High-resolution records of anthropogenic activity and geohazards from the reservoir of Sun Moon Lake, Central Taiwan

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Sun Moon Lake is the first dam reservoir constructed in Taiwan with the capability of generating hydroelectricity satisfying the whole Taiwan need during the Japanese colonial period since 1934 CE. Now, the Sun Moon Lake is one of the biggest hydropower stations in Taiwan and has become an important touring area. During World War II (1944–1945 CE), the hydroelectric power plant at Sun Moon Lake was bombed by the U.S. air force, which caused severe damage to the dam structure. More recently, the dam structure was also damaged during the 1999 CE Chi-Chi earthquake whose epicenter is nearby in the Nantou County. A suite of cores were taken from both Sun Lake and Moon Lake, and two selected cores, Sun 2–1 and SM 16 4–3, from Sun Lake were detailed studied with multiple analyses, including X-ray imaging, magnetic susceptibility, visible spectrophotometry, X-ray fluorescence (XRF) scanning, and mineral analysis. We discovered that the increase of Ca content in the sediments not only clearly indicates when the dam was constructed at Sun Moon Lake but also records evidence of structure repairs after both the World War II bombing and the Chi-Chi earthquake. Additionally, the yellow turbidite, X-ray image, and low-Ca signals in Core Sun 2–1 strongly correlate to the typhoon events that caused severe floods in the watershed of Zhuoshui River. The turbidite layers caused by the 1963 Gloria Typhoon are also characterized by conspicuous high peak of Fe/Mn in both cores. This study shows that XRF scanning results are useful for recognition of human activity and for high precipitation event correlation. Moreover, the appearance of charcoal layers shows evidence of forest burning and slash-and-burn activities by humans during the past 4,000 years back to the Middle Neolithic Age.

Keywords: Human activity, Disaster, Typhoon, XRF, Sediment, Dam

I. Introduction

1. Introduction to dam research

Dam reservoirs are important water supplies for humans; therefore, the water quality and the contamination of the sediments have always been major concerns in water management (Frémion et al., 2016). In the past, investigations of contaminants in reservoirs have mostly been focused on water sampling and analyses of the surface sediments. Without a proper chronological dating of the surface sediments and the lack of continuous long-term records sometimes make the obtained results useless for environment governance. Furthermore, severe reservoir siltation will shorten the life span of the dam reservoir, especially in the tropical area, where large rainfall initiates rapid erosion (Panagos et al., 2017).

Three major reservoirs in Taiwan including Tsengwen, Feitsui, and Sun Moon Lake have been investigated for their dioxin and pesticides pollutions (Chi et al., 2011; Chi et al., 2013; Chi et al., 2015). However, due to the limitation of available coring technique, the lengths of the obtained cores were less than 70 cm, not long enough to provide meaningful long-term records given the high sedimentation rates in those reservoirs. In order to acquire sedimentary records of the past 200 years, we first performed a full-region sonar scan that covers the entire Sun Moon Lake to map the distribution and thickness of sediments in the lake. We then...
We only showed the results of four cores (boldface) in this study.

precluded those areas where sedimentation rates are apparently too high. Previous study had investigated the variation of subbottom profile in Sun Moon Lake in 2006, 2012, and 2014 CE (Leung, 2015). They found that the maximum thickness of accumulated sediments is about 6–7 m during the interval of 2006–2012 CE and is about 4–5 m during the duration of 2012–2014 CE. It indicates a very high sedimentation rate near the top of the alluvial fan.

Nine cores were taken from sites where sediment deposits are proper in thickness as recognized by sonar imagery (Table 1). Once the cores were obtained, we used several nondestructive methods to characterize the records and use the results as templates for further sampling and interpretation. These methods include core photography and various scanning techniques, such as magnetic susceptibility (MS), visible spectroscopy, X-ray image, and X-ray fluorescence (XRF) core scanning chemical profiles to discern lithological changes of the sediments. Based on these results, in combination with mineral XRD, sediment dating using $^{210}$Pb and $^{137}$Cs, and carbon material dating of $^{14}$C, we are able to reveal the past anthropogenic influences and natural environmental changes recorded in those cores. We further correlated our sedimentary indicators with the flooding events reported by Central Weather Bureau of Taiwan. Combined with geophysics and geochemistry analyses, we recovered the anthropogenic activities and geohazards events with high-resolution, continuous XRF core scanning of several cores drilled in 2016.

Table 1. The locality, water depth, and core length of each core in Sun Moon Lake. DOI: https://doi.org/10.1525/elementa.2020.00150.t1

| Core Name | Water Depth (m) | Core Length (cm) | Latitude and Longitude |
|-----------|----------------|------------------|------------------------|
| Sun 2-1   | 25.6           | 224              | 23°51’55.2”N 120°55’09.6”E |
| Sun 2-2   | 25.6           | 221              | 23°51’55.1”N 120°55’10.1”E |
| SM 16 4-2 | 24.6           | 229              | 23°51’30.0”N 120°55’03.5”E |
| SM 16 4-3 | 24.6           | 215              | 23°51’29.9”N 120°55’03.5”E |
| Moon 1-1  | 27             | 125              | 23°50’14.9”N 120°54’46.2”E |
| Moon 1-2  | 27             | 112              | 23°50’17.3”N 120°54’45.9”E |
| Moon 1-3  | 27             | 143              | 23°50’17.6”N 120°54’46.3”E |
| SM 16 3-1 | 21             | 142              | 23°50’35.7”N 120°54’24.5”E |
| SM 16 3-2 | 21             | 156              | 23°50’35.8”N 120°54’24.6”E |

2. Sun Moon Lake reservoir in Nantou, Central Taiwan

Sun Moon Lake reservoir (23°51’N, 120°54’E), located in the Pu-Lee area, Nantou, is the largest lake in Taiwan. It was the first dam and one of the major hydraulic power plants in Taiwan (Figure 1). During the Japanese colonial period back in 1934 CE, the Wujie Tunnel was built to direct the waters dammed from Zhuoshui River into the northeast corner of Sun Lake. The water is then transported to Daguan and Mingtan power plants for hydroelectricity (Taiwan Power Company, 2018). Before 1934 CE, the average water depth of Sun Moon Lake was only 4 m, and the water level raised to 25–27 m deep after the dam was constructed. The northern part of the reservoir is called Sun Lake and the southern part is named Moon Lake. The two reservoirs are connected now (Figure 2). In 2006, the New Wujie Tunnel was completed and began to direct waters from the upper reach of Zhuoshui River (Figure 1; Taiwan Power Company, 2018).

The geological condition in the watershed of the Zhuoshui River is susceptible to erosion and makes the river to have the highest sediment load in Taiwan (Dadson et al., 2003, 2004; Kao and Milliman, 2008). Although certain hydrological measures have been applied to reduce the suspension sediments being carried into the reservoir, the sedimentary input is still very high, about 300,000 tons per year. The injected water often become turbid and muddy especially after heavy rains or typhoons that generated huge deposition particularly at the water inlet of Sun Lake at its east corner. An underwater alluvial fan can be observed from the bathymetric map (Figure 2). Now, the full water level of Sun Moon Lake is 748 m altitude above sea level. Strict regulation and monitoring have been applied in order to control the local hotels, residents, and tourists for preventing pollution under increasing touring pressure.

Aboriginal people lived in the mountainous area in Pu-Lee until Japanese took control Taiwan. Several aboriginal people fought against the Japanese around 1930 CE and then they retreated into deep mountains. The Japanese authority then took over this area completely and then built the first dam reservoir and associated power plant at Sun Moon Lake in 1934 CE (Taiwan Power Company, 2018). As one of the important power facilities back to that time, the related Daguan and Mingtan power plants, and Shuishe Dam (Figure 1) were bombed and heavily...
damaged by the U.S. air force in 1944–1945 CE during the World War II (Tu, 2017). The dam structure was damaged and repaired thereafter (Taiwan Power Company, 2018). Additionally, the Chi-Chi earthquake, a catastrophic geohazard caused serious damages of more than 80,000 buildings in Nantou country with widespread landslides and following surface erosions in the catchment of Sun Moon Lake (Dadson et al., 2004). The Chi-Chi earthquake was rated at 7.3 magnitude on the Richter scale located just 9.2 km southwest to Sun Moon Lake (Figure 1; Dong et al., 2000). The dam structure and surrounding buildings were severely damaged (Lee, 2003) and then reconstructed in around 10 years. Many hotels were damaged along the north side of Sun Lake (see Supplementary Materials, Figure S1).

3. Subbottom profiles
We started our investigation with a subbottom profiling using multibeam echo-sounder coupled with Global Positioning System (Munir et al., 2014). There are a total of 28 different probing paths undertaken (Supplementary Materials, Figure S1) in this study, covering both Sun and Moon Lakes. We used an Edgetech X-star digital multifrequency SB-216S tow sonar system. The results of subbottom profiles of the lake floor were shown in Figure 3 and Supplementary Materials, Figures S2–S4.

The effective frequency range was 2–16 kHz with penetration depths of 6 m in large-grained sand layers and 80 m in muddy layers. The SB-216S transducer vertical resolution was 10 cm in the frequency. The reflection signal strength correlated with the difference of acoustic impedance between two layers. The strong reflection indicates hard background. After 1934 CE, the mud sediments from fast injected water and original lake basement should have different sedimentary rates and densities. We did pay attention to the strong reflection basement that may cause an obstruction of our vibration corer.

Sediments have been brought in ever since 1934 CE through tunnels on the eastern side of the lake, and the plumes of sediments have dispersed to the west and south, forming a fan in a semicircular form with its center near the two entrances (inflow of the Wujie and New Wujie Tunnels, see Figures 1 and 2). The thickness of the

Figure 1. The dam of Sun Moon Lake, hydrologic power plants, other dams, and river system. Black lines mean surrounding roads, and purple dash lines mean the supplement water tunnels between the dams (Chi-Chi is the epicenter of 1999 Ml 7.3 Chi-Chi earthquake). DOI: https://doi.org/10.1525/elementa.2020.00150.f1

Figure 2. Bathymetric contour map of Sun Moon Lake reservoir (the color represents the altitude above the sea level in meter). Red stars represent the locations of the studied cores: Sun 2-1, SM 16 4-3 in Sun Lake, as well as SM 16 3-2 and Moon 1-3 in Moon Lake. The water injections are near the top of the alluvial fan on the eastern side. DOI: https://doi.org/10.1525/elementa.2020.00150.f2
accumulated sediment profile tapers off toward the west in Sun Lake (Figure 3). In the profile of Survey Line #3, there were hard sandy basement and over soft layers with mud or poor sorted muddy silt on it. The mud layer thickness ranges from 40 to 1 m, prorogating from eastern to western, forming a new deposition pile ever since the damming in 1934 CE (Figure 3).

The sedimentation rates must vary from place to place as a function of the distance of the site from the injection point and the local hydrological conditions. With several cross sections in hand as obtained from the bottom profiling, given the limitation of our corer—the maximum penetration depth is 3 m, we chose strategically coring sites to get sediments with possible longest record of time covered in Moon Lake and sediments with the highest resolution covering the time period of 1934 CE in Sun Lake. We had the cores penetrate the bottom of the newly deposited sediments after 1934’s damming and earned also the underlying original wetland sediments. The boundary between the two sets of different types of sediments can serve as a good stratigraphic control for correlating the obtained cores. We cored at two sites (Sun 2–1 and SM 16 4–3) in Sun Lake and another two (Moon 1–3 and SM 16 3–2) in Moon Lake (Figures 2 and 3 and Supplementary Materials, Figures S1–S4). Table 1 lists the location coordinates, core lengths, and water depths of these cores. We only show the analysis results of Sun 2–1, SM 16 4–3, Moon 1–3, and SM 16 3–2 in this study.

II. Methods

2.1. Nondestructive measurements and XRD

We first ran an overall physical property scan of the sealed core using a Multi-Sensor Core Logger (MSCL). After splitting the cores into two halves, the cores were scanned and examined with a color spectrophotometer and an XRF sedimentary core scanner. We then conducted dating and mineral analyses on the sediments. Details of the methods and equipment used in the study are summarized below:

1. The MSCL used in the study was manufactured by GEOTEK. The maximum core diameter is smaller than 10 cm, and maximum length of a core section is 1.5 m. Our measurements were collected every 0.5 cm interval. Data acquired include γ ray, P wave velocity, MS, resistivity, and so on (Gunn and Best, 1998). We obtained the intensity of magnetic signals and estimated the γ-density and water content of the sediments. P wave velocity shows the density variation, and it declines when the sediment is too soft or mixed with a lot of water. MS represents the volume-specific MS, which displays the variation of mineral magnetism. If the sediment is composed of organic matters, the MS intensity value would decrease.

2. We used a MINOLTA CM-700d spectrophotometer to record the reflection of the visible light spectrum and color change in the sediments. The measurements of the cores were performed every 1 cm interval and the beam diameter was about 3 mm. The wavelengths ranged from 400 to 700 nm with 10 nm interval. Information acquired also include lightness (L*), green/red color index (a*), and yellow/blue color index (b*; see CIE 15 : Technical Reports Colorimetry, 2004). As a* becomes more positive, it means that the color got redder; and when b* becomes more positive, it means that the color became more yellow (Blum, 1997; Nederbragt et al., 2005). Oxidized sediments

Figure 3. Subbottom layer profile depicted from Survey Line #03. The position of Survey Line #03 is shown in Supplementary Materials, Figure S1. The profile shows the subbottom sedimentary configuration using two-way traveling time and the depth was estimated. (The red number means survey line number and intersection of other survey line number.) DOI: https://doi.org/10.1525/elementa.2020.00150.f3
with more Fe₂O₃ content will have larger α* and b* values.

(3) The XRF core scanner used in this study was manufactured by the COX Analytical Systems. This multifunction machine provides optical image, digital X-ray radiography, and XRF measurements up to 200 μm scanning resolution. The Mo tube was used in voltage 30 kV, current 50 mA, exposure time 10 s, and resolution 1 mm for radiography (Huang et al., 2016b).

(4) The sediment samples were then grounded and examined by an X-ray powder diffractometer (D2 PHASER; Bruker, United States) with Cu target, operation voltage 45 kV, and electric current 40 mA. Diffraction angel 2θ is in the range of 3°–70° and divergent slit 0.5°. The mineral phases were identified using the database from the International Center for Diffraction Data (ICDD). For details of the analytical conditions and mineral semi-quantification method, please refer to Chen et al. (2010, 2011). The semi-quantification for calcite is based on the peak area of d-spacing at 3.02 Å by the calculation to total mineral percentage.

2.2. Chronological analyses

(1) A γ-ray spectrometer was used to analyze 210Pb, 214Pb (replacing 226Ra), 7Be, and 137Cs in the young sediments. The radioactive counting system used in this study includes an EG & GORTEC GWL-100230, a LB-GWL detector, and a digital γ-ray spectrometer (Goldberg, 1963; Hirose et al., 1987).

(2) For 14C dating of carbon materials, samples were picked from the older sediments prior to the preconstruction period. We used the 1.0 MV Tandetron 4110 BO Accelerator Mass Spectrometer housed at the Geoscience Department, National Taiwan University. The minimum amount of carbon required for the analysis is 0.2 mg (Li et al., 2019).

2.3. Data cleaning, transformation, and principal component analysis (PCA)

In order to explore the information contained in the element count data obtained by the XRF scanning, we subjected the data to PCA. The purposes of PCA are threefolds: (1) reducing dimensionality while retaining the most variance in the data with a few principal components (PCs), (2) forming several linear combinations (PCs) of individual elements while the coefficients or correlations of the elements with the PCs are indicative of the relevance among the various elements, and (3) calculating the scores of each sample on each PC, and thus, one can categorize the samples into groups of different element associations.

To ensure that the PCA results are robust, we did data cleaning and transformation before subjecting the data to multivariate analysis. First, we checked the scanning quality to exclude those data points that show weak intensity of elements due to small gaps or cracks or depressed surface. The ratios of Fe/Ar, Cu/Ar, and Ti/Ar were also used to evaluate the data quality using Ar as a proxy of air. In some instances, peculiar scanning geometry or peculiar foreign objects intercalated in the sediments can also yield abnormally high counts for particular elements such as Fe, Ti, and so on (for instance, at approximately 210 cm of Core Sun 2–1, see Figure 4). All such kinds of extremely high and low value points were discarded. Statistically, these data points are outliers. Secondly, certain elements, that are either of light atomic mass, or, in extremely low content, show very small counts, often 0 value, are not reliable measurements, and they tend to give spurious statistical results. For this reason, all the elements whose maximum counts values less than 300 were excluded for PCA. As a result, Al, P, S, Cl, Ar, V, Cr, Br, and Y were excluded.

In fact, the count of each element resulted from the XRF is only a semiquantitative measurement (Tjallingii et al., 2007; Löwemark et al., 2011; Chawchai et al., 2015; MacLachlan et al., 2015). Such a matrix effect makes the XRF data array of a scanning point a set of compositional data in nature and possess the so-called constant-sum property. To circumambulate the constant-sum problem and to make the data close to a multivariate normal distribution, all the data were transformed by centered log-ratio (clr) by adopting the methods from Aitchison (1986), Weltje and Tjallingii (2008), Lee et al. (2019), and Schwestermann et al. (2020).

After all variables are transformed, their errors are considered to be additive and approximately normally distributed. The log-ratios are easier to handle mathematically than the original raw intensity values (a ratio in a constant sum). All the PCA analyses were based on the covariance–variance matrix of the selected 16 or 17 elements, including clr Mo inc and clr Mo coh, see the resulting loading correlation matrix Tables S1 and S2 in Supplementary Materials.

III. Results and discussions

3.1. Core description and lithology in general

Since there are 2–3 cores cored at each site, we chose one core from each for detailed sampling and analyses. Cores Sun 2–1 and SM 16 4–3 were chosen for Sun Lake, while Cores Moon 1–3 and SM 16 3–2 were used for comparison and analyses for Moon Lake. From the photos and...
description of these two sets of cores (Figures 5 and 6, red arrow), the upper part is mainly consisted of gray mud whereas the lower part is made of brown colored silty mud mixed with some organic debris. We interpret that the boundary between the upper gray mud and the underlying organic-enriched mud indicates the major environment change related to the filling-up of water when the reservoir was dammed in 1934 CE. Before the damming time, this environment was a swamp environment where more aquatic plants grew nearby the lake.

The contents of the lower part of the Moon Lake SM 16 3–2 core show very different features from other cores. Its brown organic mud consists of many layers of charcoal. The charcoal was derived from burning plants on land. A clear black charcoal layer (Figures 5 and 6, red arrow) has been found at the interface between the gray mud (upper part) and the brown organic mud (lower part) in each drilled core. These black colored interface markers are observed at 105 (Sun 2–1), 152 (SM 16 4–3), 33 (Moon 1–3), and 22 cm (SM 16 3–2). This charcoal layer is possibly an evidence of tree burning in the surrounding forest area in preparation for the dam construction by the Japanese rulers. However, this layer of sediment was too young to be dated by $^{14}$C method.

3.2. Nondestructive measurements

We examined all the measurements obtained from three nondestructive means in order to have a quick glance of the lithological changes and form templates for further sampling and chemical analyses. Figure 4 represents an example using the results of Core Sun 2–1. It is clearly shown that there is a distinctive boundary separating the whole record into two parts: The upper one is characterized with higher MS, higher contents of typical elements (e.g., Ti, K, Fe) associated with terrestrial silicates and lower Mo inc/coh, as well as low values in $b^*$, signifying less yellowish or brownish in color. The Mo inc/coh (incoherent/coherent ratio) indicates organic content (Chawchai et al., 2015; Huang et al. 2016a). The boundary marks a major change in deposition, from the previous wetland, peat-rich sediments to the lake facies when the dam was completed in 1934 CE.

The MS records all show abrupt increases after the dam construction in 1934 CE (Figure 4). The interesting thing is the $^{137}$Cs peak in 1963 CE appeared at 51.5 cm in Sun 2–1 core, which correlates very well with the peak $b^*$ value (Figure 7), representing a yellowish sediment. The peak value of the yellow index $b^*$ in Sun 2–1 can also be correlate to the positions where the blue arrows are shown in Moon 1–3 and SM 16 3–2. Since the sedimentation rates are different, the blue arrows appear at different depths (Figure 7). The core photo of SM 16 3–2 clearly shows a yellow mud layer (Figure 6) located at 18 cm deep. Furthermore, the X-ray image shows the existence of a high-density turbidite marked with an orange arrow in Figures 5 (Sun 2–1) and 6 (SM 16 3–2). Since the bottom layer mud never completely dried after the dam construction, the appearance of the yellow oxidized layer represents large amount of eroded surface matters from the continent entering the lake, which is a significant event recorded.
3.3. Chronology and sedimentation rate

Since we were able to correlate the lithological property of the sediments and various scanning proxies between each cores for age comparison, we only used the mud sediments on the upper part of cores Sun 2–1 and Moon 1–3 (Supplementary Data, Figures S5 and S6) to run the 210Pb and 137Cs dating. The sources of 210Pb are derived from both sediments and atmospheric deposition to the water. 210Pb$_{ex}$ is assumed to be the extra 210Pb which activity is higher than 226Ra activity. The residual 210Pb$_{ex}$ should be from the water due to atmospheric deposition (Berner, 1971; Nittrouer et al., 1984). From the vertical distribution of 210Pb and 226Ra, both cores show 210Pb with a slightly higher value than its parent nucleus 226Ra. Therefore, the excess amount of 210Pb(210Pb$_{ex}$) in the sediment did not show a decreasing trend in value with an

Figure 5. Core photo, X-ray image, and lithology column of cores SM 16 4-3 and Sun 2-1 from Sun Lake. The red arrow indicates a distinctive boundary between the upper section (lake sediments) and the lower section (predamming wetland sediments) by the X-ray image and lithological components. Several Accelerator Mass Spectrometer 14C dates (blue line) were obtained for core Sun 2-1 as shown in Table 2. The orange arrow indicates the 1963 CE turbidite layer based on X-ray image. DOI: https://doi.org/10.1525/elementa.2020.00150.f5
increase in depth. The $^{210}$Pb and $^{137}$Cs dating results of the Tsengwen Reservoir from previous studies were not ideal either (Chi et al., 2015). According to the X-ray image of Sun 2–1 from Sun Lake, there were many turbidity current events with density differences that took place during the rapid deposition processes (Figure 5). As a result, sources of local sediments may be affected by the $^{210}$Pb from older strata. Atmosphere nuclear may be diluted by the old sediments in Sun Moon Lake area.

There are two distinctive peaks of $^{137}$Cs (core Sun 2–1) after the dam was built in 1934 CE (Figure 7). The first peak of $^{137}$Cs at 49–54 cm (average 51.5 cm) reflects the peak high of global nuclear testing at 1962 CE, the other one at 30.5 cm may show 1986 CE the radiation leak of the Chernobyl nuclear power plant explosion (Carter and Moghissi, 1977; Koide et al., 1985). In general, 1963 CE is recognized as a peak of nuclear deposition time in the sediment (Toonkel, 1981; Hirose et al., 1987). However, the 1986 event was only detected in high latitude areas in the northern hemisphere. Therefore, it is still uncertain whether or not the event has been recorded in the lake cores in this area. So far, we are only confident that the first peak of $^{137}$Cs record at 49 cm in Sun 2–1 core should represent
the deposition of nuclear testing events in 1963 CE. In the other core Moon 1–3, depth of 137Cs peak appears below 33 cm, which is the boundary of damming time 1934 CE (see Supplementary Materials, Figure S6). Therefore, the age 1963 CE according to the 137Cs peak is unreasonable to be used in this case.

In order to confirm the age of the sediment before the dam was constructed, we performed 14C dating on Sun 2–1, SM 16 4–2 (which has the same location as SM 16 4–3), and SM 16 3–2 in Table 2. We adopted the age model by using Bayesian analysis and the Bacon program for R program (Blaauw and Christen, 2011; Figure 8). The sedimentary rate in Moon Lake is slow with a cal. 9750 (+445) yr BP at 131 cm in SM 16 3–2 (Figure 6). It indicates that the sedimentation rate of Sun Lake is faster than that of Moon Lake. The

### Table 2. 14C dating results of Sun Moon Lake cores (Calibration 7.1 program: Reimer et al., 2004; Stuiver et al., 2017). DOI: https://doi.org/10.1525/elementa.2020.00150.t2

| Lab Code     | Sample ID | Depth (cm) | Material       | 14C Age (yr BP) | Calibration 7.1 Age (yr BP) | cal. yr BP |
|--------------|-----------|------------|----------------|----------------|-----------------------------|------------|
| TUAMS-3922-1 | SM 16 3-2 | 58         | Charcoal       | 385 ± 8        | 420 ± 80                    | 340 ~ 499  |
| NTUAMS-3923  | SM 16 3-2 | 70         | Charcoal       | 2,978 ± 59     | 3,155 ± 185                | 2,970 ~ 3,339|
| NTUAMS-3308  | SM 16 3-2 | 101        | Plant fragments| 5,361 ± 100    | 6,117 ± 200                | 5,920 ~ 6,313|
| NTUAMS-3294  | SM 16 3-2 | 131        | Charcoal       | 8,647 ± 177    | 9,750 ± 445                | 9,305 ~ 10,191|
| NTUAMS-3307  | SM 16 4-2 | 194        | Charcoal       | 1,072 ± 19     | 995 ± 60                   | 933 ~ 1,050|
| NTUAMS-3820-1| Sun 2-1   | 135        | Charcoal       | 589 ± 12       | 595 ± 50                   | 545 ~ 638  |
| NTUAMS-3921-1| Sun 2-1   | 205        | Charcoal       | 1,700 ± 33     | 1,620 ± 80                 | 1,542 ~ 1,698|
| NTUAMS-3310  | Sun 2-1   | 214        | Charcoal       | 2,086 ± 59     | 2,100 ± 205                | 1,899 ~ 2,301|

Figure 7. 137Cs dating results compared to b* at 50–52 cm in core Sun 2-1 (Sun Lake) with the age closed to 1960–1963 CE, which also correlates with the peak high in core SM 16 3-2 and Moon 1-3 at depth of 18 and 20 cm, respectively. (Red dash line means the sedimentary boundary of the age 1934 CE, and blue arrows indicate the age 1963 CE of each core). DOI: https://doi.org/10.1525/elementa.2020.00150.f7
The sampling location of SM 16 3–2 at Moon Lake has a water depth of 21 m only. This area has a water level very close to the shoreline before the dam was built (Supplementary Materials, Figure S7); hence, deposition could be temporarily terminated during droughts, resulting in extremely slow sedimentation rate. According to the topographic map of Sun Moon Lake's basin, it shows an alluvial fan landform (Figures 2 and 3). Combined with core photos (Figures 5 and 6), we can easily estimate the sedimentation rates. The calculated result shows the average sedimentation rate for each core after the damming time 1934 CE was constructed: 1.28 (Sun 2–1), 1.85 (SM 16 4–3), 0.40 (Moon 1–3), and 0.27 cm/y (SM 16 3–2), respectively.

### 3.4. Results of PCAs and interpretation of XRF data

The XRF data of Sun 2–1 and SM 16 4–3 were chosen for PCA because these two cores generate more continuous and good-quality scanning results with better chronological coverage. The data sets above and below the 1934 CE time line were analyzed separately for they belong to totally different depositional regimes, one in wetland while the other in deep-water lake. Basic statistics of these PCA analyses are listed in Tables 3 and 4 in the Supplementary Data. Here, we only show the most important elements recognized below.
3.4.1. Post 1934

The PCA results of Sun 2–1 and SM 16 4–3 are basically similar to each other but not exactly the same in details. The important elements that show high correlation coefficients with the resulted first 5 PCs are listed in Table 3. The most significant elements include Ca, inc, coh, Si$^+$K$^+$Ti, Pb, Mn, and Cu, and they are marked with boldface letters in Table 3. We plotted all these elements against depth and evaluated whether if they can be correlated pairs for cores Sun 2–1 and SM 16 4–3. Only Ca and (Ni$^+$Cu$^+$inc) show wide commonality for Sun Lake during the past approximately 90 years. The contents of Si, K, and Ti that represent the terrestrial mineral source are enriched in the upper core (Figure 4), and the inc/coh is related to the organic matters which also adsorbed Ni and Cu shows higher contents in the lower part of cores Sun 2–1 and SM 16 4–3 (see Supplementary Materials, Figure S8).

The PC1 accounts for 51% variance of the data matrix and has a very strong correlation with Ca (0.99; see the Supplementary Materials, Table S1). Indeed, Ca shows very distinctive fluctuations especially after 1960 (Figure 9). The low values of Ca appear to correspond to the dark layers of turbidite in the X-ray image. The high values of Ca are interpreted as to reflect the influx of calcite (see Supplementary Materials, Figure S9), probably, debris of cement, as brought in by gully waters or air dusts from the northern shore of Sun Lake, where most hotels are located. These hotels were heavily damaged during the 1999 Chi-Chi earthquake (see Supplementary Materials, Figure S1). In fact, it was a swarm of six earthquakes occurring during September 21–26, 1999. The reconstruction of the hotels started in 2000 and lasted for 10 years to complete. We designate the initial peak high of Ca in the age of year 2000. We used the following three events to build primarily an initial age model for core Sun 2–1: damming at 1934, Gloria Typhoon in 1963 (peak high of $^{137}$Cs) which caused the deposition of turbidite layers in many cores, and the initial of hotel reconstruction in 2000 as mentioned above (Figure 9).

Based on the initial age model, the low Ca values are considered to be signals of increased influence of injected waters from Zhuoshui River because the sediment loads would dilute the Ca content of the Lake. The rainfall data of Sun Moon and the flooding historical records in Central Taiwan listed in Table 4 match very well with the Ca signals (Figure 9). These low Ca intervals well correlate with the dark intervals of X-ray image (Figure 9), which corresponds to the plentiful precipitation amounts in the watershed during the most significant typhoons ever since 1959. In addition, the low Ca signal just prior to 2000’s high is regarded as a dilution effect of 1999 Chi-Chi earthquake, causing probably turbidite-like deposits. Accordingly, these low-Ca events can serve as chronological anchor points to build up an age model for core Sun 2–1 (Table 5).

It is worthy to note that the turbidite layer recognized from Sun 2–1 based on b* (see Figure 7) corresponds to the extremely high value of Fe/Mn at 490 mm (Figure 10). Such high Fe/Mn ratio is likely to be diageneisis in origin from the geologically old strata in the watershed of Zhuoshui River. This layer is made of eroded sedimentary debris brought in by the extreme flood events associated with the 1963 Gloria Typhoon (Figure 10). The sediments are characterized by a dark black band in the X-ray image. This event can be observed in several cores and it is marked by peak value in b* and can be easily correlated.
The underlined dates are those used to build the initial age model of Sun 2–1, and the ages of the organic-enriched layers in Sun 2–1 can be calculated by interpolation from the Ca-based chronology and then transferred to core SM 16 4–3 by correlation based on clr (Ni + Cu + inc). The ages of events are expressed in terms of Julian days in each year converted into decimal numbers for detailed fine tuning the chronology of the last 90 years.

### Table 5. Detailed correlation tiepoints for cores Sun 2–1 and SM 16 4–3 based upon clr Ca and clr (Ni + Cu + inc).

| Year | Event            | Depth in Sun 2–1 | Depth in SM 16 4–3 |
|------|------------------|------------------|--------------------|
| 2010.17 | Organic 1 | 42 mm | 16 mm |
| 2009.85 | Organic 2 | 55 mm | 47 mm |
| 2009.60 | Morakot Typhoon | 65 mm | |
| 2008.54 | Kalmaegi Typhoon | 108 mm | |
| 2005.24 | Organic 3 | 131 mm | 169 mm |
| 2000.50 | Repair of hotels | 164 mm | |
| 1999.87 | Organic 4 | 177 mm | 267 mm |
| 1999.72 | Chi-Chi earthquake | 180 mm | |
| 1996.57 | Herb Typhoon | 232 mm | |
| 1996.97 | Organic 5 | 225 mm | 355 mm |
| 1994.61 | Doug Typhoon | 262 mm | |
| 1991.34 | Organic 6 | 287 mm | 443 mm |
| 1978.67 | Organic 7 | 380 mm | 590 mm |
| 1963.69 | Gloria Typhoon | 490 mm | |
| 1960.58 | Shirley Typhoon | 538 mm | |
| 1959.59 | August 7 Flood | 550 mm | |
| 1959.25 | Organic 8 | 555 mm | 868 mm |
| 1955.78 | Organic 9 | 618 mm | 982 mm |
| 1951.86 | Organic 10 | 688 mm | 1,068 mm |
| 1934.50 | Damming | 998 mm | 1,577 mm |

The relatively high values of Fe/Mn in the interval of 510–560 mm (Figure 10) are indicative of a more oxidized inflow of FeO₃ sediments or a more reducing depositional environment in the lake floor, probably due to higher lake level, making MnO₂ decline in the sediments due to less degree of ventilation of the bottom waters (Davison, 1993; Abeser and Robinson, 2010).

In comparison, the expression of Ca is more distinctive in Sun 2–1 for the upper part of the record (2016–1959 CE). The Ca record in Sun 2–1 in the early part is less clear, partially due to the coring break. On the other hand, the elevation of Ca concentration after 1934 is recorded more clearly in core SM 16 4–3 but not in Sun 2–1. Such disparity in Ca contents does not allow us to have a confident correlation between these two cores (see Supplementary Materials, Figure S10). Instead, the variation in (Ni + Cu + inc) appears to show synchronized changes during the past 100 years (Figure 11). This parameter is interpreted as a reflection of the content of organic matters in the sediments. The correlation lines designated in this Figure 11 are basically parallel to those recognized by Ca correlation (Supplementary Data, Figure S10).

### 3.4.2. Prior to 1934

The XRF data of the Fe-abnormal interval in the lower part of core Sun 2–1 (Figure 4) were not included in the PCA analysis because these extremely high values are higher than the background Fe counts by 10 times. The inclusion of such high extremely high values in PCA would let it dominate the results and hinder us from recognizing other element variations in the sediments. Table 6 shows the variances explained by the first five PCs and their corresponding influencing elements. The loading and correlation patterns of these two sites are not similar as evident by the elements and numbers in Table 6. The elements common to both cores are boldfaced, and down core variation of all these elements were plotted and evaluated, but, none of them show common features to their counterparts in the other core, indicating that the deposition history prior to 1934 at these two sites is not comparable at all. Figure 12 shows an example to demonstrate the lack of commonality between these two cores.

After the total correlation of age controls by clr Ca and clr (Ni + Cr + inc) between cores Sun 2–1 and SM 16 4–3, we checked the typhoon events prior to 1959 CE from the Central Weather Bureau (http://photino.cwb.gov.tw/rdcweb/lib/clm/typhonlx.htm). We recognized three strong typhoon disasters in Central Taiwan, including the Kit and Nina Typhoons of 1953, #174 Typhoon in 1944, and #164 Typhoon in 1940 from core SM 16 4–3 (Figure 13). It is evident that the initial construction and the repair of the dam in the period of 1934–1950 can be well identified in core SM 16 4–3, whereas the reconstruction signals of hotels located on the norther shore of Sun Lake after 1999 Chi-Chi earthquake are well recorded in core Sun 2–1.

### 3.5. Charcoal layer and human activity

Each core has a distinctive charcoal layer at the boundary between the gray mud and organic mud. This is a good time line indicator to show when the dam was constructed. When Japanese Government fought against the local aborigines in Nantou, they burned the forests many times and kept failing to build the dam for a long time (1919–1934 CE). Multiple charcoal layers have also been observed in the brownish organic mud or peat in the lower portion of the core SM 16 3–2 in Moon Lake (Figure 6). This shows the evidence of burning activities by human or natural fire hazards that took place before the
construction of the dam. According to the archeological evidence, indigenous people cut and burn plants in the forest for farmland use (Wang and Tien, 2009). In addition, the frequency of charcoal layers appearing in the core reflects local forest fire that originated from natural fire hazards or artificial fires ignited by men. The record shows that fire hazards were quite frequent in the recent 4,000 years since the Neolithic Age (Wenske et al., 2009). According to previous studies on archaeological sites and prehistoric culture of the Puli area, the pollen research

Figure 10. Variation of Mn in comparison to X-ray image and color photo of the upper part of core Sun 2-1. The turbidite layer caused by the 1963 Gloria Typhoon is highlighted. DOI: https://doi.org/10.1525/elementa.2020.00150.f10

Figure 11. Bi-plot of clr (Ni + Cu + inc) versus depth (mm) of core Sun 2-1 and SM 16 4-3 for the intervals post 1934. The red pointing lines represent the correlation lines between the two records based on clr (Ni + Cu + inc), an indicator of the content of organic matters. Note that the variation of organic matters is more distinctively expressed in SM 16 4-3. DOI: https://doi.org/10.1525/elementa.2020.00150.f11
pointed out that Graminae increased significantly at Sun Moon Lake since 4200 yr BP. This indicates the beginning of rice and millet agriculture in the local area, which was about the Middle Neolithic Age, namely, Late Taiwanese Tapenkeng Culture (Hung and Carson, 2014; Kuo, 2020). According to the long-term archaeological findings in the Puli area, human activities have been detected in this area as early as 17,000 yr BP in the Paleolithic Age. However, strong evidence of agricultural behaviors did not appear until 3,700 yr BP (Shi and Liu, 1987). This conclusion strongly collaborates with the beginning of concentrated appearance of charcoal layers in the core SM 16 3–2, which has abundant charcoal particles in 55–80 cm (Figure 6). In addition, Sun 2–1 core has rich charcoal from 170 cm in depth to the bottom (Figure 5). According to the Bacon model calculation, the earliest age of charcoal layer in the core SM 16 3–2 at 80 cm is about cal. 4100 yr BP that fits the pollen records.

Table 6. Important elements for the lower parts (prior to 1934 CE) of cores Sun 2-1 and SM 16 4-3. DOI: https://doi.org/10.1525/elementa.2020.00150.t6

| Principal Component | Sun 2-1 | SM 16 4-3 |
|---------------------|---------|-----------|
| PC1 Variance (%)    | 46.6    | 42.7      |
| Elements            | Mn + Fe | Pb/(Ni + inc + coh) |
| PC2 Variance (%)    | 22.5    | 19.1      |
| Elements            | (Ca + Ni + inc + coh)/(Ba + K) | (coh + Ar)/(Si + K + Ti + Ba) |
| PC3 Variance (%)    | 11.1    | 14.1      |
| Elements            | Pb      | Ca/Rb    |
| PC4 Variance (%)    | 6.5     | 7.1       |
| Elements            | Si      | Ba       |
| PC5 Variance (%)    | 5.3     | 5.1       |
| Elements            | Ba      | Cu       |

Figure 12. Down core variation of clr (Ni + Cu + inc) of the whole cores of Sun 2-1 and SM 16 4-3. The red lines represent the damming age 1934 CE, while the blue triangles indicate the 14C dates in core Sun 2-1. DOI: https://doi.org/10.1525/elementa.2020.00150.f12
IV. Conclusions

The $^{210}\text{Pb}$ dating method does not provide a good chronological model for Sun Moon Lake sedimentary cores. Instead, we used three events easily identified in core Sun 2–1 to establish a primary chronological scheme: the damming event at 1934, the high Fe/Mn event caused by the 1963 Gloria Typhoon, and the high-Ca marker of hotel reconstruction starting from 2000 after the 1999 catastrophic Chi-Chi earthquake. Through the PCA of the covariance matrix made of centered log-ratio transformation of element intensity data resulted from XRF scanning, (Ni + Cu + inc) and Ca were recognized as two major parameters responsible for most of the variation in the record and offer the most reliable correlation markers. Low Ca values result from the dilution of high precipitation and related influx sediments from the watershed of Zhuoshui River allowed to tie the low-Ca points to the typhoon/flood events (Figures 9 and 13). Meanwhile, the similarity in (Ni + Cu + inc) pattern in cores Sun 2–1 and SM 16 4–3 facilitated a good correlation between the two cores and allowed an adequate age model of SM 16 4–3 to be built. It is evident that the initial construction and the repair of the dam in the period of 1934–1950 can be well identified in core SM 16 4–3, whereas the reconstruction signals of hotels located on the norther shore of the Lake are well recorded in core Sun 2–1 (Figure 13).

Before the dam was built, water level was very shallow, organic matters were abundant, and depositional environments were heterogeneous for Sun Lake. The charcoal layers that appear in the core records not only show evidence of large woodland burning by the Japanese government before the dam construction but also record the slash and burn activities of early human in this area back to the Middle Neolithic Age.

Data accessibility statement

All the experimental raw data are available in figshare with the identifier (https://doi.org/10.6084/m9.figshare.14330492.v1).

Supplemental files

The supplemental files for this article can be found as follows:

   Tables S1–2. Figures S1–10. Docx

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**Competing interests**

The authors have no competing interests to declare.

**Author contributions**

- Contributed to project design, coring, writing, and interpretation: KYW, HFC, TQL, HLC.
- Contributed to paper writing and interpret: HFC, KYW, JJH.
- Contributed to analysis and data collection: CCL, HFC, TQL.
- Contributed to 210Pb, 137Cs dating: CCS.
- Contributed to Accelerator Mass Spectrometer 14C dating: HCL.
- Contributed to X-ray fluorescence experiment: JJH, SRS.
- Contributed to principal component analysis: KYW.
- Contributed to color reflectance analysis: HJP.

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