰Pb, estimated from the asymptotic behavior of the deep sediment layers, ranges from 0.90 to 1.36 dpm g⁻¹, showing relatively limited variation among the four cores.

The vertical distributions of total ²¹⁰Pb (²¹⁰Pb_{tot}) and unsupported ²¹⁰Pb (²¹⁰Pb_{un-sup}) activities are shown in **Figure 2**. Total ²¹⁰Pb activity decreases systematically with depth in all four cores, reflecting the progressive decline of ²¹⁰Pb_{un-sup}. The ²¹⁰Pb_{un-sup} activity profiles exhibit well-defined declines with depth, consistent with conditions appropriate for ²¹⁰Pb geochronology. Minor deviations from ideal exponential behavior are observed in some sediment intervals, particularly in WP-3, and may reflect localized sediment focusing or short-term variability in sediment deposition.

7.2. ²¹⁰Pb Inventories, Fluxes, and Sediment Focusing

The measured ²¹⁰Pb_{un-sup} inventories ranged from 28.56 to 44.16 dpm cm⁻². For comparison, **Kada & Heit (1992)** reported an expected atmospheric ²¹⁰Pb_{un-sup} inventory of 34.14 dpm cm⁻² for the Adirondack region. Relative to this reference inventory, the calculated focusing factors range from 0.84 for WP-1 to 1.29 for WP-3. Values greater than unity indicate enrichment relative to the reference atmospheric inventory and are consistent with sediment focusing, whereas values below unity indicate a lower inventory relative to the regional reference. The highest inventory and focusing factor occur in WP-3, consistent with enhanced sediment focusing at this core location.

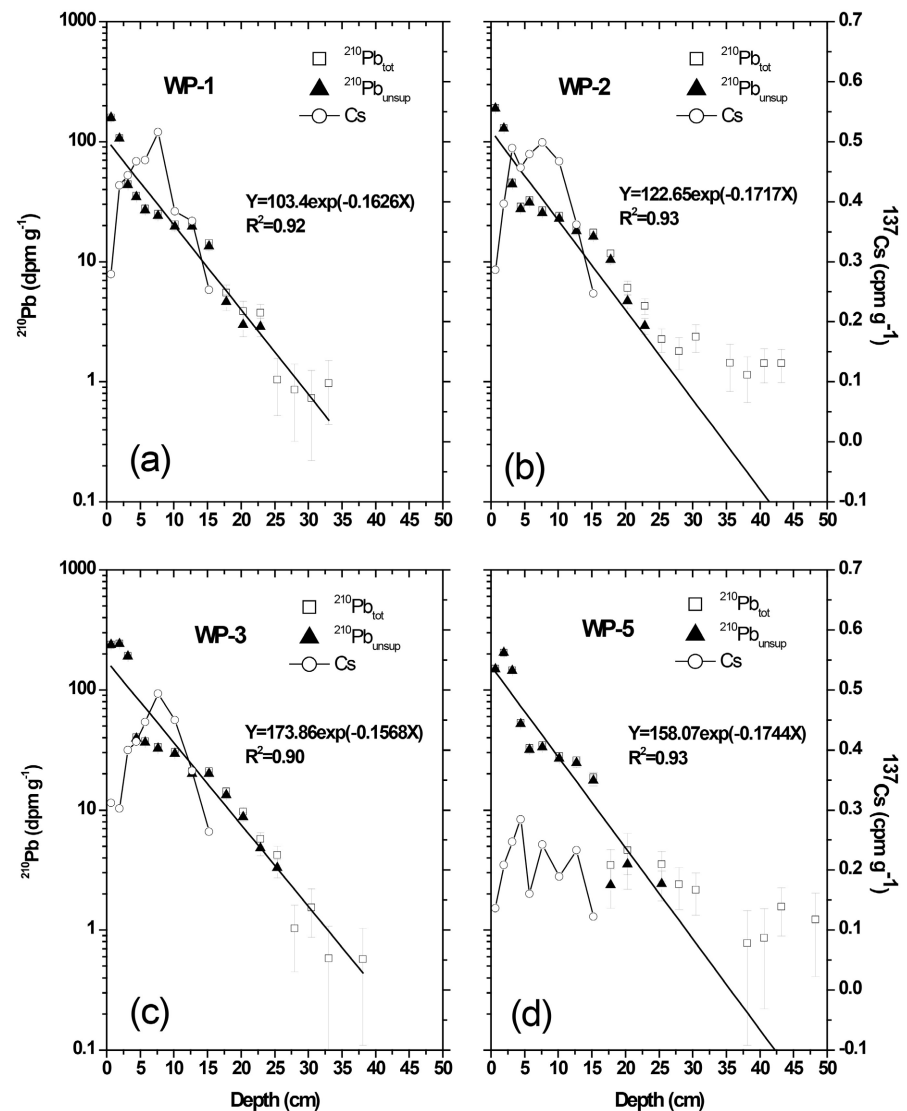


Figure 2. $^{210}\text{Pb}_{\text{tot}}$, $^{210}\text{Pb}_{\text{unsup}}$, and ^{137}Cs activities vs. depth (cm) profiles in four sediment cores from West Pine Pond in the Adirondack region of NY. The activity measured for each sediment interval is plotted at the midpoint depth of that interval. The fitted relationship in each panel represents the CIC model.

The corresponding $^{210}\text{Pb}_{\text{unsup}}$ fluxes range from 0.89 to 1.38 dpm $\text{cm}^{-2} \text{yr}^{-1}$. Differences in focusing factors among the four cores indicate spatial variation in sediment deposition within the sampled portion of West Pine Pond, consistent with the established influence of lake morphology on sediment focusing (Blais & Kalff, 1995). Comparison of these fluxes and inventories with previously reported regional values is discussed further in Section 7.6.

7.3. Sediment Chronologies and Model-Derived Rates

The CIC model yields core-averaged linear sedimentation rates ranging from approximately 0.18 to 0.20 cm yr^{-1} , with high coefficients of determination ($R^2 = 0.90 - 0.93$). These results indicate relatively similar long-term sedimentation rates

among the four sampled core locations.

The CF-CS model produces core-averaged mass accumulation rates ranging from 0.0106 to $0.0177 \text{ g cm}^{-2} \text{ yr}^{-1}$, indicating moderate variation among the four sampled core locations. Among the four cores, WP-3 has the highest core-average mass accumulation rate ($0.0177 \text{ g cm}^{-2} \text{ yr}^{-1}$), whereas WP-5 has the lowest ($0.0106 \text{ g cm}^{-2} \text{ yr}^{-1}$).

In contrast to the long-term core-averaged rates, the CRS-derived sediment accumulation profiles shown in **Figure 3** exhibit greater depth-dependent variability, with accumulation rates ranging from approximately 0.006 to $0.030 \text{ g cm}^{-2} \text{ yr}^{-1}$. The CRS profiles show substantial variability among individual sediment intervals, with WP-5 exhibiting the highest localized accumulation rate at approximately 20 cm depth. This variability may reflect short-term variations in sediment deposition as well as the greater sensitivity of the CRS model to changes in unsupported ^{210}Pb inventory.

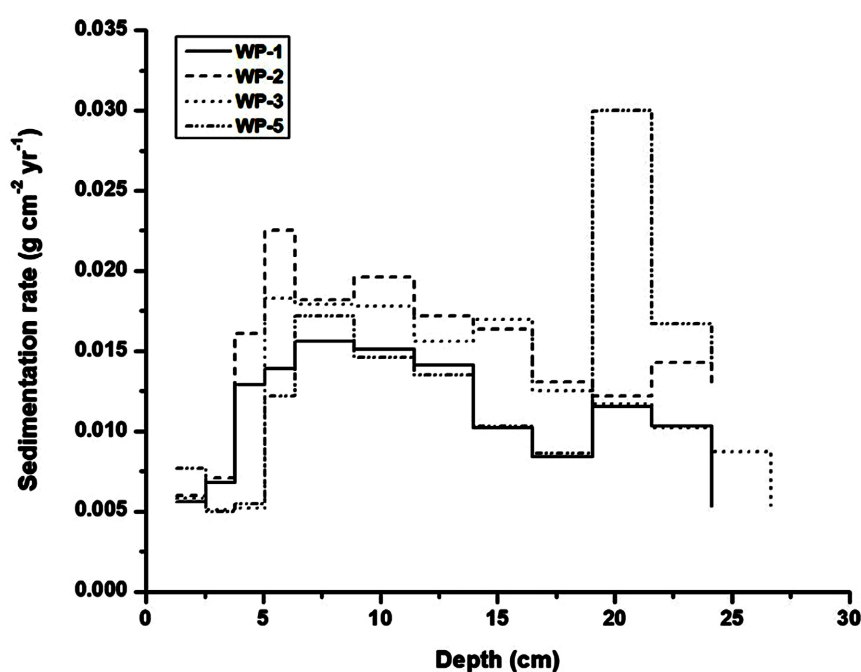


Figure 3. CRS-derived sediment accumulation rates ($\text{g cm}^{-2} \text{ yr}^{-1}$) for the four West Pine Pond sediment cores.

The difference between the highest core-averaged accumulation rate in WP-3 and the highest localized CRS-derived accumulation rate in WP-5 illustrates the distinction between long-term average accumulation and depth-dependent variations in sediment deposition. The observed patterns indicate spatial and temporal variability in sediment accumulation among the four sampled core locations and may reflect localized sediment focusing or variations in sediment delivery.

The CF-CS mass-depth profiles shown in **Figure 4** exhibit well-defined linear relationships between the logarithm of $^{210}\text{Pb}_{\text{unsp}}$ activity and cumulative dry mass depth, consistent with the assumptions of constant ^{210}Pb flux and constant mass

accumulation rate. Minor deviations from linearity in selected intervals suggest localized variations in sediment input or depositional conditions. Thus, the CF-CS model provides a useful representation of long-term, core-averaged mass accumulation, whereas the CRS model provides additional information on depth-dependent variability in sediment accumulation.

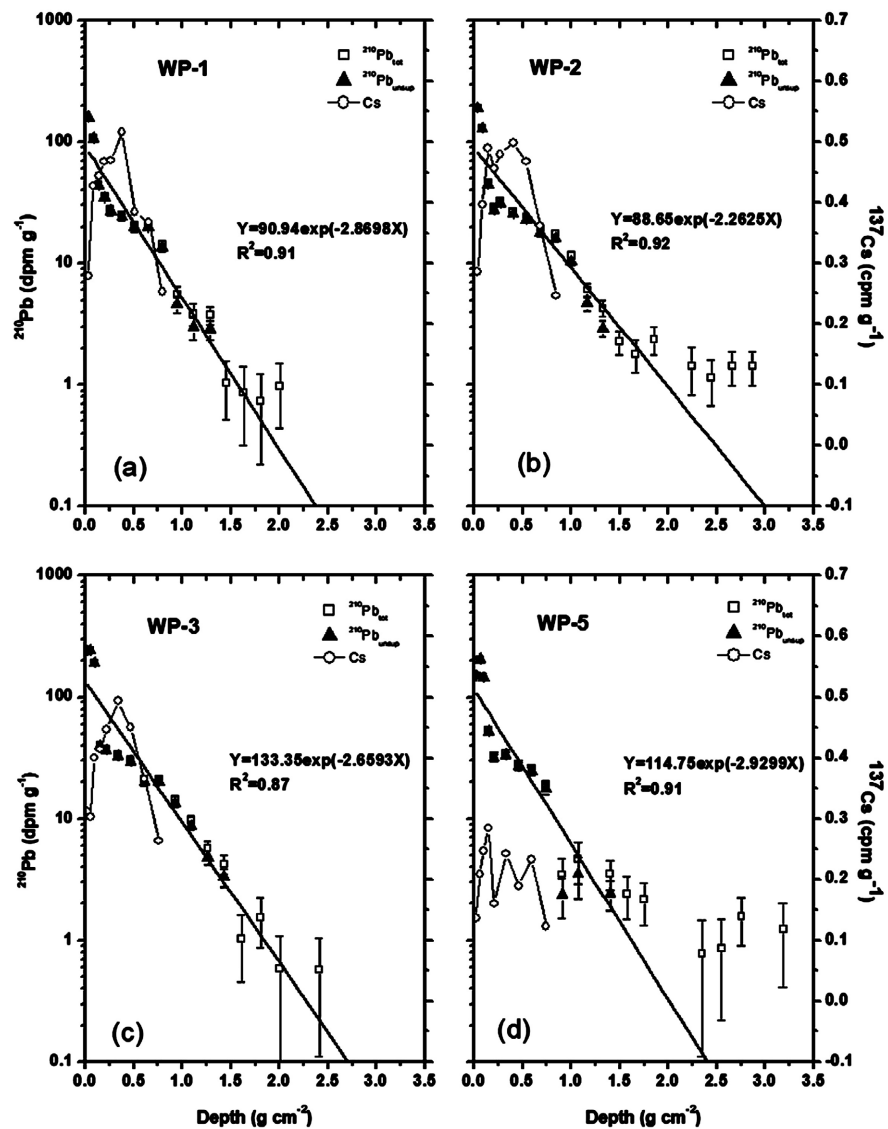


Figure 4. $^{210}\text{Pb}_{\text{tot}}$, $^{210}\text{Pb}_{\text{unsup}}$ and ^{137}Cs activities vs Cumulative mass depth (g cm^{-2}) profiles in four sediment cores. The least-squares linear regression line in each panel is derived from CF-CS model.

7.4. Validation Using ^{137}Cs

The age-depth relationships derived from the CIC, CF-CS, and CRS models, together with the ^{137}Cs activity profiles, are shown in **Figure 5**. The ^{137}Cs record provides an independent basis for evaluating the ^{210}Pb -derived chronologies. A distinct ^{137}Cs peak corresponding to the 1963 atmospheric nuclear-testing

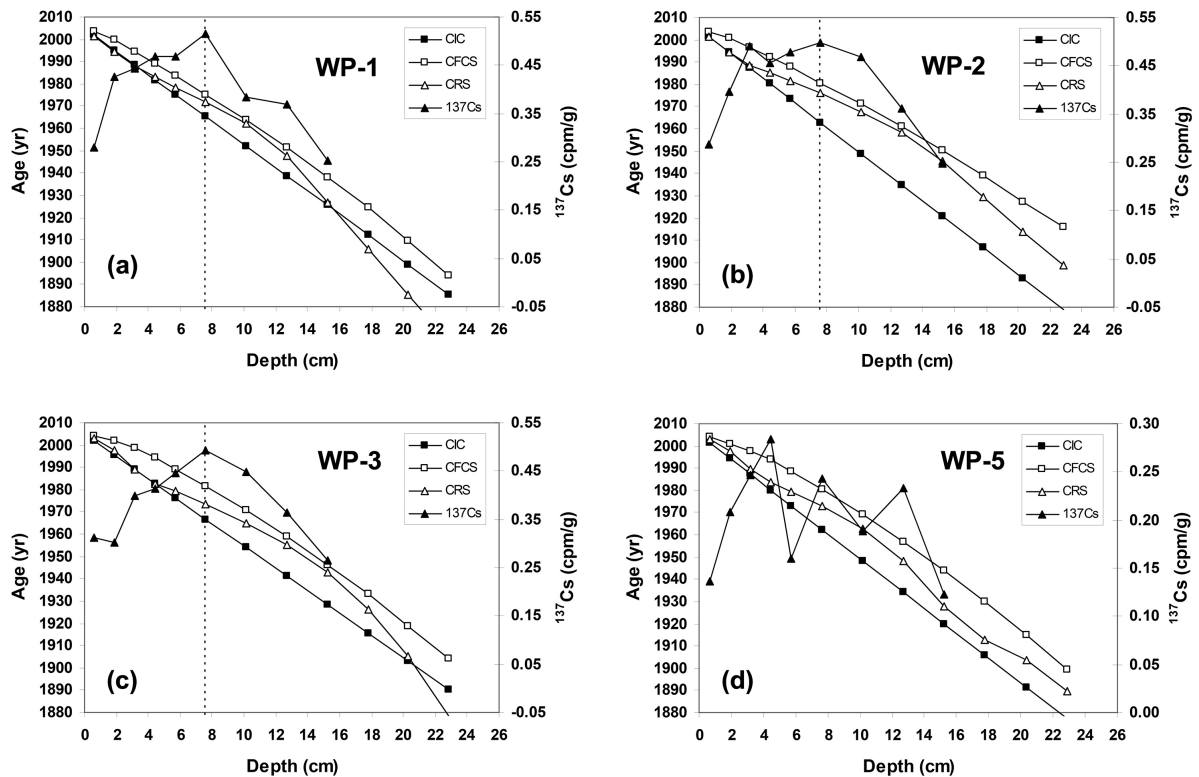


Figure 5. Ages derived from the CIC, CF-CS, and CRS models, for four cores from West Pine Pond in the Adirondack region of New York State.

maximum is observed in cores WP-1, WP-2, and WP-3 at depths of approximately 6.35 - 8.89 cm. These depths align most closely with ages predicted by the CIC model, supporting the reliability of the derived chronologies.

In contrast to WP-1, WP-2, and WP-3, the ^{137}Cs profile in WP-5 does not exhibit a distinct subsurface maximum that can be confidently assigned to the 1963 atmospheric-fallout maximum. Instead, the activity distribution is comparatively irregular, suggesting that the ^{137}Cs fallout record may not have been preserved at this location in the same manner as in the other three cores. Localized sediment redistribution, mixing, sediment focusing, or post-depositional mobility of ^{137}Cs may have contributed to this behavior; however, the available data do not permit a specific mechanism to be identified. Consequently, WP-5 was not used as an independent ^{137}Cs chronological marker for evaluating the ^{210}Pb dating models, and its chronology is interpreted with appropriate caution.

Overall, comparison of the three ^{210}Pb dating models with the independent ^{137}Cs fallout record indicates that the CIC model shows the closest correspondence with the identifiable 1963 ^{137}Cs fallout maximum in WP-1, WP-2, and WP-3.

7.5. Uncertainty and Model Sensitivity

The three ^{210}Pb dating models differ in their sensitivity to measurement uncertainty and to variations in sediment accumulation. The CIC and CF-CS approaches provide mean sedimentation or mass accumulation rates based on the

overall decline of $^{210}\text{Pb}_{\text{unSUP}}$ activity with depth or cumulative mass depth, respectively. In contrast, the CRS model depends on cumulative $^{210}\text{Pb}_{\text{unSUP}}$ inventory and is therefore more sensitive to variations in activity and inventory among successive sediment intervals.

The greater depth-dependent variability observed in the CRS-derived accumulation rates (**Figure 3**) should therefore not be interpreted solely as analytical uncertainty. It may reflect a combination of measurement uncertainty, cumulative inventory uncertainty, and actual temporal variability in sediment deposition. Consequently, differences among the CIC, CF-CS, and CRS results are interpreted in the context of their respective model assumptions and the independent ^{137}Cs chronological information shown in **Figure 5**.

The mathematical framework used to describe propagation of measurement uncertainty through the three ^{210}Pb dating models is provided in Appendix A. Independent chronological markers and careful evaluation of radionuclide profiles are important for assessing confidence in sediment chronologies (Crusius & Kenna, 2007). Because individual confidence intervals were not determined for each model-derived age reported in **Tables 2-5**, the present study does not use formal confidence-interval comparisons to distinguish among the model chronologies.

7.6. Regional Context and Environmental Implications

The $^{210}\text{Pb}_{\text{sup}}$ activities, $^{210}\text{Pb}_{\text{unSUP}}$ inventories, and $^{210}\text{Pb}_{\text{unSUP}}$ fluxes obtained for West Pine Pond are compared with previously published values for lakes in the Adirondack region and northeastern United States in **Table 6**. The $^{210}\text{Pb}_{\text{unSUP}}$ fluxes measured in this study, ranging from 0.89 to 1.38 $\text{dpm cm}^{-2} \text{yr}^{-1}$, fall within the ranges reported for comparable regional lakes. Similarly, the measured $^{210}\text{Pb}_{\text{unSUP}}$ inventories of 28.56 - 44.16 dpm cm^{-2} and supported ^{210}Pb activities of 0.90 - 1.36 dpm g^{-1} are within the ranges reported in these regional studies.

Table 6. Comparison of calculated $^{210}\text{Pb}_{\text{sup}}$ activities, $^{210}\text{Pb}_{\text{unSUP}}$ inventories, and $^{210}\text{Pb}_{\text{unSUP}}$ fluxes from our cores with values previously published for comparable lakes in the northeastern U.S.

Lake	$^{210}\text{Pb}_{\text{sup}}$ (dpm g^{-1})	$^{210}\text{Pb}_{\text{unSUP}}$ Inventory (dpm cm^{-2})	$^{210}\text{Pb}_{\text{unSUP}}$ Flux ($\text{dpm cm}^{-2} \text{yr}^{-1}$)	Reference
West Pine Pond, Adirondack, NY	0.90 - 1.36	28.56 - 44.16	0.89 - 1.38	This Study
13 Lakes, Adirondack, NY	0.26 - 1.54	5.54 - 48.88	0.18 - 1.52	Binford et al. (1993)
8 Lakes, Adirondack, NY	—	7.8 - 45.54	—	Kada & Heit (1992)
10 Lakes in Vermont and New Hampshire	0.62 - 5.5	14.89 - 48.44	0.48 - 1.56	Kamman & Engstrom (2002)

This agreement indicates that the ^{210}Pb activities, inventories, and fluxes meas-

ured in West Pine Pond are consistent with those observed in comparable lakes in the Adirondack region and northeastern United States. At the same time, the variability among the individual West Pine Pond cores indicates differences in sediment accumulation within the sampled portion of the lake. The higher core-averaged mass accumulation rate and focusing factor at WP-3, together with the depth-dependent variability observed in the CRS profiles, indicate spatial and temporal differences in sediment accumulation among the sampled locations. These patterns are consistent with basin-scale processes such as sediment focusing, watershed inputs, and hydrodynamic transport.

7.7. Statistical Interpretation and Synthesis of Sedimentation Processes

The combined results from **Tables 1-5** and **Figures 2-5** demonstrate both similarities and differences in sediment accumulation among the four sampled core locations. Because successive depth intervals within an individual core represent measurements from the same sediment sequence and are therefore not independent replicates, formal inferential comparisons among cores were not performed. Instead, differences among the four cores are interpreted descriptively based on their radionuclide profiles, model-derived chronologies, depth-dependent accumulation patterns, and core-specific sedimentation characteristics.

The long-term CIC sedimentation rates are relatively uniform among the four cores, ranging from 0.18 to 0.20 cm yr⁻¹, whereas CF-CS core-averaged mass accumulation rates range from 0.0106 to 0.0177 g cm⁻² yr⁻¹. WP-3 has the highest core-averaged mass accumulation rate and the highest ²¹⁰Pb_{unsp} inventory and focusing factor. In contrast, the CRS-derived profiles show substantially greater depth-dependent variability, ranging from approximately 0.006 to 0.030 g cm⁻² yr⁻¹, with WP-5 exhibiting the highest localized accumulation rate at approximately 20 cm depth. WP-1 shows comparatively lower and more uniform CRS-derived accumulation rates, while WP-2, WP-3, and WP-5 exhibit varying degrees of depth-dependent behavior.

These differences demonstrate spatial and temporal variability among the individual sediment records; however, because only one core was analyzed at each coring location, they are interpreted as descriptive differences among the sampled cores rather than statistically significant differences representative of the broader lake basin.

Comparison of the CIC, CF-CS, and CRS age-depth models with the independent ¹³⁷Cs fallout record provides an additional basis for evaluating the reconstructed chronologies. The CIC model shows the closest overall correspondence with the identifiable ¹³⁷Cs fallout maximum in WP-1, WP-2, and WP-3, whereas WP-5 does not contain a sufficiently distinct ¹³⁷Cs maximum for independent chronological validation. Differences among the three ²¹⁰Pb models reflect their different assumptions regarding sediment accumulation and unsupported ²¹⁰Pb supply and are therefore interpreted in conjunction with the radionuclide profiles

and associated analytical uncertainties.

8. Environmental Implications

The sediment chronologies developed for West Pine Pond preserve a valuable historical record of environmental change within the Adirondack region over approximately the past century. The deeper sediment intervals coincide with periods of intensive logging, watershed disturbance, and enhanced erosion that characterized portions of the Adirondacks during the late 19th and early 20th centuries, whereas the more recent sediments indicate comparatively stable depositional conditions. Elevated near-surface unsupported ^{210}Pb activities and relatively consistent modern sedimentation rates suggest reduced sediment delivery in recent decades, likely associated with forest regrowth, watershed stabilization, and improved land-use management throughout the region.

The reconstructed sediment records also coincide with major changes in atmospheric deposition across the northeastern United States. Previous studies have documented substantial declines in sulfate and nitrate deposition in the Adirondacks since the implementation of air-quality regulations, particularly following the Clean Air Act and subsequent emission-control programs. These reductions have been linked to improvements in lake-water chemistry and partial ecological recovery in Adirondack aquatic systems. The preservation of a distinct ^{137}Cs fallout horizon corresponding to the 1963 atmospheric nuclear testing maximum further confirms the integrity of the sediment record and indicates limited post-depositional mixing or disturbance within most cores.

Although long-term sedimentation patterns in West Pine Pond appear relatively stable, CRS-derived depth profiles revealed localized and depth-dependent variations in sediment accumulation among the four cores, consistent with sediment focusing, hydrological variability, episodic sediment inputs, or changes in watershed conditions.

Overall, the combined application of CIC, CF-CS, and CRS ^{210}Pb dating models together with independent ^{137}Cs validation provides a robust framework for reconstructing sedimentation dynamics and environmental change in lacustrine systems. The results provide a chronological framework for interpreting documented environmental recovery and landscape changes in the Adirondack region, while also highlighting the continuing influence of climatic and watershed-scale processes on sediment transport and deposition.

9. Conclusions

This study provides a comprehensive ^{210}Pb and ^{137}Cs based chronostratigraphic reconstruction of four sediment cores from West Pine Pond, offering one of the most detailed assessments of recent sedimentation processes in a remote Adirondack Lake. All three ^{210}Pb dating models CIC, CF-CS, and CRS were evaluated, but the CIC model consistently yielded chronologies most consistent with the independently observed ^{137}Cs fallout peak from 1963 in three of the four cores.

Long-term sedimentation rates were remarkably uniform across the lake, ranging from 0.18 to 0.20 cm yr⁻¹, while mass accumulation rates (0.0106 - 0.0177 g cm⁻² yr⁻¹) demonstrated only moderate spatial variability. CRS-derived depth profiles revealed localized and depth-dependent variations in sediment accumulation among the four cores, consistent with sediment focusing, hydrological variability, episodic sediment inputs, or changes in watershed conditions. The agreement between measured ²¹⁰Pb inventories and derived ²¹⁰Pb_{unsp} fluxes and values previously reported for regional lakes supports the reliability of the radiometric measurements and the reconstructed chronologies.

The clarity of the ¹³⁷Cs peak in most cores and the absence of major sediment mixing further strengthen confidence in the depositional integrity of the cores and the preservation of environmental signals. Together, these chronologies capture approximately 150 years of environmental history, providing essential insights into sediment accumulation, atmospheric deposition, and watershed processes in the Adirondack Park.

Beyond methodological validation, the sediment records reflect broader environmental trends, including reductions in erosion and pollutant deposition associated with forest recovery, improved land-use practices, and national air-quality regulations. As such, this study not only contributes to regional geochronology but also establishes a valuable baseline for tracking future environmental change, climate-driven hydrological responses, and ecosystem recovery in sensitive high-elevation lake systems. Continued monitoring and application of multi-model radiometric dating will remain critical for understanding the long-term dynamics of Adirondack lakes and other comparable environments worldwide. This study demonstrates that multi-model ²¹⁰Pb analysis, when combined with independent ¹³⁷Cs validation, provides a robust and transferable framework for reconstructing sediment chronologies in heterogeneous lacustrine environments.

Acknowledgements

The authors are grateful to Karen Roy, Jed Dukett, Susan Capone, Paul Casson and James S. Webber for advice on lake selection and sediment coring. This work was partly funded by an NSF grant ATM 0503850.

Author Contributions

AK: Writing—review & editing, Writing—original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Project design, measurements. TA: Writing—review & editing, Data curation, Visualization, Validation, Methodology.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Abril-Hernández, J. M. (2023). ^{210}Pb -Dating of Sediments with Models Assuming a Constant Flux: CFCS, CRS, PLUM, and the Novel X-Mapping. Review, Performance Tests, and Guidelines. *Journal of Environmental Radioactivity*, 268, Article 107248. <https://doi.org/10.1016/j.jenvrad.2023.107248>
- Abril-Hernández, J. M. (2025). Assessment of the Performance of ^{210}Pb -Based Dating Models with a Challenging Sediment History in Maryport Harbour (UK). *Journal of Marine Science and Engineering*, 13, Article 144. <https://doi.org/10.3390/jmse13010144>
- Anderson, S., Dimova, N. T., & Brande, S. (2024). Validating Ex^{210}Pb Sediment Dating Methods Applied to a Large Anthropogenically-Impacted River Basin. *Quaternary Geochronology*, 85, Article 101615. <https://doi.org/10.1016/j.quageo.2024.101615>
- Appleby, P. G. (1993). Forward to the Lead-210 Dating Anniversary Series. *Journal of Paleolimnology*, 9, 155-160. <https://doi.org/10.1007/bf00677517>
- Appleby, P. G. (2000). Radiometric Dating of Sediment Records in European Mountain Lakes. *Journal of Limnology*, 59, 1-14. <https://doi.org/10.4081/jlimnol.2000.s1.1>
- Appleby, P. G. (2001). Chronostratigraphic Techniques in Recent Sediments. In W. M. Last, & J.P. Smol (Eds.), *Developments in Paleoenvironmental Research* (pp. 171-203). Kluwer Academic Publishers. https://doi.org/10.1007/0-306-47669-x_9
- Appleby, P. G. (2004). Environmental Change and Atmospheric Contamination on Svalbard: Sediment Chronology. *Journal of Paleolimnology*, 31, 433-443. <https://doi.org/10.1023/b:jopl.0000022545.73163.ed>
- Appleby, P. G., & Oldfield, F. (1978). The Calculation of Lead-210 Dates Assuming a Constant Rate of Supply of Unsupported ^{210}Pb to the Sediment. *Catena*, 5, 1-8. [https://doi.org/10.1016/s0341-8162\(78\)80002-2](https://doi.org/10.1016/s0341-8162(78)80002-2)
- Appleby, P. G., & Oldfield, F. (1983). The Assessment of ^{210}Pb Data from Sites with Varying Sediment Accumulation Rates. *Hydrobiologia*, 103, 29-35. <https://doi.org/10.1007/bf00028424>
- Appleby, P. G., Richardson, N., & Nolan, P. J. (1991). ^{241}Am Dating of Lake Sediments. *Hydrobiologia*, 214, 35-42. <https://doi.org/10.1007/bf00050929>
- Beier, C. M., Stella, J. C., Dovčiak, M., & McNulty, S. A. (2012). Local Climatic Drivers of Changes in Phenology at a Boreal-Temperate Ecotone in Eastern North America. *Climatic Change*, 115, 399-417. <https://doi.org/10.1007/s10584-012-0455-z>
- Benninger, L. K. (1978). ^{210}Pb Balance in Long Island Sound. *Geochimica et Cosmochimica Acta*, 42, 1165-1174. [https://doi.org/10.1016/0016-7037\(78\)90111-4](https://doi.org/10.1016/0016-7037(78)90111-4)
- Benninger, L. K., Lewis, D. M., & Turekian, K. K. (1975). The Use of Natural Pb-210 as a Heavy Metal Tracer in the River—Estuarine System. In T. M. Church (ED.), *ACS Symposium Series* (pp. 202-210). American Chemical Society. <https://doi.org/10.1021/bk-1975-0018.ch012>
- Binford, M. W. (1990). Calculation and Uncertainty Analysis of ^{210}Pb Dates for PIRLA Project Lake Sediment Cores. *Journal of Paleolimnology*, 3, 253-267. <https://doi.org/10.1007/bf00219461>
- Binford, M. W., Kahl, J. S., & Norton, S. A. (1993). Interpretation of ^{210}Pb Profiles and Verification of the CRS Dating Model in PIRLA Project Lake Sediment Cores. *Journal of Paleolimnology*, 9, 275-296. <https://doi.org/10.1007/bf00677218>
- Blais, J. M., & Kalff, J. (1995). The Influence of Lake Morphometry on Sediment Focusing. *Limnology and Oceanography*, 40, 582-588. <https://doi.org/10.4319/lo.1995.40.3.0582>
- Carroll, J., Lerche, I., Abraham, J. D., & Cisar, D. J. (1999). Sediment Ages and Flux Varia-

- tions from Depth Profiles of ^{210}Pb : Lake and Marine Examples. *Applied Radiation and Isotopes*, 50, 793-804. [https://doi.org/10.1016/s0969-8043\(98\)00099-2](https://doi.org/10.1016/s0969-8043(98)00099-2)
- Crusius, J., & Kenna, T. C. (2007). Ensuring Confidence in Radionuclide-Based Sediment Chronologies and Bioturbation Rates. *Estuarine, Coastal and Shelf Science*, 71, 537-544. <https://doi.org/10.1016/j.ecss.2006.09.006>
- Currie, L. A. (1968). Limits for Qualitative Detection and Quantitative Determination. Application to Radiochemistry. *Analytical Chemistry*, 40, 586-593. <https://doi.org/10.1021/ac60259a007>
- Driscoll, C. T., Driscoll, K. M., Roy, K. M., & Dukett, J. (2007). Changes in the Chemistry of Lakes in the Adirondack Region of New York Following Declines in Acidic Deposition. *Applied Geochemistry*, 22, 1181-1188. <https://doi.org/10.1016/j.apgeochem.2007.03.009>
- Durham, R. W., & Joshi, S. R. (1980). Recent Sedimentation Rates, ^{210}Pb Fluxes, and Particle Settling Velocities in Lake Huron, Laurentian Great Lakes. *Chemical Geology*, 31, 53-66. [https://doi.org/10.1016/0009-2541\(80\)90067-4](https://doi.org/10.1016/0009-2541(80)90067-4)
- Erten, H. N. (1997). Radiochronology of Lake Sediments. *Pure and Applied Chemistry*, 69, 71-76. <https://doi.org/10.1351/pac199769010071>
- Goldberg, E. D. (1963). Geochronology with ^{210}Pb . In *Proceedings of a Symposium of Radioactive Dating* (pp. 121-131). International Atomic Energy Agency.
- Heldal, H. E., Helvik, L., Appleby, P., Haanes, H., Volynkin, A., Jensen, H. et al. (2021). Geochronology of Sediment Cores from the Vefsnfjord, Norway. *Marine Pollution Bulletin*, 170, Article 112683. <https://doi.org/10.1016/j.marpolbul.2021.112683>
- Hunter, H. N., Gowing, C. J. B., Marriott, A. L., Lacey, J. H., Dowell, S., & Watts, M. J. (2023). Developments in Pb-210 Methodologies to Provide Chronologies for Environmental Change. *Environmental Geochemistry and Health*, 45, 1173-1181. <https://doi.org/10.1007/s10653-022-01215-x>
- Husain, L., Khan, A. J., Ahmed, T., Swami, K., Bari, A., Webber, J. S. et al. (2008). Trends in Atmospheric Elemental Carbon Concentrations from 1835 to 2005. *Journal of Geophysical Research: Atmospheres*, 113, D13102. <https://doi.org/10.1029/2007jd009398>
- Kada, J., & Heit, M. (1992). The Inventories of Anthropogenic Ph, Zn, As, Cd, and the Radionuclides ^{137}Cs and Excess ^{210}Pb in Lake Sediments of the Adirondack Region, USA. *Hydrobiologia*, 246, 231-241. <https://doi.org/10.1007/bf00005700>
- Kamman, N. C., & Engstrom, D. R. (2002). Historical and Present Fluxes of Mercury to Vermont and New Hampshire Lakes Inferred from ^{210}Pb Dated Sediment Cores. *Atmospheric Environment*, 36, 1599-1609. [https://doi.org/10.1016/s1352-2310\(02\)00091-2](https://doi.org/10.1016/s1352-2310(02)00091-2)
- Krishnaswami, S., & Lal, D. (1978). Radionuclide Limnology. In A. Lerman (Ed.), *Lakes* (pp. 153-177). Springer. https://doi.org/10.1007/978-1-4757-1152-3_6
- Krishnaswamy, S., Lal, D., Martin, J. M., & Meybeck, M. (1971). Geochronology of Lake Sediments. *Earth and Planetary Science Letters*, 11, 407-414. [https://doi.org/10.1016/0012-821x\(71\)90202-0](https://doi.org/10.1016/0012-821x(71)90202-0)
- Lewis, D. M. (1977). The Use of ^{210}Pb as a Heavy Metal Tracer in the Susquehanna River System. *Geochimica et Cosmochimica Acta*, 41, 1557-1564. [https://doi.org/10.1016/0016-7037\(77\)90167-3](https://doi.org/10.1016/0016-7037(77)90167-3)
- Lorey, P., & Driscoll, C. T. (1999). Historical Trends of Mercury Deposition in Adirondack Lakes. *Environmental Science & Technology*, 33, 718-722. <https://doi.org/10.1021/es9800277>
- Miguel, S., Bolívar, J. P., & García-Tenorio, R. (2003). Mixing, Sediment Accumulation and Focusing Using ^{210}Pb and ^{137}Cs . *Journal of Paleolimnology*, 29, 1-11.

- <https://doi.org/10.1023/a:1022864615111>
- New York State Energy Research and Development Authority (2015). *Importance of Acidic and Mercury Deposition in Relation to Climate Change in the Adirondack Mountains: Biogeochemical Responses*. NYSERDA Report 15-04s.
- Nozaki, Y., DeMaster, D. J., Lewis, D. M., & Turekian, K. K. (1978). Atmospheric ^{210}Pb Fluxes Determined from Soil Profiles. *Journal of Geophysical Research: Oceans*, 83, 4047-4051. <https://doi.org/10.1029/jc083ic08p04047>
- Parekh, P. P., Semkow, T. M., Bari, A., Torre, M. A., Haines, D. K., Harris, P. R. et al. (2004). Multifarious Application of Well-Type Germanium Detector. *Journal of Radioanalytical and Nuclear Chemistry*, 262, 317-323. <https://doi.org/10.1023/b:jrnrc.0000046759.64434.27>
- Parekh, P., Bari, A., & Harris, P. (2003). Rapid Radiochemical Analysis of ^{131}I in Environmental Samples Using a Well-Type Ge-Detector. *Journal of Radioanalytical and Nuclear Chemistry*, 256, 225-230. <https://doi.org/10.1023/a:1023972914817>
- Robbins, J. A. (1978). Geochemical and Geophysical Application of Radioactive Lead Isotopes. In J. O. Nriagu (Ed.), *Biogeochemistry of Lead in the Environment* (pp 285-393). Elsevier Scientific.
- Ruiz-Fernández, A. C., Alonso-Hernández, C., Espinosa, L. F., Delanoy, R., Solares Cortez, N., Lucienna, E. et al. (2020). ^{210}Pb -Derived Sediment Accumulation Rates across the Wider Caribbean Region. *Journal of Environmental Radioactivity*, 223, Article 106366. <https://doi.org/10.1016/j.jenvrad.2020.106366>
- Sanak, J., Gaudry, A., & Lambert, G. (1981). Size Distribution of ^{210}Pb Aerosols over Oceans. *Geophysical Research Letters*, 8, 1067-1069. <https://doi.org/10.1029/gl008i010p01067>
- Sarkar, S., Ahmed, T., Swami, K., Judd, C. D., Bari, A., Dutkiewicz, V. A. et al. (2015). History of Atmospheric Deposition of Trace Elements in Lake Sediments, ~1880 to 2007. *Journal of Geophysical Research: Atmospheres*, 120, 5658-5669. <https://doi.org/10.1002/2015jd023202>
- Semkow, T. M., Bradt, C. J., Beach, S. E., Haines, D. K., Khan, A. J., Bari, A. et al. (2015). Calibration of Ge Gamma-Ray Spectrometers for Complex Sample Geometries and Matrices. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 799, 105-113. <https://doi.org/10.1016/j.nima.2015.07.064>
- Sima, O., Arnold, D., & Dovlete, C. (2001). GESPECOR: A Versatile Tool in Gamma-Ray Spectrometry. *Journal of Radioanalytical and Nuclear Chemistry*, 248, 359-364. <https://doi.org/10.1023/a:1010619806898>
- Taylor, H. W., Svoboda, J., Henry, G. H. R., & Wein, R. W. (1988). Post-Chernobyl ^{134}Cs and ^{137}Cs Levels at Some Localities in Northern Canada. *ARCTIC*, 41, 231-241. <https://doi.org/10.14430/arctic1735>
- Turner, L. J., & Delorme, L. D. (1996). Assessment of ^{210}Pb Data from Canadian Lakes Using the CIC and CRS Models. *Environmental Geology*, 28, 78-87. <https://doi.org/10.1007/s002540050080>

Appendix A

(Uncertainty Propagation Framework)

A.1 General propagation equation

Uncertainty propagation for ^{210}Pb -based chronologies follows standard error propagation principles, where the combined variance of a derived quantity is expressed as a function of the variances of the contributing variables.

For a function:

$$U = f(x_1, x_2, x_3, x_4, \dots, x_n) \quad (\text{A1})$$

the combined variance is:

$$\sigma_U^2 = \sum_{i=1}^n \left(\frac{\partial U}{\partial x_i} \right)^2 \sigma_{x_i}^2 \quad (\text{A2})$$

where $\sigma_{x_i}^2$ is the variance of variable x_i , and $\partial U / \partial x_i$ represents the sensitivity coefficient. Correlations between variables are assumed negligible.

A.2 Unsupported ^{210}Pb

Unsupported activity is defined as:

$$C_{\text{unsup}} = C_{\text{tot}} - C_{\text{sup}} \quad (\text{A3})$$

with propagated uncertainty:

$$\sigma_{C_{\text{unsup}}}^2 = \sigma_{C_{\text{tot}}}^2 + \sigma_{C_{\text{sup}}}^2 \quad (\text{A4})$$

$$\sigma_{C_{\text{unsup}}} = \sqrt{\sigma_{C_{\text{tot}}}^2 + \sigma_{C_{\text{sup}}}^2} \quad (\text{A5})$$

A.3 CIC Model

The CIC model is given by:

$$C(x) = C(0) e^{-\frac{\lambda x}{\omega}} \quad (\text{A6})$$

Taking natural logarithms:

$$\ln C(x) = \ln C(0) - \frac{\lambda x}{\omega} \quad (\text{A7})$$

The regression slope:

$$b = -\frac{\lambda}{\omega} \quad (\text{A8})$$

$$\sigma_{\omega} = \left| \frac{\lambda}{b^2} \right| \sigma_b \quad (\text{A9})$$

$$\sigma_{\omega} = \omega^2 \left(\frac{\sigma_b}{\lambda} \right) \quad (\text{A10})$$

CIC age:

$$t = \frac{x}{\omega} \quad (\text{A11})$$

With uncertainty:

$$\sigma_t = t \sqrt{\left(\frac{\sigma_x}{x} \right)^2 + \left(\frac{\sigma_{\omega}}{\omega} \right)^2} \quad (\text{A12})$$

A.4 CF-CS Model:

$$C(m) = C(0)e^{-\frac{\lambda m}{r}} \quad (\text{A13})$$

where m is cumulative mass depth.

$$\ln C(m) = \ln C(0) - \frac{\lambda m}{r} \quad (\text{A14})$$

regression slope be:

$$b_m = -\frac{\lambda}{r} \quad (\text{A15})$$

The accumulation rate is:

$$r = \frac{\lambda}{b_m} \quad (\text{A16})$$

$$\sigma_r = \left| \frac{\lambda}{b_m^2} \right| \sigma_{b_m} \quad (\text{A17})$$

$$\sigma_r = r^2 \frac{\sigma_{b_m}}{\lambda} \quad (\text{A18})$$

Mass depth:

$$m_i = \sum_{j=1}^i \rho_j \Delta x_j \quad (\text{A19})$$

The variance of cumulative mass depth is:

$$\sigma_{m_i}^2 = \sum_{j=1}^i \left[(\Delta x_j)^2 \sigma_{\rho_j}^2 + \rho_j^2 \sigma_{\Delta x_j}^2 \right] \quad (\text{A20})$$

A.5 CRS Model uncertainty

$$t(x) = \frac{1}{\lambda} \ln \left(\frac{A(0)}{A(x)} \right) \quad (\text{A21})$$

where,

$$A(x) = \sum_{i=x}^n C_i \rho_i \Delta x_i \quad (\text{A22})$$

$$A(0) = \sum_{i=1}^n C_i \rho_i \Delta x_i \quad (\text{A23})$$

Inventory uncertainty:

$$\sigma_A^2 = \sum_i \left[(\rho_i \Delta x_i)^2 \sigma_{C_i}^2 + (C_i \Delta x_i)^2 \sigma_{\rho_i}^2 + (C_i \rho_i)^2 \sigma_{\Delta x_i}^2 \right] \quad (\text{A24})$$

$$\sigma_t^2 = \left(\frac{1}{\lambda A(0)} \right)^2 \sigma_{A(0)}^2 + \left(\frac{1}{\lambda A(x)} \right)^2 \sigma_{A(x)}^2 \quad (\text{A25})$$

The uncertainty in age is:

$$\sigma_t = \frac{1}{\lambda} \sqrt{\left(\frac{\sigma_{A(0)}}{A(0)} \right)^2 + \left(\frac{\sigma_{A(x)}}{A(x)} \right)^2} \quad (\text{A26})$$

A.6 CRS Mass accumulation rate

The CRS mass accumulation rate is:

$$r(x) = \frac{\lambda A(x)}{C(x)} \quad (\text{A27})$$

With uncertainty:

$$\sigma_r = r \sqrt{\left(\frac{\sigma_{A(x)}}{A(x)} \right)^2 + \left(\frac{\sigma_{C(x)}}{C(x)} \right)^2} \quad (\text{A28})$$

A.7 ^{210}Pb Flux:

$$P = \lambda A(0) \quad (\text{A29})$$

$$\sigma_P = \lambda \sigma_{A(0)} \quad (\text{A30})$$

A.8 Sediment focusing factor

The sediment focusing factor (FF) is:

$$FF = \frac{A_{\text{measured}}}{A_{\text{expected}}} \quad (\text{A31})$$

$$\sigma_{FF} = FF \sqrt{\left(\frac{\sigma_{A_{\text{measured}}}}{A_{\text{measured}}} \right)^2 + \left(\frac{\sigma_{A_{\text{expected}}}}{A_{\text{expected}}} \right)^2} \quad (\text{A32})$$