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## Innovative multi-method geochronological approach to decipher (sub-)modern floodplain sedimentation in the Upper Rhine Plain, France

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20 **Keywords:** Upper Rhine floodplain, geochronology, IRSL single-grain, <sup>137</sup>Cs, <sup>210</sup>Pb<sub>xs</sub>, IRSL screening, portable luminescence reader, planimetric, stratigraphic and hydrological analyses, age-depth model

## Abstract

The precise dating of sedimentary archives covering the last 200 years in highly human impacted alluvial floodplains is a major challenge. Combination of geochronological approaches is necessary to accurately date sub-actual sedimentary deposits. Here, we use a combination of a wide range of methods to unravel floodplain sedimentary dynamics, through the example of the Upper Rhine which is a highly engineered river. This comprises short-life radionuclides ( $^{137}\text{Cs}$ ,  $^{210}\text{Pb}_{\text{xs}}$ ), Infrared Stimulated Luminescence (IRSL) single-grain dating, as well as a global hydrogeomorphological approach (historical planimetric data, historical hydrological data, knowledge of engineering works and the morpho-sedimentary adjustments they induced). Luminescence profiling methods (IRSL screening, portable luminescence reader) were also used to further characterise sediment dynamics. Our study has demonstrated the value of old historical maps, which provide precise time markers for dating the sedimentary archive under study. We illustrate different assumptions, validity domains and limitations inherent to each method, especially the complexity of the often used  $^{137}\text{Cs}$  to date floodplain sediments and the potential of luminescence methods for dating and estimating the sedimentation continuity. We also show the synergetic advantage of method combination in the construction of robust age models for young floodplain sedimentary archives.

## 1. Introduction

40 As human settlements are mainly located along rivers (Lockaby *et al.*, 2008), reconstructing the temporal evolution of their past (i) hydro-geomorphological characteristics, (ii) sediment dynamics, and (iii) water/sediment chemical composition is crucial. It not only allows understanding the human-induced impacts on their past and present functioning but also helps predicting their future evolution and building sustainable management and restoration strategies (Kondolf *et al.*, 2006; Desmet *et al.*,  
45 2012). Human impacts and human-made modifications on fluvial hydrosystems increased over the last two millennia and reached huge tipping points after the onset of the Industrial Revolution in many parts of Europe, with very frequent river regulation works (Allen, 2009; Waters *et al.*, 2014; Vauclin *et al.*, 2020b). In this framework, several studies focused on monitoring suspended loads (e.g., Garzanti *et al.*, 2011; Fan *et al.*, 2020; Dendievel *et al.*, 2022) to constrain the historical releases of pollutants  
50 and the human-induced impacts on hydrosystems. However, these sedimentary and/or hydrogeochemical surveys intrinsically are limited in time, starting in the second half of the 20<sup>th</sup> century at best.

Whilst the study of floodplain (including their side-channels) sediments recording periodic fluvial overbank deposition represents the best alternative for more ancient historical periods (Müller, 1977;  
55 Matys Grygar *et al.*, 2012), the ability to accurately and precisely date young fluvial deposits is a crucial limitation. This is all the more true since depositional dynamics, hence sediment archival capacity, strongly varies with the spatio-temporal evolution of hydrologic connectivity between the main channel and floodplains (Dhivert *et al.*, 2015; Vauclin *et al.*, 2020a). Importantly, there is no single protocol for efficient dating of recent (<100-200 yr) fluvial deposits to date. On the one hand, classical  
60 indirect approaches involve the study of historical maps (Preusser *et al.*, 2016; Hohensinner *et al.*, 2021) or historical hydrological data (Hobo *et al.*, 2010; Dhivert *et al.*, 2015; Toonen *et al.*, 2015), associated with the temporal evolution of both lateral hydrological connectivity and sediment characteristics (Eschbach *et al.*, 2018; Vauclin *et al.*, 2020b). On the other hand, both isotopic and palaeodosimetric dating methods can yield numerical ages assessing the timing of floodplain  
65 deposition over the last centuries (Rixhon, 2022). In this context, the former primarily are short-life radionuclides, encompassing <sup>137</sup>Cs, <sup>241</sup>Am and <sup>239+240</sup>Pu (Morereau, 2017; Foucher *et al.*, 2021; Klemt *et al.*, 2021), along with the method of lead excess (<sup>210</sup>Pb<sub>xs</sub>; e.g., Gobeil, 1999; Stam, 1999; Matys Grygar *et al.*, 2012; Sun *et al.*, 2019), and post-bomb radiocarbon (Ely *et al.*, 1992). Luminescence methods, originally developed to date late Pleistocene deposits (e.g., Cordier *et al.*, 2006), have been increasingly  
70 applied to young fluvial environments (e.g., Madsen *et al.*, 2005; Preusser *et al.*, 2011), including the Rhine River (Preusser *et al.*, 2016; Eschbach *et al.*, 2018). Furthermore, luminescence profiling methods based on *in situ* measurements of portable readers (e.g., Sanderson and Murphy, 2010) or sample

response to test doses in the lab, so-called IRSL screening (May *et al.*, 2018). While the former were developed to identify deposition breaks or erosional phases (e.g., Muñoz-Salinas *et al.*, 2011; Kinnaird *et al.*, 2017; May *et al.*, 2018; Robins *et al.*, 2021), the latter approach provides semi-quantitative age information (e.g., Schulze *et al.*, 2022). It should be noted that the different approaches mentioned above have rarely been combined, although their combination seems very promising for improving chronological reconstructions of recent floodplain environments (Rixhon, 2022).

In this study, we foster the potential of multi-method geochronological approaches for dating recent fluvial sediments (<100-200 yr) by combining (i) relative methods based on historical maps and historical hydrological record with (ii) numerical dating using short-life radionuclide methods ( $^{137}\text{Cs}$  and  $^{210}\text{Pb}_{\text{xs}}$ ) and (iii) a palaeodosimetric approach, in our case single-grain infra-red stimulated luminescence (IRSL). We also use high resolution sedimentary profile scanning using a portable Optically Stimulated Luminescence (OSL) reader and lab-based IRSL screening. This large array of methods was applied to young fine-grained floodplain deposits, for which grain-size, mineralogy and chemical composition are characterized. The study site at Rhinau is located in the Upper Rhine Plain (Fig. 1 and 2), where the hydro-geomorphological adjustments induced by regulation works during the last two centuries are well known (Maire and Sanchez-Perez, 1992; Chardon *et al.*, Submitted). This innovative methodological combination aims to both (i) better grasps the limitations of each individual method and the methodological advantage of combining them and (ii) robustly constrain the history of the Rhinau sedimentary deposits.

## 2. Study area

The study site is located on the Rhinau Island along the Upper Rhine Plain, ~30 km upstream of the city of Strasbourg (Fig. 1). The plain represents the inner part of a major graben structure running some 350 km from SSW to NNE, from the Jura Mountains to the Rhenish Massif (e.g., Rotstein *et al.*, 2006). Up to the beginning of the 19<sup>th</sup> century, the Upper Rhine exhibited a marked downstream channel pattern evolution, with (i) a braided, (ii) a braided/anastomosing (including the Rhinau island), (iii) an anastomosing/meandering and (iv) a meandering reach (Carbiener, 1969, 1983, Fig. 1b). The functionality of the hydrosystem was heavily altered by three phases of engineering works during the 19<sup>th</sup> and 20<sup>th</sup> centuries (Honsell, 1885; Lefoulon, 1959; Schneider, 1966; Lévy, 1982; Tricart and Bravard, 1991; Descombes and Robineau, 1996; Schmitt *et al.*, 2019). The correction (AD 1840-1870) primarily aimed to control floods and to enhance navigation and agriculture. It narrowed both the braided belt within two stabilized banks spaced by 200 to 250 m and the flooding area (from 5-7 km to 1-2 km) via the construction of two high-flow dikes (Tricart and Bravard, 1991; Bernhardt, 2000; Herget *et al.*, 2005). Significant thalweg shortening resulted in a widespread average incision of 1 to

2 m over the next 150 years, peaking around 7 m at Ottmarsheim in the upstream reach (Felkel, 1969). The Rhinau area differs from this trend with a slight aggradation of  $\sim 0.5$  m over the same timespan (Carbiener and Dillmann, 1992; Maire and Sanchez-Perez, 1992; Buck et al., 1993; Schmitt et al., 2016). The regularization (AD 1930- 1958) consisted in constructing alternate groyne fields in the main corrected channel to improve navigation (Schneider, 1966). The canalisation (AD 1928-1977) aimed to produce hydropower, develop navigation and limit floods. It mainly consisted in the construction of the so-called *Grand Canal d'Alsace* (GCA) which bypasses thanks to a diversion dam the corrected main channel, referred then to as the Old Rhine. While the GCA is continuous between Basel and Neuf-Brisach (50 km), its next downstream reach (to Strasbourg) is composed by four discontinuous sections forming artificial islands, including Rhinau. From Strasbourg to Iffezheim, the canalisation directly reworked the main corrected channel. The canalisation lead to massive functional impacts, including the disconnection of (i) numerous side channels and (ii)  $\sim 130$  km<sup>2</sup> of supplementary flooding areas (Dister et al., 1990; Schmitt et al., 2018). Finally, a large number of restoration actions such as the lowering of dikes to increase connectivity to the floodplain, have been undertaken since the 1980's (Carbiener and Schmitt, 2022; Schmitt et al., 2018).

Rhinau Island is surrounded by the GCA (constructed in AD 1963) to the West and by the by-passed Old Rhine to the East (Fig. 2a,b; Fig. 3). It is crossed by a side channel named Schaftheu, which increases the island flooding. The Old Rhine discharge is  $15 \text{ m}^3 \text{ s}^{-1}$  (instream flow) when the Rhine flow measured at Basel is below  $1,550 \text{ m}^3 \text{ s}^{-1}$ . Over this threshold, the excess discharge is spilled into the Old Rhine by the diversion dam (Fig. 4b). Three 3.5 m-high agricultural weirs were built across the Old Rhine in AD 1963 to prevent water table (surface water and groundwater) deepening linked to the discharge drop. Consequently, the discharge threshold to flood the whole island increased from  $2,000 \text{ m}^3 \text{ s}^{-1}$  to  $2,650 \text{ m}^3 \text{ s}^{-1}$  after AD 1963, thereby decreasing both flood frequency and duration ( $Q_{\text{md}}$ , mean daily discharge, Maire and Sanchez-Perez, 1992; Sánchez-Pérez, 1992; Chardon et al., Submitted). Floods are induced by three processes (Maire and Sanchez-Perez, 1992): (i) bank overflows of the Old Rhine and the Schaftheu, (ii) backwater effect upstream the third agricultural weir (Fig. 2a) between AD 1963 and 2005, affecting the median section of the Schaftheu on which the study site is located (fig. 2b), and (iii) floods due to groundwater elevation above the topographical surface. Locally around the study site, the backwater effect upstream the agricultural weir compensated the Old Rhine by-passing and dewatering so the canalisation did not reduce the flood regime. Different phases of restauration works were conducted onsite (Maire et al., 1999; Meyer et al., 2013), especially in AD 2005, with the Schaftheu upstream hydrological connection enhanced (Meyer et al., 2013) (max.  $Q = \sim 400 \text{ m}^3 \text{ s}^{-1}$ ), and interrupted the connection between the Old Rhine and the median section of the Schaftheu (except

during very high flows), dropping the backwater effect. Those restoration works probably did not  
140 change significantly local flood regime since the first action roughly compensated the second.

### 3. Materials and methods

#### 3.1. Field strategy: site selection and sediment sampling

Site selection to achieve the main goal of this study had two prerequisites: (i) fine-sediment deposition  
starting directly after the Rhine correction and (ii) regular flooding conditions undisturbed by major  
145 engineering works since then. Based on thorough analysis of both historical maps and LiDAR data, we  
thus selected the site on the Rhinau island close to the Schaftheu side channel (Fig. 2a). A 1.05 m-deep  
and 2 m-wide pit was dug under a forest cover (Fig. 2c) in July 2020. The stratigraphy of the fine-grained  
deposits was logged onsite. Twenty-one 3 cm-thick sediment samples were collected each 5 cm for  
grain-size, chemical and mineralogical analyses (Fig. 2c). Short half-life radionuclides were measured  
150 in ten out of these twenty-one samples, from the subsurface (i.e., 10 cm) to a depth of 55 cm. Two  
supplementary sets of twenty-one samples each were collected each 5 cm for two luminescence  
profiling techniques, i.e., portable OSL reader and IRSL screening (Fig. 2c). Three samples for single-  
grain IRSL dating (SG-IRSL) were collected at 76 cm, 90 cm and 105 cm depth, along with surrounding  
material for dose-rate measurement. To avoid sunlight exposure, all luminescence samples were  
155 collected in opaque tubes hammered in the freshly cleaned surface of the pit and sealed immediately.  
In March 2021, a supplementary core was collected one meter away from the pit to enhance the  
vertical resolution of sampling for short half-life radionuclides: 39 samples were collected each ~2 cm  
from the surface 80 cm depth. During the 8-month apart period between pit and core sampling, a flood  
occurred (~Q<sub>2</sub> at Basel) and generated new deposition onsite (Fig. 2,c).

#### 3.2. Planimetric and hydrological data

160 Already successfully applied to some sections of the Upper Rhine River (e.g., Diaz-Redondo *et al.*, 2016;  
Eschbach *et al.*, 2018) and its tributaries (e.g., Bruche River, Jautzy *et al.*, 2022), multi-secular  
planimetric study provides insights into lateral river dynamics and geomorphological impacts induced  
by engineering works. Our study is based on a set of ten successive historical co-registered maps, in  
165 low flow conditions, ranging from AD 1778 to 2012, which has been manually digitalised for AD 1778,  
1828, 1838, 1872, 1926 and 2012 (Fig. 3). A set of two historical aerial photographs from AD 1948 and  
1976 has also been used. Hydro-morphological units separation on each digitized map is based on the  
classification from Eschbach *et al.*, (2018) and Chardon *et al.* (2022b). The spatial reliability of the  
digitized former maps is guaranteed by an Root Mean Square Error (RMSE) around 20 m (Chardon *et*  
170 *al.*, 2022a), so it is possible to discuss changes and heterogeneities larger than 20 m. It allows for a

temporal comparison of different hydro-morphological units especially lateral evolution of the main braided belt along with the anastomosing and anabranching channels.

As no major water inflows exist between Basel, Rhinau and Rust (location in Fig. 1 and 2), flow data from Basel as well as the Rhine level in Rust are used to evaluate the evolution of these parameters on Rhinau island. Measured discharges at Basel, from AD 1830 to 2021 by the Federal Office for the Environment (FOEN, Fig. 4) as well as water-level variation between AD 1830 and 1991 at Rust (Fig. 4, from Maire and Sanchez-Perez, 1992) were combined to geomorphological data and data related to human infrastructures, to propose a reconstruction of the flooding history (Fig. 4).

### 3.3. Grain-size, mineralogical and geochemical analyses

After collection, sediment samples were dried at 40°C during 14 days, sieved at 2 mm and quartered with a Retsch Riffelteiler 6.5. The cumulative grain-size distribution was obtained by a Beckman Coulter laser diffraction particle size analyser. The characterization of the transport and deposition processes was based on the CM Diagram of Passega (1964, 1977), as already done on the Upper Rhine by Eschbach *et al.* (2018).

For mineralogy, bulk sediments were crushed with a Retsch agate disc mill and sieved to <125µm. Samples were mounted by lateral holder to avoid any preferred orientation of the particles. Then, analysis was conducted on a copper anticathode equipped Bruker D8 Advance instrument at 40kV and 25mA, at Institut Terre Environnement de Strasbourg (ITES) - Strasbourg - France. The angular scanning is 3-65°/2θ angular scanning every 0.014° over 0.4sec.

Analysis of major element concentrations were performed following the standard method used at ITES laboratory (e.g., Chabaux *et al.*, 2013; Rihs *et al.*, 2020) by inductively-coupled plasma atomic emission spectrometer (ICP-AES) after lithium tetraborate fusion. Samples were first crushed to <100µm and ignited in an oven successively at 110°C, 375°C (proxy of organic matter content, Heiri *et al.*, 2001) and 1000°C to evaluate sample wetness and loss on ignition (LOI). The analytical uncertainty on major element concentration was of 33 % for P<sub>2</sub>O<sub>5</sub>, <15 % for Na<sub>2</sub>O, K<sub>2</sub>O and <2 % for other major elements. Duplicates shows similar concentrations with a maximum relative difference 3 %. Measured concentration for the rock standards G-SN and BR are in good agreement with its recommended values, with less than 10 % relative difference.

### 3.4. <sup>210</sup>Pb and <sup>137</sup>Cs dating methods

Both sedimentary core and pit samples were analysed by gamma spectrometry. Dry samples were conditioned in 17- or 60-mL tightly closed plastic boxes for gamma counting using low-background and high-resolution Germanium Hyper pure detectors at the IRSN/LMRE laboratory in Orsay (Bouisset and



Calmet, 1997). The boxes were placed in vacuum sealed packages and stored during at least one month before measurement to ensure the secular equilibrium of the  $^{210}\text{Pb}$  necessary to determine the concentration of  $^{210}\text{Pb}_{xs}$  ( $^{210}\text{Pb}$  in excess). Efficiency calibrations were constructed using gamma-ray sources in a  $1.15 \text{ g cm}^{-3}$  density solid resin–water equivalent matrix. Activity results were corrected for true coincidence summing and self-absorption effects (Lefèvre *et al.*, 2003). Measured activities, expressed in  $\text{Bq kg}^{-1}$  dry weight are decay-corrected to the date of sampling. The activity uncertainty was estimated as the combination of calibration uncertainties, counting statistics summing and self-absorption correction uncertainties. A wide range of gamma emissions are detected with a germanium detector including  $^{137}\text{Cs}$ ,  $^{210}\text{Pb}$  and  $^{214}\text{Bi}$  used to determine  $^{210}\text{Pb}_{xs}$ . Those latter are widely used to date recent sediment deposits of the last hundred years because their half-life covers several decades: 30.08 years for the  $^{137}\text{Cs}$  and 22.20 years for the  $^{210}\text{Pb}$  (Goldberg, 1963).

#### 3.4.1. $^{210}\text{Pb}$ dating

Lead-210 ( $^{210}\text{Pb}$ ) is a daughter radionuclide of the  $^{238}\text{U}$  radioactive decay series produced by gaseous  $^{222}\text{Rn}$  decay. The  $^{210}\text{Pb}$  is produced in soils and sediments where it reaches a secular equilibrium with its parents (supported  $^{210}\text{Pb}$ ) and in the atmosphere from radioactive decay of gaseous  $^{222}\text{Rn}$  (unsupported  $^{210}\text{Pb}$  or  $^{210}\text{Pb}_{xs}$ ). The  $^{210}\text{Pb}_{xs}$  reaches soils through dry and wet deposition from the atmosphere and is currently used for dating lake sediments where inputs of  $^{210}\text{Pb}$  are continuous (Appleby, 2008; Foucher *et al.*, 2021). In such systems,  $^{210}\text{Pb}_{xs}$  generally exponentially decreases with depth reflecting the radioactive decay of the  $^{210}\text{Pb}_{xs}$  after deposition. For an evolution in closed system, the latter follows the classical radioactive decay law.

$$^{210}\text{Pb}_{xs} = ^{210}\text{Pb}_{0\ xs} e^{-\lambda t} \quad (1)$$

With  $^{210}\text{Pb}_{0\ xs}$  the initial  $^{210}\text{Pb}_{xs}$  at the time of deposit,  $\lambda$  the radioactive decay constant of  $^{210}\text{Pb}$  ( $0.0311 \text{ yr}^{-1}$ ) and  $t$  the age of the deposits (e.g., in years).

By considering that the  $^{210}\text{Pb}_{xs}$  flux is constant, the apparent sedimentary rate can be estimated from the linear regression of the neperian logarithm  $\ln(^{210}\text{Pb}_{xs})$  versus depth (Goldberg, 1963).

$$^{210}\text{Pb}_{xs} = ^{210}\text{Pb}_{0\ xs} e^{-\lambda t} \quad (2)$$

For a constant sedimentation rate,  $v$ , equation (1) can be expressed as:

$$\ln(^{210}\text{Pb}_{xs}) = \ln(^{210}\text{Pb}_{0\ xs}) - \left(\lambda \frac{x}{v}\right) \quad (3)$$

with  $x$  the sediment depth relative to the surface (e.g. cm) and  $v = \left(\frac{x}{t}\right)$  the sedimentation rate (e.g.,  $\text{cm yr}^{-1}$ ). In a system where the initial  $^{210}\text{Pb}_{xs}$  is constant over time, equation 2 shows that depth variation of  $^{210}\text{Pb}_{xs}$  in the sediment column provides the sedimentation rate  $v$ .

### 3.4.2. $^{137}\text{Cs}$ dating

235  $^{137}\text{Cs}$  is an anthropogenic radionuclide with a half-life of 30.2 years initially injected into the atmosphere after nuclear tests and then incorporated into soils or sediments as a result of atmospheric fallout. In western Europe two well-constrained chronological-benchmarks can be identified and used to date sedimentary records: (1) the maximum atmospheric nuclear tests in AD 1963 (Ritchie and McHenry, 1990) with worldwide fallouts and (2) the AD 1986 Chernobyl nuclear accident fallouts  
240 which, unlike those of Fukushima AD 2011 (Klemt *et al.*, 2021), were generalised in Europe (Walling and He, 1997). The  $^{137}\text{Cs}$  dating principle consists in identifying  $^{137}\text{Cs}$  enrichment in the sediment/soil column and correlating them to specific enrichment events to infer deposition ages. As  $^{137}\text{Cs}$  is not prone to be affected by chemical leaching or bioturbation processes (Owens *et al.*, 1996; Schimmack *et al.*, 1997; Jagercikova *et al.*, 2015), it is assumed to remain in place after deposition. The upper Rhine  
245 river has been nuclearized and affected by regular releases of  $^{137}\text{Cs}$  since the late 1960's, thereby superimposing this signal onto the atmospheric signals of AD 1963 and 1986. Here, we compare first the variations in  $^{137}\text{Cs}$  content measured along the depth profiles (pit and core) with the known-values of the AD 1963 atmospheric fallout in the region (Renaud and Pourcelot, 2015; Meusburger *et al.*, 2020). Comparison with the AD 1986 Chernobyl fallout as well as nuclear powerplant (NPP) releases  
250 that happened in the same period was achieved using (1) the  $^{137}\text{Cs}$  values of sediment samples collected between AD 1985 and 2020 by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) along the Rhine floodplain around the Fessenheim NPP (Fig.1b) and (2)  $^{137}\text{Cs}$  releases from Swiss NPPs (Klemt *et al.*, 2021).

### 3.5. Luminescence methods

255 Luminescence dating measures a latent signal that accumulates in sediment mineral grains with time, induced by the energy of ionising radiation emitted from radioactive decay (e.g., Rhodes, 2011). When exposed to light or heat stimulation, the latent signal is removed while emitting a light signal (luminescence). The strength of this signal is proportional to the amount of energy absorbed since the last resetting event and is known as the equivalent dose ( $D_e$ ), which would have been required to  
260 produce such a signal (in Gray =  $\text{J kg}^{-1}$ ). The process of signal release is called bleaching of the signal and can be incomplete when the sediment grains are not exposed long enough to a light stimulation. After burial, ionising radiation induced by cosmogenic radiation and the radioactive decay of K, Th, and U (Rhodes, 2015) is interacting with the mineral grains at a constant energy level, known as dose rate ( $D$ , Gray per year).  $D_e$  is hence directly dependent on the dose rate ( $D$ ) and the burial time.

265 Sediment dating is done measuring the  $D_e$  in quartz (Optically Stimulated Luminescence, OSL) or feldspar (Infra-Red Stimulated Luminescence, IRSL). However, Preusser *et al.* (2016) have shown for recent sediments (200 year or less) of the Upper Rhine that the OSL signal from quartz is too dim for

proper measurement and that IRSL dating must be used. These authors also demonstrated the need to use single-grains to deal with the problem of partial bleaching and this approach is hence used in the present study.

### 3.5.1. Single-grain IRSL Luminescence dating

The approach used here is thoroughly described in Preusser *et al.* (2016). Sample preparation was done under red-light conditions to avoid bleaching of the IRSL signal. Samples were first sieved at 150-200  $\mu\text{m}$  followed by usual chemical treatments (HCl,  $\text{H}_2\text{O}_2$ , Na-oxalate) to dissolve carbonate and break down aggregates in samples. The feldspar fraction was then isolated by density separation of the fraction  $< 2.58 \text{ g cm}^{-3}$ . Samples were measured using special single-grain discs with a grid of 10x10 holes, which were filled under a binocular.

For each sample, the  $D_e$  measurement, following the SAR protocol (Murray and Wintle, 2000), was performed on a Risø DA-20 (detection through 4 mm Schott BG39 and 2.1 mm Corning 7-59 glass filter), with a preheat at 150 °C for 10 s (ramp  $2^\circ\text{s}^{-1}$ ) and stimulation for 5s using a 140mW 830 nm laser (90 % laser power) with a RG-780 filter to attenuate the second harmonic frequency (415 nm). The first 0.2s and the last 0.5s of the IR50 signal were used for  $D_e$  determination and background subtraction and the results were analysed using Analyst 4.57 (Duller, 2018) and further processed in home-made Excel sheets. For  $D_e$  determination, only grains respecting the following criteria were selected: a signal  $>3\sigma$  above background, a test dose error  $<15\%$ , a recuperation  $<10\%$ , and a recycling ratio between 0.90 and 1.10 (considering uncertainties). Between 20.8 and 26.4 % of all measured grains passed the above rejection criteria and were used for  $D_e$  calculation.

For each sediment sample, a mean  $D_e$  value was calculated using both the Central Age Model (CAM) and the Minimum Age Model (MAM-3; Galbraith *et al.*, 1999). MAM-3 calculations were carried out using the R-Luminescence package (Kreutzer *et al.*, 2012; Fuchs *et al.*, 2015) applying a sigma b value of 0.20, following Preusser *et al.*, (2016). For the correction of anomalous fading (Wintle, 1973; Huntley and Lamothe, 2001), g-values were determined by storage test according to Auclair *et al.* (2003) using 2 mm multigrain discs.

The concentration of dose-rate ( $D$ ) relevant elements (K, Th, U) was determined by high-resolution gamma spectrometry on the sediment surrounding 30 cm of the  $D_e$  samples, similar to the procedures described by Preusser and Kasper (2001). No evidence for radioactive disequilibrium in the Uranium decay chain was observed using the approach of Preusser and Degering (2007).

Age calculation was carried out using ADELE 2017 software (Degering and Degering, 2020), with present day geographic position and burial depth for cosmic dose rate calculation. An a-value of  $0.07 \pm 0.02$  and an internal K-content of  $12.5 \pm 1.0\%$  were used, following values reported for northern

Switzerland (Gaar *et al.*, 2014). Sediment moisture was estimated at  $25 \pm 5$  % for the 76 cm and 90 cm samples and  $30 \pm 5$  % for the 105 cm sample, based on sediment composition (Fig. 5) and hydrological context (§4.3).

### 3.5.2. Luminescence profiling: portable reader and IRSL screening

305 Samples for both methods were collected in opaque tubes in the field and under red-light conditions with removal of the outer material possibly bleached during sampling. The portable luminescence reader uses measures both IRSL and OSL net intensities from bulk samples. All samples were heated 72 hours at 60°C, manually crushed and subdivided into two aliquots to test for reproducibility. In laboratory conditions (University of Strasbourg, France), samples were successively stimulated at 880  
310  $\pm 40$  (IR) and  $470 \pm 20$  nm (post IR-BSL) following Sanderson and Murphy's (2010) measurement protocol. The R package developed by Kreutzer *et al.* (2012) was used for post-treatment. For each aliquot the mean value of the total photon counts for the first 10 s of IRSL and post IR-OSL stimulation (minus the background value) is used.

IRSL screening measures first the natural luminescence signal emitted during IR stimulation ( $L_n$ ) and  
315 compares it to the sample response to a second stimulation after application of a fixed laboratory dose ( $T_n$ ). Variations of the calculated  $L_n/T_n$  ratio approximates  $D_e$  as long as the signal is in the quasi-linear growing part (May *et al.*, 2018). Samples were treated first by  $H_2O_2$  to remove organic matter content and then dried one week at 50°C. After crushing, for each sample three aliquots were prepared on steel discs and measured in a Lexsyg Smart device (Richter *et al.*, 2015) at the University of Freiburg  
320 (Germany). For each aliquot the two first cycles of the SAR protocol were conducted for  $L_n/T_n$  ratio determination. The measurement includes a preheating at 250°C for 60 s, followed by IR stimulation (850 nm) at 50°C for 60 s. For the second cycle, a given test dose of ca. 22 Gy was applied with a  $^{90}Sr$  source of  $0.11 \text{ Gy s}^{-1}$ . The ratio  $L_n/T_n$  was determined using the initial 20 s of stimulation with subtraction of the last 20 s as background of the measured IRSL signal.

## 325 4. Results

### 4.1. Geomorphological dynamics based on planimetric data

Between AD 1778 and 1828 (Fig. 3a,b), before the Rhine correction, no significant human impact affected the complex channel pattern composed by different braided belts, divided by vegetated islands, along with anabranching and anastomosing channels. The study site is located in the western  
330 braided belt in AD 1778, while it is located ~300m western the braided belt in AD 1828, in the forested floodplain crossed by anastomosing and anabranching channels. As flow energy was decreasing with the distance to the braided areas, moderate-energy conditions for the study site can be proposed for

AD 1838. The Rhine correction works started locally (Fig. 3c) in AD 1838 notably, with the erection of a 1 km-long transverse dike whose western extremity is located ~400 m north-eastern the study site. Old maps indicates that during the period AD 1838-1855 (Fig.3c,d,e) the thalweg migrated westward and reached the sampling site between AD 1852 and 1855 (Fig. 3d,e). Such a migration may have resulted in the erosion of the previous fine-grained sediments (and forest). In AD 1855, the study site was located ~100 m eastern the thalweg, into the braided belt, which implies high-energy conditions with mostly coarse channel bottom sediments (gravel). During the period AD 1852-1855, the downstream thalweg curvature migration was blocked by the transverse dike, which was extended towards the west (~200 m north the study site). The artificial banks of the corrected main Rhine bed were fixed between AD 1855 and 1863 (Fig. 3e,f). The study site was in floodable conditions in AD 1863 due to the presence of local openings on the left dike of the corrected main bed, as wells as a ~1 km-long opening upstream the study site. The high-flow dike was built at around 1 km western the corrected main bed, from AD 1838 to 1863. This hydraulic configuration led to floodplain low-energy conditions, with dynamic fine sediment deposition. This also explains an important side channel narrowing, especially from AD 1855 to 1872 (Fig. 3e,f,g,h). The correction works were finished around AD 1869 (Fig. 3g), but a second high-flow dike was built from AD 1872 to 1926 (Fig. 3h,i), ~150 m western the study site. This reduced the width of the flooding area to 500 m, but probably did not modify flow energy conditions and sedimentation dynamics. The study site gradually turned, from AD 1872 to 1948 (Fig. 3h,i,j), into a forest environment associated to a decrease of the number of anastomosing channels. The AD 1948 photograph shows a moderate morphodynamic activity of the Schaftheu side channel (e.g., high variability of the channel width, flood channels close to the Schaftheu, small vegetated bars), confirming the occurrence of floods. The canalisation works induced huge planimetric changes (Fig. 3k,l), with the construction of the GCA (AD 1963) whose total width is 260 m. This explains why the upstream section of the Schaftheu was relocated eastern.

#### 4.2. Limnimetric and hydrological evolution

The limnimetric monitoring at Rhinau shows (Fig. 4a) a mostly stable mean water level between AD 1830 and 1875, with a small lowering of about 0.25 m from 1850 to 1875. A gradual rise of about 0.5 m occurred from AD 1875 to 1930, resulting from the Rhine correction (AD 1840-1870), especially local bed aggradation due to upstream incision. The mean level remained stable until AD 1950 (nodata during AD 1938-1945). From AD 1950 to AD 1967, the mean water level decreased by 0.5 m, as a consequence of the regularization works (AD 1930-1958) and probably also of the canalisation works at Rhinau (AD 1961-1963) and Gerstheim (AD 1965-1967). Then, it abruptly raised by about 3 m in AD 1967-1968 with the backwater effect upstream the Gerstheim dam (AD 1967), which also decreased the water level fluctuation amplitude from 3 to 1-2 m.

Over the last 200 years, several intense floods ( $> Q_{10}$ ) occurred, in AD 1852, 1876, 1881, 1882, 1910, 1999 and 2007 (Fig. 4b,c). Only three occurred since the beginning of the 20<sup>th</sup> century, but several less intense were quite relatively long (Fig. 4c). Three floods exceeding  $Q_{100}$  occurred during the 19<sup>th</sup> century, while only one occurred thereafter. The mean yearly duration of widespread flooding of the island decreased from 11 to 2 d yr<sup>-1</sup> with the canalisation (Table 1). Nevertheless, as, at the local scale of the study site the flood threshold of 2,000 m<sup>3</sup> s<sup>-1</sup> remained roughly stable, the yearly flooding duration did not change significantly by the canalisation and certainly even increased slightly (from 11 to 14 d yr<sup>-1</sup>, Table 1) due to the higher flood occurrence after the canalization than before (Fig. 4b,c).

#### 4.3. Sedimentological, mineralogical and chemical results

In the field, macroscopic description of the sedimentary trench (e.g., colour, structure, dominant grain-size, macro-rests, roots) allowed identifying six stratigraphic units (SU; Fig. 5a) with a first gravel unit associated to sand (unit 1) below 105 cm. Unit 2 (105-92 cm), is composed by light brown-grey clayey silt (15.1 % and 70.0 % respectively). Unit 3 (92-80 cm) is brown-grey in colour and mostly composed of sand (75.7 %), with a unique mode at 213  $\mu$ m, and secondly by silt (19.8 %) (Fig. 6a). During sampling, this unit contained the groundwater table. Unit 4 (80-43 cm) is of brown-ochre-grey colour, and reflects clayey silt (18.5 % and 65.7 % respectively). It contains oxidation marks. Unit 5, is of brown-grey colour and composed of silt (71.1 %) and clay (22.4 %). The structure shows no aggregates below 33 cm, whereas some aggregates are visible above, and contains organic matter and fine roots. The dark grey-brown unit 6 is composed of clayey silt (21.3 and 72.8 % respectively) and shows many aggregates and roots.

The Passega diagram indicates that the two sandy samples of unit 3 are included in the RQ segment, indicating a graded suspension, and therefore a relatively high-energy environment (Fig. 6.b). It probably corresponds to extreme flood events after the beginning of the correction works such as the  $Q_{\geq 300}$  floods of 1876 with a  $Q_{md,max} = 5,530 \text{ m}^3 \text{ s}^{-1}$  and/or the floods of 1881 ( $Q_{md,max} = 4,764 \text{ m}^3 \text{ s}^{-1}$ ,  $\sim Q_{200}$ ) and 1882 ( $Q_{md,max} = 4,371 \text{ m}^3 \text{ s}^{-1}$ ,  $\sim Q_{70}$ ) (Fig. 4b). All other samples fall into the SR segment, corresponding to a uniform suspension and a low energy environment. The grain-size distributions show multiple modes, revealing a poor sediment sorting, which is common for floodplain decantation deposits. The 90 cm sample corresponds to an intermediate situation linked to a sampling bias, as it combines sediments of both units 2 and 3.

Mineralogical composition is relatively homogenous along the sedimentary column with mean composition of 32 % quartz, 31 % calcite, 18 % dolomite, 7 % albite, 3 % orthoclase, 3 % clinoclere ferroan, 3 % muscovite, 2 % montmorillonite, 1 % kaolinite and less than 1% riebeckite. The unique

exception is the sandy unit (SU3), for which the quartz content is twice as high (~57 %), while the calcite and dolomite content is twice as low (~15 % and ~10 %, respectively).

Geochemical composition and LOI<sub>375°C</sub> show important variations for the sandy unit, with the highest SiO<sub>2</sub> (46 to 68 %) and Na<sub>2</sub>O (0.7 to 1.2 %) concentrations, while Al<sub>2</sub>O<sub>3</sub>, CaO, Fe<sub>2</sub>O<sub>3</sub>, MgO, TiO<sub>2</sub>, MnO, P<sub>2</sub>O<sub>5</sub> and LOI<sub>375°C</sub> are lower, except for K<sub>2</sub>O. No variation from 82 cm to 52/42 cm is visible, while secondary variations exist above (Fig. 5d). This concerns Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, MgO, Fe<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub> and MnO, which increase between 42 and 22 cm, followed by a progressive decrease to the top. CaO, on the other hand, decreases from 16 % to 13 % between 47 and 27 cm, before increasing towards the top (15 %). Na<sub>2</sub>O is stable from 82 cm to the top. From 52 cm to the top, SiO<sub>2</sub> decreases slightly and regularly (from 49 to 42 %) while P<sub>2</sub>O<sub>5</sub> and LOI<sub>375°C</sub> increases regularly (from 0.12 to 0.19 % and from 3 to 10 % respectively).

#### 4.4. Short-life radionuclides

##### 4.4.1. <sup>137</sup>Cs results

The figure 7a shows very similar variations with depth for both data sets. In the core the <sup>137</sup>Cs concentrations have <2 Bq kg<sup>-1</sup> values from the deepest sample up to ~39 cm underlying pre-bomb test ages. Above and up to 21 cm, <sup>137</sup>Cs increase to ~91 Bq kg<sup>-1</sup> before decreasing from 21 cm to the top where <sup>137</sup>Cs concentrations are at ~10 Bq kg<sup>-1</sup>. This value is similar to <sup>137</sup>Cs concentrations measured in current Rhine sediments deposited in the Fessenheim area (~9 Bq kg<sup>-1</sup>, Fig. 8). For the pit samples similar variations are observed, with a shift of ~5 cm, in comparison to the core, in the maximum <sup>137</sup>Cs concentration levels.

Core and pit data, taken less than 1 m away, show a global strong similarity, but differences with notably the 5 cm gap of the <sup>137</sup>Cs peak as well as a deposit thickness difference (101.5 cm on the core versus 105 cm on the pit) and the sandy level depth difference (73-80 cm on the core versus 80-92 cm on the pit). It is probably linked to historical higher irregular surface micro-topography than today, as well as a probable high variability of sand deposition. To compare the results of the pit (portable luminescence reader, IRSL screening, IRSL SG dating, grain-size, chemistry) and the core (<sup>210</sup>Pb<sub>xs</sub>, <sup>137</sup>Cs), an adjustment based on identified benchmarks (sampling dates, <sup>137</sup>Cs peaks and sandy level) has been done (Fig. 8a).

In the Upper Rhine area, atmospheric fallout from the AD 1986 Chernobyl NPP accident was significant and typically results in a peak concentration of <sup>137</sup>Cs in sedimentary records or soil profiles of these regions (Meusburger *et al.*, 2020). Monitoring of radionuclide concentrations in Rhine sediments by the French radio-protection service (IRSN) shows in particular a decrease in <sup>137</sup>Cs activity (decay corrected) since AD 1987. If the <sup>137</sup>Cs concentration peak in Rhinau pit and core is attributed to

atmospheric fallout from the Chernobyl accident our results would indicate an average sedimentation rate of  $0.6 \pm 0.3 \text{ cm yr}^{-1}$  for the upper 21 cm of the core and of  $0.76 \pm 0.04 \text{ cm yr}^{-1}$  for the first 26.5 centimeters of the pit (Table 2).

#### 435 4.4.2. $^{210}\text{Pb}_{\text{xs}}$

The plot of the  $^{210}\text{Pb}_{\text{xs}}$  values from the pit and the core with depth shows a good consistency between the two data sets with a linear decrease with depth (Fig.7b and Fig. 9). Interpreting that variation with the classical scheme of a closed system evolution with a same initial  $^{210}\text{Pb}_{\text{xs}}$  for all the sediments at the time of their deposition (equation 2) leads to a mostly constant sedimentation rate  $\epsilon$  of 0.27-0.82  
440  $\text{cm yr}^{-1}$  with a mean value of  $0.41 \text{ cm yr}^{-1}$  for the top 35 cm, on the core. With these sedimentation rates, the 35 cm depth sediments were deposited in AD 1894-1979.

### 4.5. Luminescence results

#### 4.5.1. IRSL Single-Grain D and $D_e$ values

IRSL dating on feldspar single-grain was applied on three samples collected at 76 cm, 90 cm and 105 cm  
445 depth respectively. The  $D_e$  values of the individual feldspar of each sample are represented on Fig. 10a,b. The  $D_e$  scattering is, however, quite large with a more or less clear shift towards high  $D_e$  values (positive skewness). Such a shift is commonly interpreted as reflecting an incomplete resetting of some feldspar grains before their deposition, i.e. a partial bleaching of the feldspars (Murray *et al.*, 1995; Fuchs and Lang, 2001). In such a context it is recommended to calculate the age of a sample by  
450 using not the  $D_e$  mean value of the feldspar population but a minimum  $D_e$  value representative of the feldspar grains without bleaching effect. These two  $D_e$  values ( $D_{e,\text{CAM}}$  and  $D_{e,\text{MAM}}$ ) are calculated by the CAM and MAM, respectively. The respective values are shown in Fig. 10a,b and the two resulting ages for each sample are given in Table 3. Determination of these ages requires the calculation of the dose rate  $D$  for each sample. The two sediment samples of 76 cm and 90 cm similar D values of  $2.67 \pm 0.12$   
455 and  $2.41 \pm 0.16 \text{ Gy ka}^{-1}$ , respectively, while the deeper sample has a much lower value of  $1.62 \pm 0.17 \text{ Gy ka}^{-1}$  (Table 3).

#### 4.5.2. Luminescence profiling

The results of IRSL screening and the  $L_x/T_x$  signal versus depth is plotted in Figure 7c. Variations of the  $L_x/T_x$  ratio measured for each aliquot range between 0.17 and 0.85, while mean inter-aliquot  $L_x/T_x$  ratio  
460 ranges between 0.23 and 0.67. Inter-aliquots variations are small, except for 40 and 30 cm with one aliquot plotting apart from the two others. The  $L_x/T_x$  ratios in the lower half of the section (from 105 to 50 cm) increases from 0.31 to 0.62 except in the sandy layer (80-92 cm; SU3; Fig. 5a) where they are at the lowest ( $\sim 0.23$ ). They remain stable around 0.6 from 50 cm to 20 cm and decrease to 0.43 at the top.



465 Both IRSL and post-IR BSL profiles measured by the portable reader (in **Figure 7d**) display identical  
variation trends with depth which are therefore described in the following only for the post IR-BSL  
total photon counts marked by a lower standard deviation. After increasing between 95 and 90 cm to  
reach 54,400 photon count at 90 cm, the post IR-BSL signal decrease between 90 and 80 cm. Then it  
remains globally stable at ~14,200 photon count between 80 and 65 cm. From 65 to 45 cm, the signal  
470 increases and varies significantly with two peaks of ~35,000 and 49,000 photons count at 60 and 50 cm,  
respectively. These peaks, as well as the 80 cm peak, correspond to high inter-aliquots variability unlike  
other samples for which aliquots have similar results. From 45 cm to the top, the post IR-BSL signal  
steadily decreases from 23,400 to 10,400 photon counts. For the interpretation, it should be noted  
that signal build-up depends on (i) the burial duration of the sediment, (ii) the dose rate, (iii) the  
475 inherited dose at time of burial, (iv) the mineral composition and (v) the luminescence sensitivity of  
the minerals (Sanderson and Murphy, 2010; Brill *et al.*, 2016).

## 5- Discussion

Using floodplain sedimentary deposits as environmental archive requires their accurate and reliable  
dating and this can only be reached by combining complementary geochronological approaches (Hobo  
480 *et al.*, 2010; Rixhon, 2022). Against this background, this study stands out because of its innovative  
combination of different geomorphological and geochronological approaches. Analysis of historical  
maps and aerial photographs associated with the long-term hydrological chronicles of the Rhine and  
the successive engineering works, allowed us to propose a first chronologic framework for the  
temporal trajectory of the studied sedimentary deposits.

### 485 5-1 Sedimentological evolution linked to engineering works

Historical maps (**Fig. 3**) show that the thalweg, associated with high-energy flow conditions, migrated  
from east to west and flew over the study site between AD 1852 and 1855. We can assume that the  
uppermost gravel unit (SU1, **Fig.5 a**) reached at a depth of 105 cm in the pit was deposited during this  
short timespan (AD 1852/1855). Atop the gravel unit, the sharp grain-size boundary characterised by  
490 the absence of any transitional sandy deposits (i.e. gravels overlain by silts) points to a sudden energy  
drop in flow conditions and thereby well matches the first engineering works, i.e. between AD 1855-  
1863. Since most of the flow was concentrated into a new bed during the Rhine correction, we can  
assume fine deposition during this timespan at our sampling sites matching the 10 cm-thick silty unit  
(SU2, **Fig.5a**). The 10 cm-thick sandy unit deposited atop (SU3, **Fig.5a**) bears witness of higher flow  
495 conditions as attested by the Passega diagram (**Fig.6b**) which could be correlated with flooding as the  
corrected riverbed would have been stabilized at this period. Two major flood events at AD 1876 and

1881-1882 (fig.4b,c) are concerned in the first place since no other major flood event happened until AD 1910.

This temporal framework, summarized on Figure 11, was completed by using independent geochronological approaches. We discuss hereafter the limits of these numerical approaches before showing the interest of combining them with the hydro-geomorphological data to constrain the history of the Rhinau sedimentary deposits.

### 5-2 $^{137}\text{Cs}$ dating in a nuclearized river

Dating sedimentary deposits by the artificial  $^{137}\text{Cs}$  radionuclide method, emitted after AD 1950/55 is generally based on the identification of well-known  $^{137}\text{Cs}$  concentration maxima in sediments associated to the atmospheric nuclear weapons testing maximum (1963) and the Chernobyl nuclear accident (1986) in Europe. Because of NPPs installed along the Rhine upstream of our study area,  $^{137}\text{Cs}$  in the sediment can also be impacted by authorized  $^{137}\text{Cs}$  liquid releases into the river. This may complicate the  $^{137}\text{Cs}$  signal in sediments as illustrated by Eyrolle *et al.*, (2019) for the Loire River where the NPPs implanted since AD 1957 lead to increasing  $^{137}\text{Cs}$  concentrations in the sediments before the AD 1986 Chernobyl peak. For the Aare and Rhine rivers upstream our study site, Klemm *et al.* (2021) observed five and six  $^{137}\text{Cs}$  maxima in different sediment cores: two attributed to the classical  $^{137}\text{Cs}$  signals from the AD 1963 and 1986 fallouts, others attributed to known  $^{137}\text{Cs}$  releases from upstream NPPs.

By contrast, the vertical distribution of  $^{137}\text{Cs}$  in the Rhinau's core shows only one maximum at a depth of 21 cm (Fig.8a). As top-core-sediments have similar  $^{137}\text{Cs}$  values (10 Bq kg<sup>-1</sup>, Fig.8a) to those of the Rhine sediments measured in AD 2020 by IRSN (Fig. 8b), it can be assumed that the  $^{137}\text{Cs}$  fixed by the river sediments is directly transferred to the floodplain deposit through sedimentation processes. In the core and the pit, both the absence of bioturbation and the constant clay content - which fixes  $^{137}\text{Cs}$  - further suggests that no secondary  $^{137}\text{Cs}$  vertical redistribution occurred after deposition. This implicitly validates the classical interpretation that  $^{137}\text{Cs}$  variations in the sediment column represent  $^{137}\text{Cs}$  concentration variation at its deposition time on the sediment surface (Leenaers, 1991; Łokas *et al.*, 2010; Buchty-Lemke *et al.*, 2019; Poręba *et al.*, 2019). However, this does not explain why only one  $^{137}\text{Cs}$  maximum is observed and does not allow age correlation (Table 2).

The onset of  $^{137}\text{Cs}$  is usually attributed to the beginning of atmospheric nuclear weapons testing (i.e. AD 1950-55; Meybeck *et al.*, 2007; Foucher *et al.*, 2021). The  $^{137}\text{Cs}$  concentration in sediments is relatively constant at the bottom of the core (from 80 to 40 cm) with values between 0.18 and 1.8 Bq kg<sup>-1</sup> close to the detection limits (Fig.8a).  $^{137}\text{Cs}$  increases from 39 cm and reach a 21 cm maximum which can be correlated to the Chernobyl event based on its  $^{137}\text{Cs}$  activity (~90 Bq kg<sup>-1</sup>) which is close

530 to the  $^{137}\text{Cs}$  activity measured for the Chernobyl peak ([70-80]  $\text{Bq kg}^{-1}$ ) in the Rhine and Aare rivers by Klemt *et al.* (2021). Such an assumption implies an average sedimentation rate of 0.57-0.63  $\text{cm yr}^{-1}$  from 0 to 21 cm and hence dates to AD 1953-1959 the beginning of  $^{137}\text{Cs}$  concentrations increase at 39 cm depth in the core. This is consistent with the beginning of atmospheric  $^{137}\text{Cs}$  fallouts in AD 1950-55, that implicitly supports the interpretation linking the maximum  $^{137}\text{Cs}$  concentration at the Rhinau site to the Chernobyl peak. This age model is also reinforced by the consistency between (i) the mean sedimentation rates deduced from  $^{137}\text{Cs}$  (0.57-0.63  $\text{cm yr}^{-1}$  for 0-21 cm) and  $^{210}\text{Pb}_{\text{xs}}$  ( $\in$  0.27-0.82  $\text{cm yr}^{-1}$ ) and (ii) the expected  $^{137}\text{Cs}$  value for the sediment deposited in AD 1963 and the effective  $^{137}\text{Cs}$  value measured at Rhinau. Indeed, with a mean sedimentation rate of 0.6  $\text{cm yr}^{-1}$  for the core, the AD 1963 level would correspond to 33.5-36 cm in the core, for which the  $^{137}\text{Cs}$  concentration is 13  $\text{Bq kg}^{-1}$ .  
540 According to Renaud and Pourcelot (2015) and Meusburger *et al.* (2020), the atmospheric deposition of  $^{137}\text{Cs}$  in AD 1963 reached an intensity of  $\sim 3,000 \text{ Bq m}^{-2}$ , and  $\sim 1,200$  to  $1,800 \text{ Bq kg}^{-1}$ , respectively. Taking the higher value, and given our measurements were performed on a 2 to 5 cm-thick slice, whose density is 1.5-2.5  $\text{g cm}^{-3}$  (measured onsite for some samples), deposition in AD 1963 would be [20-100]  $\text{Bq kg}^{-1}$  and thus  $\sim [5-25] \text{ Bq kg}^{-1}$  measured in AD 2021.

545 This points altogether to the interpretation that the  $^{137}\text{Cs}$  peak in the Rhinau core represents the  $^{137}\text{Cs}$  deposition related to the Chernobyl accident in AD 1986. The absence of a clearly identified AD 1963  $^{137}\text{Cs}$  peak may be explained by the combination of three factors: (i) the sample thickness (2 cm on average but 2.5 and 3.5 cm for the depths corresponding to AD 1963), (ii) the relatively low sedimentation rate (0.6  $\text{cm yr}^{-1}$ ) and (iii) the occurrence of  $^{137}\text{Cs}$  releases into the Rhine river from NPPs upstream Rhinau, i.e., Fessenheim in France (started in AD 1978) and Swiss NPPs (starting in AD 1969; Klemt *et al.*, 2021). Klemt *et al.* (2021) show significant  $^{137}\text{Cs}$  releases into the Rhine as early as AD 1969-70. With an average sedimentation rate of 0.6  $\text{cm yr}^{-1}$  and assimilating the  $^{137}\text{Cs}$  peak to the Chernobyl accident, the sample corresponding to the AD 1963 level actually covers the period AD 1960-1965 and the sample just above the period AD 1965-1970. The  $^{137}\text{Cs}$  peak therefore includes a significant contribution of  $^{137}\text{Cs}$  released by Swiss NPPs, which explains its high  $^{137}\text{Cs}$  activity and makes it impossible to identify the AD 1963 peak in the Rhinau sedimentary deposits. Identification of the latter would require a thinner sampling thickness than that we used - at least at this depth range. The identification of peaks for the AD 1963 nuclear fallout in the sediment profiles of the Swiss sites studied by Klemt *et al.*, (2021) was also facilitated by higher sedimentation rates (always  $> 1 \text{ cm yr}^{-1}$ ) and higher resolution sampling.  
560

The Rhinau example illustrates well that care must be taken when using  $^{137}\text{Cs}$  for dating, and associated with  $^{210}\text{Pb}_{\text{xs}}$  to infer sedimentation rates, in the case of nuclearized rivers like the Rhine with relatively low sedimentation rates. Using  $^{137}\text{Cs}$  NPP release chronicles and/or data of  $^{137}\text{Cs}$  monitoring in river

sediments is important to interpret the vertical  $^{137}\text{Cs}$  variation of sedimentary archives. An alternative solution would consist in using independent tracers specific to nuclear activities, as Am-Pu, to provide complementary chronologic benchmarks (e.g., Morereau, 2017; Foucher *et al.*, 2021; Klemt *et al.*, 2021). This is, however, beyond the scope of our study.

For the top of the deposit, age-depth model (Fig.11) is precise and well-framed by  $^{137}\text{Cs}$  which allowed calculation of two similar sedimentation rates of  $\sim 0.6 \pm 0.3 \text{ cm yr}^{-1}$ . Those sedimentation rates are consistent with the  $^{210}\text{Pb}_{\text{xs}}$  one which is much less precise because of great uncertainties (grey dotted lines, Fig.11).

### 5-3 IRSL single-grain dating

The fading corrected MAM single grain ages for the two upper samples of  $179 \pm 13 \text{ yr}$  (AD 1828-1854) and  $163 \pm 11 \text{ yr}$  (AD 1846-1868) overlap within uncertainties and fall into the mid of the 19<sup>th</sup> century (mean estimate AD 1840-1860). This is some 30 years older (ca. 15%) than the estimate deduced from historical and hydrological data. There are different reasons that may explain a slight apparent overestimation of the SG-IRSL ages such as a presence of either small residual IRSL in the grains at the time of deposition or a minimal thermal transfer (0.04 Gy would account for the apparent offset but will be difficult to measure). Dosimetric issues related to, for example, the assumed average water content during sediment burial could also be responsible for the offset. Nevertheless, while this highlights the limitations to date very young sediment, we regard the overall age assignment as satisfying.

More pronounced is the offset between the expected basal age of the sequence, which according to historical maps should date around AD 1860. The SG-IRSL age of  $243 \pm 27 \text{ yr}$  (AD 1750-1804) is significantly overestimating this estimate. However, it is striking that this much higher age is entirely explained by a much lower dose rate determined for this sample ( $1.62 \pm 0.17 \text{ Gy ka}^{-1}$  for 105 cm versus  $2.41 \pm 0.16 \text{ Gy ka}^{-1}$  for 92 cm), whereas the  $D_e$  is identical to the sample above. The sample RAU1\_105 was taken just above the contact to underlying gravel deposits (SU1, Fig. 5a) and will almost likely have a different concentration in K, Th and U. Unfortunately, it was not considered to address this issue during fieldwork. Hence, we explain the higher basal SG-IRSL to be caused by inhomogeneity in the gamma radiation field.

### 5-4 Luminescence profiling techniques

Portable luminescence reader and IRSL screening methods were developed to study Quaternary sediment deposition regularity. If a sediment sequence is characterised by rather constant (i) grain size, (ii) mineralogical composition, and (iii) sedimentation rate, one can expect a gradual decrease of Ln/Tn values (May *et al.*, 2018) and portable luminescence reader signals (Portenga and Bishop, 2016)

towards the surface because of progressively shorter burial time. Any major change in sediment age would be materialized by slope breaks in Ln/Tn profiles and portable luminescence reader or (e.g. Muñoz-Salinas *et al.*, 2011; Abdulkarim *et al.*, Submitted). As no major breaks in both portable  
600 luminescence reader signals are observed between 45 and 0 cm, i.e. AD 2020~1960 according to the independent <sup>137</sup>Cs data, this possibly points to a relatively constant sedimentation rate of silty material over this time period. This well matches our interpretation inferred from historical maps and hydrological records, suggesting a steady sedimentation at Rhinau since the Rhine canalisation (i.e. AD 1963- around the study site) and possibly slightly before.

605 However, the IRSL screening and portable luminescence reader signals do not show a joint decrease from 45 cm to the top as expected for a sedimentation of a homogeneous material at a constant rate. The data also show that all signals tend to increase from 80 to 15 cm and from 80 to 50 cm, respectively. The portable luminescence reader signals (Fig. 7d) increasing at 85 and 90 cm corresponds to major changes in the grain size with the sandy level (80-92 cm, SU3, Fig. 5a). This sandy  
610 deposit probably affects the portable luminescence reader signal with (i) less bleached deposits resulting of more intense flooding events and (ii) grain size and mineralogical changes (Sanderson and Murphy, 2010; Munyikwa *et al.*, 2021). This kind of heterogeneity in recent overbank sediment deposits shows the applicability limit of the portable reader method.

The two dose rate *D* measured at 92 and 76 cm are similar (Table 3), indicating a probably low vertical  
615 variation in the downer part of the profile. In the upper part, variations in the IRSL screening L<sub>x</sub>/T<sub>x</sub> ratio seem to correlate with variations in the concentrations of elements such as Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O or MnO of the sedimentary profile (Fig. 5c). Altogether this data suggests that the variation of L<sub>x</sub>/T<sub>x</sub> ratio the upper 50 cm of the Rhinau sediments could results from mineralogical changes and possible vertical variations of the local dose rate *D* (Sanderson and Murphy, 2010; Munyikwa *et al.*, 2021). This  
620 illustrates one of the limitations for applying portable luminescence reader and IRSL screening methods for the study of depositional rates. Indeed, for short periods of deposition, portable luminescence reader or IRSL screening signals will rather reflect changes in grain size and mineralogical variations, whereas the signal increase related to the burial time might be masked.

## 625 5-5 Advantages of multi-method reconstruction of the age-depth model of sediment deposit

Each geochronological method used in this study reached its limit of applicability in this recent sedimentary deposition context. Nevertheless, we built an innovative robust chronometric framework by combining river planform evolution as well as stratigraphic and historical hydrological analysis with the geochronological data. The applied multi-method geochronological approach shows the advantage

630 of combining different dating tools such as old maps combined with a good knowledge of past  
engineering works, grain-size and hydrology, sediment composition, and luminescence profiling  
techniques (IRSL screening, portable luminescence reader), with dating methods for recent <100-200  
years deposits ( $^{137}\text{Cs}$  and luminescence dating). It allows establishing robustly chronologies of the 105-  
80 cm and the 40-0 cm sections of the sedimentary deposit. Old maps and hydrology based  
635 chronological tags were generally confirmed by IRSL SG dating.

The obtained sedimentation rates extrapolated based on the different chronological tags (Fig.11) are  
low in compared to the one obtained along the Rhone (2.9 to 7.9 cm yr<sup>-1</sup>), but comparable with the  
Loire ones (0.8 to 1.2 cm yr<sup>-1</sup>) according to Morereau, 2017. In the upper 40 cm of the deposit, the  
sedimentation rates calculated from  $^{137}\text{Cs}$  results are of ~0.6 cm yr<sup>-1</sup> (Table 2). In detail, sedimentation  
640 could be slightly accelerated on the upper 26 cm by river restauration works as shown by the  
sedimentation rates obtained from the pit (Fig.11b).

Some important information is still missing on the deposition chronology between 70 and 40 cm  
(Fig.11a), i.e., for the first half of the 20<sup>th</sup> century. No chronological tag could be established due to the  
absence of  $^{137}\text{Cs}$  or  $^{210}\text{Pb}_{\text{xs}}$  and insufficient sands quantity for proper luminescence dating. Estimation  
645 of the sedimentation rate is important because deposits resulting from floods are discontinuous.  
Luminescence profiling methods could not confirm this sedimentation regularity because of the  
methodological limits, certainly connected to heterogeneity of sediment deposition processes before the  
canalisation. Homogeneous grain size and mineralogy suggest a relatively regular deposition and no  
major changes in the sedimentation context since the beginning of the 20<sup>th</sup> century, with a mean  
650 sedimentation rate of the 40-70 cm sediments similar or slightly lower than ontop of the profile  
(Fig.11b). However, IRSL SG dating measured above the sandy layer suggest that part of the fine  
deposits could be partly induced by the same flooding event as the sandy level, implying a much lower  
sedimentation rate at the beginning of the 20<sup>th</sup> century than at the end of the 20<sup>th</sup> century.  
Consequently, our results show that the canalization increased flooding around the sedimentary pit  
655 and core. This change remains local as the canalisation lead to a hydraulic connectivity decrease of the  
whole island of Rhinau (Maire et Sanchez-Perez, 1992; Chardon *et al.*, Submitted). This sedimentation  
rate evolution at Rhinau differs from the natural filling of palaeochannels which is typically rapid at  
start and decreases as the filling progresses (Malavoi and Bravard, 2011). This difference results of the  
sedimentation dynamics induced by the specific Rhine engineering works.

## 660 Conclusions

No single method allowing to date a current sedimentary archive that goes back over the last few  
centuries exist. Due to potential sedimentary discontinuities, the precise dating of floodplain archives

in strongly engineered rivers represents an important challenge along the Upper Rhine, as well as for many other rivers. The overall historical framework was defined on the basis of former maps, hydrology, isotopic ( $^{137}\text{Cs}$ ,  $^{210}\text{Pb}$ s) and palaeodosimetric methods (IRSL SG, portable luminescence reader, IRSL screening). We discussed advantages and limitations of both isotopic and palaeodosimetric methods in dating recent overbank sediments in a fluvial environment heavily impacted by successive engineering works over the last two centuries.

The historical maps define the beginning of the sedimentation (AD 1855-1863 here). The history of major floods generates remarkable sedimentary changes (AD 1876 inducing grain-size and mineralogical change). The IRSL SG, supports ages estimated by former maps and flood history. Although developed and optimal for dating older sediments, luminescence dating can support the deposition chronology for <200 years deposits. Finally, the upper part, post-1950, is dated with  $^{137}\text{Cs}$  with which a sedimentation rate of  $\sim 0,6 \text{ cm yr}^{-1}$  for the first 40 cm was obtained.

675 Annexe: Age-depth calculated based on <sup>210</sup>Pb<sub>xs</sub> and <sup>137</sup>Cs sedimentation

rates

Figure 1: table of ages obtained by <sup>137</sup>Cs and <sup>210</sup>Pb<sub>xs</sub> for each sample of the pit and the sediment core with harmonized depths. In bold are the actual samples for the core and sediment pit, with depths recalculated based on sedimentation rates obtained for the pit and core and based on the following benchmarks: end of sedimentation (2020.5 for the pit and 2021.25 for the core), base of AD 1986 peak <sup>137</sup>Cs and beginning of <sup>137</sup>Cs record (AD ~1945).

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Depth		137Cs		210Pb	
pit	core	Age (mean)	Uncertainties	Age (mean)	Uncertainties
-	0,0	2021,3	-	2021,3	
-	0,5	2020,4	-	2020,0	[2019,42-2020,64]
<b>0</b>	<b>0,5</b>	<b>2020,5</b>	-	<b>2020,2</b>	[2019,60-2020,70]
-	1,5	2018,8	-	2017,6	[2015,75-2019,43]
<b>1,5</b>	<b>1,6</b>	<b>2018,6</b>	-	<b>2017,3</b>	[2015,33-2019,29]
-	2,5	2017,1	-	2015,1	[2012,08-2018,21]
-	3,5	2015,4	-	2012,7	[2008,41-2017,00]
-	4,5	2013,8	-	2010,3	[2004,74-2015,79]
<b>6,5</b>	<b>5,5</b>	<b>2012,1</b>	-	<b>2007,8</b>	[2001,11-2014,59]
-	5,5	2012,1	-	2007,8	[2001,08-2014,57]
-	6,5	2010,4	-	2005,4	[1997,41-2013,36]
-	7,5	2008,8	-	2002,9	[1993,74-2012,14]
-	8,5	2007,1	-	2000,5	[1990,07-2010,93]
<b>11,5</b>	<b>9,4</b>	<b>2005,6</b>	-	<b>1998,4</b>	[1986,89-2009,88]
-	9,5	2005,4	-	1998,1	[1986,40-2009,72]
-	11,0	2002,9	-	1994,4	[1980,90-2007,90]
-	11,5	2002,1	-	1993,2	[1979,07-2007,29]
-	13,0	1999,6	-	1989,5	[1973,56-2005,47]
<b>16,5</b>	<b>13,2</b>	<b>1999,2</b>	-	<b>1988,9</b>	[1972,67-2005,17]
-	15,0	1996,3	-	1984,6	[1966,23-2003,04]
-	16,5	1993,8	-	1981,0	[1960,73-2001,22]
-	17,0	1992,9	-	1979,8	[1958,89-2000,62]
<b>21,5</b>	<b>17,1</b>	<b>1992,7</b>	-	<b>1979,5</b>	[1958,44-2000,46]
-	19,0	1989,6	-	1974,9	[1951,56-1998,18]
<b>26,5</b>	<b>21,0</b>	<b>1986,3</b>	-	<b>1970,0</b>	[1944,22-1995,76]
-	21,5	1985,5	[1985,34-1985,6]	1968,8	[1942,39-1995,15]
-	23,0	1983,2	[1982,63-1983,65]	1965,1	[1936,88-1993,33]
-	25,0	1980,2	[1979-1981,04]	1960,2	[1929,55-1990,90]
<b>31,5</b>	<b>26,2</b>	<b>1978,4</b>	[1976,84-1979,49]	<b>1957,3</b>	[1925,17-1989,45]
-	26,5	1977,9	[1976,28-1979,09]	1956,6	[1924,05-1989,08]
-	27,0	1977,2	[1975,38-1978,44]	1955,3	[1922,21-1988,47]
-	29,0	1974,1	[1971,75-1975,83]	1950,5	[1914,88-1986,04]
<b>36,5</b>	<b>31,4</b>	<b>1970,5</b>	[1967,42-1972,73]	<b>1944,6</b>	[1906,12-1983,15]
-	31,5	1970,3	[1967,22-1972,58]	1944,4	[1905,71-1983,01]
-	31,8	1970,0	[1966,77-1972,25]	1943,7	[1904,79-1982,71]
-	34,8	1965,4	[1961,33-1968,35]	1936,4	[1893,78-1979,06]
-	36,5	1962,8	[1958,16-1966,07]	1932,2	[1887,37-1976,94]
<b>41,5</b>	<b>36,6</b>	<b>1962,6</b>	[1958,01-1965,96]	<b>1932,0</b>	[1887,07-1976,84]
-	37,0	1962,0	[1957,25-1965,42]	1930,9	[1885,53-1976,33]
-	39,0	1959,0	[1953,63-1962,81]	1926,0	[1878,19-1973,90]
-	41,0	1955,9	[1950-1960,21]	1921,2	[1870,86-1971,48]
-	41,5	1955,2	[1949,09-1959,56]	1919,9	[1869,02-1970,87]
<b>46,5</b>	<b>41,8</b>	<b>1954,8</b>	[1948,6-1959,2]	<b>1919,3</b>	[1868,02-1970,54]
<b>51,5</b>	<b>47,0</b>	<b>1946,9</b>	[1939,18-1952,44]	<b>1906,6</b>	[1848,97-1964,23]
<b>56,5</b>	<b>52,2</b>	<b>1939,0</b>	[1929,77-1945,68]	<b>1893,9</b>	[1829,92-1957,93]
<b>61,5</b>	<b>57,4</b>	<b>1931,2</b>	[1920,36-1938,91]	<b>1881,2</b>	[1810,87-1951,62]
<b>66,5</b>	<b>62,5</b>	<b>1923,3</b>	[1910,94-1932,15]	<b>1868,6</b>	[1791,82-1945,32]
<b>71,5</b>	<b>67,7</b>	<b>1915,4</b>	[1901,53-1925,39]	<b>1855,9</b>	[1772,77-1939,01]
<b>72</b>	<b>68,6</b>	<b>1914,0</b>	[1899,89-1924,21]	<b>1853,7</b>	[1769,45-1937,91]
<b>76,5</b>	<b>72,9</b>	<b>1907,5</b>	[1892,12-1918,63]	<b>1843,2</b>	[1753,72-1932,71]
<b>81,5</b>	<b>78,1</b>	<b>1899,7</b>	[1882,7-1911,86]	<b>1830,5</b>	[1734,67-1926,40]
<b>86,5</b>	<b>83,3</b>	<b>1891,8</b>	[1873,29-1905,1]	<b>1817,9</b>	[1715,62-1920,10]
<b>91,5</b>	<b>88,5</b>	<b>1883,9</b>	[1863,88-1898,34]	<b>1805,2</b>	[1696,57-1913,79]
<b>96,5</b>	<b>93,7</b>	<b>1876,1</b>	[1854,46-1891,58]	<b>1792,5</b>	[1677,52-1907,49]
<b>101,5</b>	<b>98,9</b>	<b>1868,2</b>	[1845,05-1884,81]	<b>1779,8</b>	[1658,47-1901,18]
<b>104</b>	<b>101,5</b>	<b>1864,3</b>	[1840,34-1881,43]	<b>1773,5</b>	[1648,94-1898,03]



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