Recent sedimentation rates in Garaet El Ichkeul Lake, NW Tunisia, as affected by the construction of dams and a regulatory sluice

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Abstract

Purpose Ichkeul National Park, NW Tunisia, is a UNESCO Biosphere Reserve. Garaet El Ichkeul Lake is known for its seasonal variability in water level and salinity. In recent decades, the waterbody has been affected by the construction of new hydraulic structures. To reduce the impacts of dams and to maintain the sustainability of the ecosystem, a sluice was built at the outlet of the lake, and it operated for the first time in 1996. This paper describes an investigation of recent sedimentation dynamics in Ichkeul Lake, determined by radiometric dating of sediment cores.

Materials and methods A sediment core was collected with a UWITEC gravity corer at the deepest, central part of the lake in August 2009. Specific activities of unsupported lead-210 (^{210}Pb) and caesium-137 (^{137}Cs) were measured in the core, enabling calculation of recent sediment accumulation rates (SAR). Published radiometric data from nearby sediment cores, collected in 1997 and 1982, provide a comparison.

Results and discussion The measured excess ^{210}Pb inventory was 5300 ± 500 Bq m^{-2}, leading to an estimation of constant flux of 165 ± 16 Bq m^{-2} yr^{-1}, a value higher than the best estimate for local atmospheric fluxes (123 ± 12 Bq m^{-2} yr^{-1}) and the flux estimated from the core collected in 1982 (48 Bq m^{-2} yr^{-1}). The ^{137}Cs inventory was 3550 ± 120 Bq m^{-2}, two times higher than the historical ^{137}Cs atmospheric deposition in the area. The ^{137}Cs profile displayed a distinct peak, but the ^{137}Cs depth-distribution did not follow the pattern expected from atmospheric deposition. Application of the constant rate of supply (CRS) model, with the reference point method, produced a chronology and SAR values comparable to those found in previous work. The whole ^{137}Cs profile was quantitatively reconstructed from the historical records of atmospheric deposition, using the system-time-averaged (STA) model.

Conclusions The CRS and STA models provide consistent sediment accumulation results for the whole data set, considering the time resolution of the chronology (~6 years) and analytical uncertainties. Results from cores sampled in 1982, 1997 and 2009 reveal an increasing SAR trend, from

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~0.25 $g cm^{-2} yr^{-1}$ in the early 1940s to ~0.67 $g cm^{-2} yr^{-1}$ at present. In the 13 years since installation of sluice gates at Tinja, SAR in the central Ichkeul Lake has not declined. Thus, if siltation continues at the present rate, shallowing of the lake will seriously affect the hydromorphology and ecology of this important lake.

Keywords Pb dating · ^{137}Cs dating · CRS reference point · Ichkeul lake · Sediment accumulation rates · STA model

1 Introduction

Ichkeul National Park was created by the Tunisian government in 1977 in recognition of its important international role as a wintering ground for waterfowl (Scott 1980; Hollis 1986). It lies at the southern end of the Mogods Mountains on the Mediterranean coast of NW Tunisia, and contains a large, shallow, euryhaline lake that extends over 87 km^2 at its summer minimum. The park has been designated a Biosphere Reserve by UNESCO.

According to the Tunisian National Agency for Environmental Protection (ANPE 2009), three dams were constructed around the lake over the last three decades: (i) Joumine in 1983, (ii) Ghezala in 1984 and (iii) Sejnane in 1994. An important fraction of the annual freshwater supplied by the catchment of the Ichkeul Lake is now diverted towards agriculture uses and human consumption (140 $Mm^3 yr^{-1}$, on average, for the period 2003–2008, accounting yearly for 20% to 70% of the total catchment freshwater, as reported by ANPE 2009). Although anthropogenic disturbance in the catchment has occurred since at least Roman times, recent river canalization, installations of dams on inflow rivers and agricultural intensification have had profound effects on the lake's hydrology, water quality and biodiversity (i.e., bird populations).

Hollis et al. (1983) and Hollis (1986) evaluated how Ichkeul might respond to various dam management strategies and ameliorative measures. Tamisier and Boudouresque (1994) studied the water bird populations as possible indicators of seasonal nutrient flow at Ichkeul Lake. They concluded that the new dams around the lake were changing drastically the nutrient (N and P) balance and would lead to an important loss of the main characteristics of the lake, making Ichkeul an ordinary human-managed wetland. To reduce the impacts of these dams, and therefore ensure the sustainability of the Ichkeul ecosystem, a sluice was built in 1993 at the outlet of the lake in the Oued Tinja, allowing for the control of the water level and the net outflow. The sluice of Tinja operated for first time in April 1996 by closing its gates.

There is observational evidence of large resuspension of surface sediments under moderate and strong wind episodes (more frequent in the autumn-winter period), as well as the formation of new sedimentary deposits upstream of Tinja when the sluice is closed. Internal redistribution seems to play an important role in the sedimentary dynamics of this shallow lake. The rate at which the deepest areas are being filled up by sediments has important implications, among others, for the evolution of the morphology of the lake, and in the final fate of this aquatic ecosystem.

The most common technique for dating sediment cores from continental waterbodies, and therefore to estimate fluxes at the sediment-water interface (e.g. sediment accumulation rates), uses the natural fallout radionuclide lead-210 (^{210}Pb). The method was proposed by Goldberg (1963) and first applied to marine sediments by Koide et al. (1973). Several ^{210}Pb dating models were developed (e.g. Appleby and Oldfield 1978; Robbins 1978; Christensen 1982; Abril et al. 1992), but they sometimes yield different chronologies when applied to the same dataset. Consequently, it is advisable to check the reliability of model-derived ^{210}Pb dates using an independent dating tool (Smith 2001). This is often accomplished by comparing ^{210}Pb model dates against ages determined using artificial fallout radionuclides, such as caesium-137 (^{137}Cs) (Pennington et al. 1973), plutonium-239 and 240 ($^{239,240}Pu$) (Wan et al. 1987) and americium-241 (^{241}Am) (Appleby et al. 1991). In the case of ^{137}Cs and transuranic elements, global fallout began in 1954, following atmospheric nuclear bomb testing which peaked in the early 1960s, and declined following the nuclear test ban treaty signed in 1963. There have also been local releases, such as the Chernobyl nuclear power plant accident in 1986 (Mabit et al. 2008).

Stevenson and Battarbee (1991) conducted a palaeoecological and documentary study of the site, which included analysis of a sediment core, taken in 1982, and dated using the constant rate of supply (CRS) ^{210}Pb model. More recently, Appleby et al. (2001) analysed another sediment core from this water body as part of the CASSARINA Project's study of recent sediments in North African wetland lakes. The core was collected in 1997 and analysed for ^{210}Pb and ^{137}Cs activity. Due to the collection date, these cores were not able to account for the potential effects of the latest hydraulic infrastructures on the sedimentary regime of Ichkeul Lake.

The present work involved study of recent sedimentation dynamics in Ichkeul, using a dated sediment core collected from the centre of the lake in 2009, after 13 years of operation of the sluice at Tinja. ^{210}Pb and ^{137}Cs specific activities were measured and sediment accumulation rates (SAR) were calculated using CRS and system time averaged (STA) radiometric dating models. Comparison with the two previous studies will provide some further insight on the recent changes, and on within-lake variability, in SAR.

In shallow, wind-stressed lakes the usual assumptions of conformable sedimentation and ^{210}Pb inputs may not hold, and other independent dating methods are needed (Schottler and Engstrom 2006). Simple identification of distinct ^{137}Cs peaks has typically been used as a dating tool. Nevertheless, Abril (2003, 2004) demonstrated that this method does not always yield an unambiguous time-stratigraphic marker. Thus, in the present investigation, quantitative modelling of the whole ^{137}Cs profile was undertaken.

2 Materials and methods

2.1 Study site

Garaet El Ichkeul Lake is a shallow, euryhaline lake that covers over 87 km^2 at its summer minimum. Located in NW Tunisia (37° 09.45′ N, 09° 04.01′ E) the lake basin is very shallow with mean summer and winter depths of 1.4 and 2.5 m, respectively. The south shore of Ichkeul Lake is dominated by a limestone mountain, Jebel Ichkeul (Fig. 1). Five major rivers feed the lake, of which the Sejnane, draining 580 km^2 of the southern Mogods, is the most important, accounting for 43% of the total water input. The rivers flood after the first winter rains, and with the exception of the Sejnane, dry completely during the summer months. Outflow from Ichkeul Lake drains via the Oued Tinja to Lac de Bizerte, a tidal marine bay of the Mediterranean Sea. The Oued Tinja is unusual because its flow reverses in summer when the level of Ichkeul falls below that of Lac de Bizerte. This reversal is caused by cessation of flow in the major input rivers and the high evaporation rate from the lake. As a consequence, saline (thalassic) water enters Ichkeul.

About 340×10^6 m^{3}yr^{-1} of freshwater entered the lake from the catchment when first measured (ANPE 2009), but after the construction of dams (Joumine 1983; Ghezala 1984; Sejnane 1994) an important fraction of this flow is now diverted towards agriculture uses and human consumption (Fig. 2). The exchange of water with Bizerte Lake is regulated through a sluice gate at Tinja Oued (Table 1). Between 1996 and 2003, damming and drought drastically diminished the freshwater supply (ANPE 2009). Rainfall was plentiful during the winter of 2002–2003 and the dry marshlands were again flooded.

The lake level and salinity fluctuate throughout the year (ANPE 2009). Water levels are routinely recorded by ANPE at the Tinja station. Lake levels increase during the rainy period in the region (January to March), from <0.5 m in drought years (e.g., 2000) up to 2.5 m in rainy years (e.g. 2005), then drop to reach the initial reference level at the end of autumn. As expected, salinity is negatively correlated with water level. Drought from 1999 to 2003 caused lake salinity to rise to twice that of seawater (ANPE 2009).

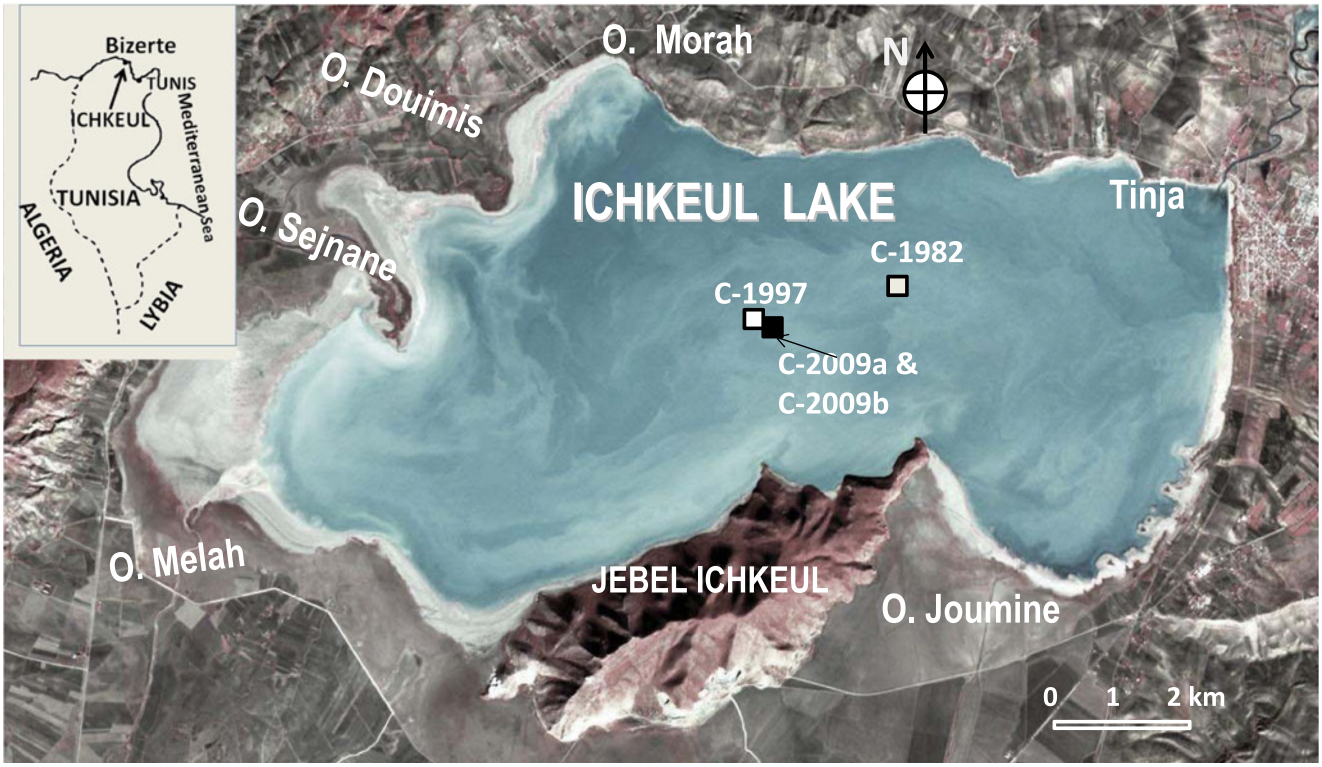


Fig. 1 Ichkeul Lake (NASA-ASTER image, November 2001). The core was sampled at the centre of the lake (C-2009a and C-2009b). The square at C-1982 is the position of the core sampled in 1982 by Stevenson and Battarbee (1991), and the square at C-1997 is the estimated location of the core collected in 1997 by Appleby et al. (2001)

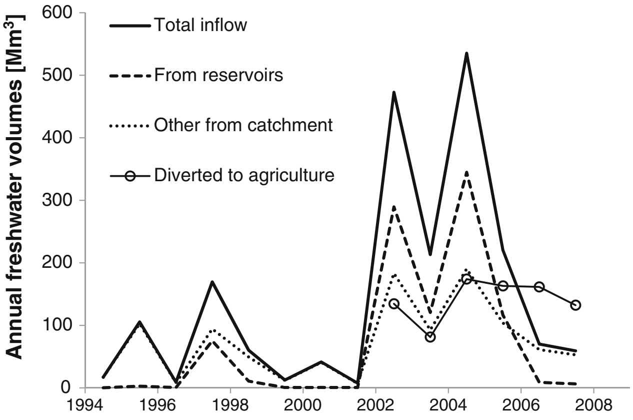


Fig. 2 Annual water inputs to Ichkeul Lake for the period 1994–2007 and volumes diverted to agriculture (data from the Tunisian National Agency of Environment Protection)

In shallow Ichkeul Lake, strong winds enhance resuspension of surface sediments. The most frequent winds blow from the WNW. During spring and summer, wind speeds are relatively constant, while they are highly variable in autumn and winter. Turbidity is higher during winter (10 to 80 cm, determined from a turbidity tube), because of the stronger winds and riverine discharges, while in summer the waters become clearer (20 to 110 cm). Eutrophication and accumulation of sediments upstream of Tinja have been reported in the lake during periods when the sluice gate is closed (Ben M'Barek and Slim-Shimi 2002).

The lake is dominated by extensive beds of salt-tolerant *Potamogeton pectinatus*, along with *Ruppia cirrhosa*, *Lamprothamnium papulosum* and *Zostera noltii*. At the beginning of October 2008, the surface coverage of macrophytes represented nearly 57% of the average area of the lake. Taken separately, the percentages of dominant macrophytes were, respectively: 53% for macro-algae, 45% for *Potamogeton pectinatus* and 20% for *Ruppia cirrhosa* (ANPE 2009). A more detailed description of the site can be found in Stevenson and Battarbee (1991) and Stevenson et al. (1993), as well as in several papers produced within the CASSARINA Project (e.g., Flower 2001; Flower et al. 2001; Ramdani et al. 2001).

2.2 Methods

In August 2009, a sediment core was collected with a UWITEC gravity corer in the central, deepest part of the lake, at 37° 09.45′N, 09° 04.01′E (Core C-2009a in Fig. 1). The water depth was 1.20 m, and the salinity was 13.59 g l^{-1}. This area of the lake remains free of rooted aquatic plants. The gravity corer takes a 60 cm long core that is 6.0 cm in diameter. The core was immediately extruded on the lake shore and sectioned at 5 cm intervals. Sediment samples were freeze-dried, ground to a fine powder and homogenized for radioactivity measurements. Visual inspection of the sediment core did not reveal evident lamination or evidence of bioturbation. The colour was very dark at the top, but became lighter with depth. A second core was collected at the same location (Core C-2009b in Fig. 1) and immediately sectioned at 2 cm intervals. These samples (Core C-2009b) were used for bulk density measurements, i.e. the dry mass per unit wet volume. The water content of fresh sediment aliquots was determined by weighing before and after drying at 100°C until the weight was constant. Bulk density was calculated from water content and the density of the solid fraction. As the whole fresh mass of each sediment slice was oven dried, and the bulk volume of the slice was known (from the core section and the 2 cm thickness), it was possible to use these values as an alternative way to determine bulk densities, which served to ensure the consistency of the data.

Measurements of ^{137}Cs and radium-226 (^{226}Ra) radioactivities were made using a Canberra coaxial P-Type HPGe detector with a resolution of 2 keV and a relative efficiency of 30% at 1.33 keV. The ^{137}Cs activity was measured through its gamma emission at 662 keV. The ^{226}Ra activity concentration was determined indirectly through the detection of the 609 keV photon emitted by bismuth-214 (^{214}Bi), after sealing samples for a period of 21 days to allow ingrowth of radon-222 (^{222}Rn) and its short-lived daughters. Calibration of the detection system was performed using a certified multi-gamma source and was controlled by reference materials IAEA 327 and IAEA 375. Generally, 30 to 35 g of dry sediment was placed in 100-ml cylindrical

Table 1 Contributions to the annual water balance in Ichkeul Lake

Water inflow/outflow [Mm^3]	2003–2004	2004–2005	2005–2006	2006–2007	2007–2008
Input from reservoirs	120.5	345	116	9	6.3
Other inputs from catchment	92.5	190	104	61	52.9
Rain	65	80	54.5	58	65.4
Evaporation	108	111	124	102	99.3
Output to Bizerte Lake	173	542	216	95	92.7
Input from Bizerte Lake	16	35	50	50	52.3
Net balance	13	−3	−15.5	−19	−15.1

¶Data from ANPE (Tunisian National Agency of Environment Protection) containers. Counting times varied from 12 to 24 h, providing a relative statistical error <10% at the 95% confidence level. Under these experimental conditions, the minimum detection activities (MDA) for ^{137}Cs and ^{214}Bi were 1.3 and 2.1 Bq kg^{-1}, respectively.

Total ^{210}Pb activity in sediment samples was estimated by measurement of the daughter product ^{210}Po, using alpha spectrometry (Benmansour et al. 2006). About 1 g of dry, homogenised sediment was weighed into an acid-cleaned Teflon beaker, spiked with ^{209}Po yield tracer and totally digested using a mixture of concentrated HNO$_3$-HF. The acid digest was transferred to a clean beaker and treated by repeated evaporation with HCL-boric acid solution, and then dissolved in 80 ml of 0.5 M HCL. Polonium was self-deposited on a Pt disc and the activity was measured over a period of 4 to 6 h using alpha-spectrometry with silicon surface barrier detectors (EG&G) coupled to a PC running MaestroTM data acquisition software. Relative uncertainties under these conditions were <8% and the detection limit was 0.2 Bq kg^{-1}. Unsupported ^{210}Pb activity was obtained by subtracting ^{226}Ra activity from the total ^{210}Pb activity. All radioactivity measurements were carried out at the CNESTEN laboratories in Rabat (Morocco).

3 Results and discussion

3.1 Bulk density and radionuclide concentrations

Figure 3 shows measured bulk density versus depth for the Ichkeul sediment core. Relative uncertainties of 3% were estimated from the methodology described above. Bulk densities from previous work on other cores taken in this lake (see Fig. 1) are also presented for comparison.

Specific activities of ^{226}Ra, total ^{210}Pb and ^{137}Cs are reported in Table 2. There were no statistically significant differences in ^{226}Ra activities between the topmost sample (0–5 cm) and underlying deposits, except for the deepest section (45–50 cm), which had slightly greater activity. The relatively constant ^{226}Ra activities enabled us to use these values as good estimations of the supported ^{210}Pb component. There were no statistically significant differences between unsupported ^{210}Pb activities in the three uppermost sediment samples, at the 95% confidence level. Likewise, at this confidence level, unsupported ^{210}Pb activities at 15–20 cm and 25–30 cm were not statistically different. The ^{137}Cs maximum at 30–35 cm was statistically significant at the 95% confidence level.

Stevenson and Battarbee (1991) reported that the gross stratigraphy of the 13 cores sampled in 1982—most of them located in the eastern area of Ichkeul Lake—were similar. The surface 2 cm were composed of reddish flocculated silt/clay, overlying darker, more cohesive material. This suggests sediment homogeneity in the eastern area of the lake in 1982. Bulk density data from cores collected later by Appleby et al. (2001) and in the present work, suggest changes in sedimentation with time and according to site location. Nevertheless, the 50-cm core collected in 2009 cannot consist only of recent material, deposited after collection of the core by Stevenson and Battarbee 1991, because our core preserves a distinct ^{137}Cs maximum equated with the 1963 fallout peak, and excess ^{210}Pb reaches background levels within this 50-cm deep core. Consequently, the hypothesis of site-to-site variability seems more realistic.

Figure 4 shows excess ^{210}Pb activity versus cumulative mass for the three cores; core 2009 (this work); core 1997 (Appleby et al. 2001); and core 1982 (Stevenson and Battarbee 1991). To reconstruct the 1982 profile, a reverse CRS model has been applied to the published

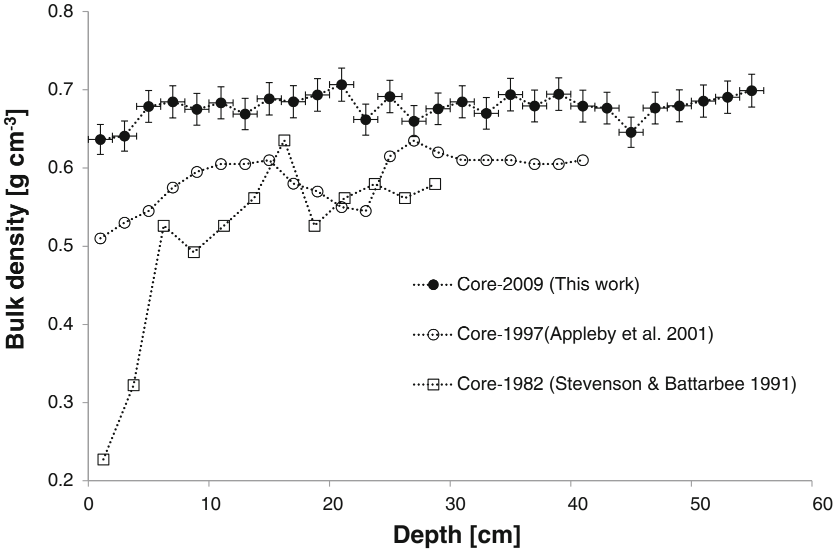


Fig. 3 Bulk density versus depth for the Ichkeul core. Error bars correspond to uncertainties of 3%. Bulk densities reported in previous work for other cores from this lake are shown for comparison

Table 2 Specific activities of ^{226}Ra, total ^{210}Pb, ^{210}Pb$_{excess}$ and ^{137}Cs in the sediment core from Ichkeul Lake (Core sampled in August 2009)

Depth	^{226}Ra	^{210}Pb	^{210}Pb$_{excess}$^{a}	^{137}Cs
[cm]	[Bq kg^{-1}]			
0–5	24.2±1.9	51±3	26±4	7.1±0.6
5–10	27.8±2.4	53±3	25±4	7.1±0.8
10–15	25.7±2.6	48±4	22±5	9.5±0.9
15–20	25.2±2.2	52±5	27±5	9.3±0.8
20–25	27.7±2.4	42±4	15±5	15.7±1.1
25–30	26.8±2.3	45±4	18±5	19.8±1.3
30–35	31±4	37±3	6±5	24.8±2.2
35–40	29.5±2.8	38±4	8±5	7.7±0.9
40–45	28±4	33±4	5±5	2.6±0.6
45–50	30.9±2.7	32±3	2±4	<1.28

^{a}Total ^{210}Pb minus ^{226}Ra activity concentrations.

data on SAR and chronology. Activities for cores 2009 and 1997 were comparable within analytical uncertainties, as were trends with respect to mass-depth, while a noticeable depletion in activity concentrations appears in the uppermost sediment layers of core 1982, and its profile extends over a much shorter mass thickness.

3.2 Radionuclide inventories and atmospheric fallout

The excess ^{210}Pb inventory derived from activities in Table 2 and bulk densities in Fig. 3 was Σ_0=5300±500 Bq m^{-2} (mean ± SD). This may be an underestimate, as completeness of the unsupported inventory cannot be ensured within the detection limits of the method. Appleby et al. (2001) reported an excess ^{210}Pb inventory of 4300±500 Bq m^{-2} for their 1997 core, using linear interpolation for unmeasured depth intervals. The estimated ^{137}Cs inventory in the 1997 core was 3500±90 Bq m^{-2}. After correction for radioactive decay, i.e. the 12 year elapsed time between collection of the two cores, it was 2650±70 Bq m^{-2}, a value less than that measured in the present work: 3550±120 Bq m^{-2}.

Appleby et al. (2001) estimated for the Ichkeul Lake area an atmospheric ^{210}Pb fallout rate of 55–110 Bq m^{-2} yr^{-1}, based on the Liverpool University ERRC global database and the mean annual rainfall. García-Orellana et al. (2006), based on the analysis of soil cores, reported a mean value of atmospheric ^{210}Pb flux of 75 Bq m^{-2} yr^{-1} for the western Mediterranean Sea. They also proposed a linear relationship with the annual rainfall which results in an estimation of 123±12 Bq m^{-2} yr^{-1} for the Ichkeul area (mean annual rainfall of 920 mm yr^{-1}). Bouchlaghem et al. (2009) reported noticeable Saharan dust outbreaks affecting the Mediterranean coast of Tunisia, which could contribute to the local values of atmospheric ^{210}Pb fluxes. García-Orellana et al. (2006) provided a gross estimate of 13–50 Bq m^{-2} yr^{-1} for the western Mediterranean area; an effect already integrated into the analysis of their soil cores.

Concerning the atmospheric deposition of ^{137}Cs, Appleby et al. (2001) estimated from the ERRC global

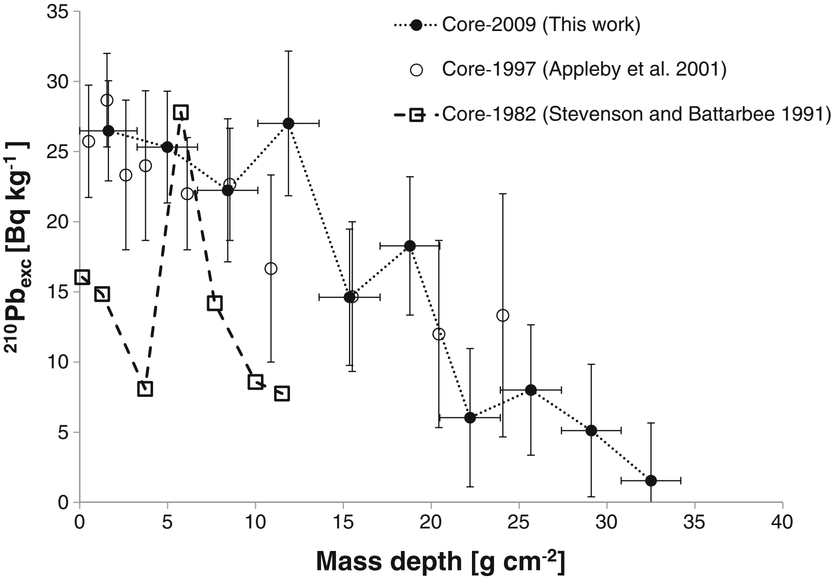


Fig. 4 Excess ^{210}Pb (^{210}Pb$_{exc}$) activity versus cumulative mass for the cores sampled in 2009 (this work), 1997 (data from Appleby et al. 2001) and 1982 (reconstructed by reverse CRS model from published data of SAR and chronologies by Stevenson and Battarbee 1991). Vertical error bars correspond to 1σ analytical errors (data not available for core 1982), and the horizontal bars correspond to the thickness of the measured sediment slice

database a value of 1674 Bq m^{-2} for the Ichkeul area (decay corrected to 2009), which is comparable to the measured ^{137}Cs deposition at Gibraltar (1460 Bq m^{-2}, after Wright et al. 1999; historical records for Gibraltar are shown in Fig. 5).

Stevenson and Battarbee (1991) reported an excess ^{210}Pb flux to the sediment of 48.1 Bq m^{-2} yr^{-1}, which corresponds to an inventory of only 1540 Bq m^{-2} (assumed to be steady sate). This value for ^{210}Pb flux falls below the lowest estimates of local atmospheric fallout rate. On the other hand, the unsupported ^{210}Pb flux derived for core 1997 (138±15 Bq m^{-2} yr^{-1}) agrees well with the best estimates of local atmospheric fallout rate. It could be argued that core 1982 suffered some erosion episode; its excess ^{210}Pb inventory is 2.9±0.4 times lower than that of core 1997, and it extends within a mass depth which is 2.048±0.011 times lower than the one containing the inventory in core 1997. Nevertheless, a series of solid arguments support the consistency of the chronology established for this core, as demonstrated by Stevenson and Battarbee (1991): (i) the biostratigraphic correlation between all 16 Ichkeul cores collected in their work; (ii) the agreement with pollen analysis; and (iii) the correlation between the recent increases in sedimentation rates (or the depletion in the unsupported ^{210}Pb activity concentrations) with the modifications in the course of the Oued Joumine. Furthermore, the exponential decrease observed in the deepest part of the unsupported ^{210}Pb profile (core-1982 in Fig. 4) is consistent with SAR values of 0.14±0.02 gcm^{-2} yr^{-1} (R^2=0.944, p=0.03).

The excess ^{210}Pb inventory in core 2009 is 1.20±0.17 times higher than that of core 1997, and this inventory is contained in a mass depth which is 1.386±0.004 times higher than that of core 1997. The corresponding estimate of the unsupported ^{210}Pb flux to the sediment is 165±16 Bq m^{-2} yr^{-1}. This situation can be reconciled from the understanding of the kinetic reactive transport in these lacustrine environments. Abril et al. (2004) showed, through a modelling exercise, how a uniform atmospheric input of Pu in Lake Härsvatten, with a water circulation forced by dominant winds, coupled with the dynamics of the suspended particulate matter (SPM) and the kinetics of the uptake of Pu by SPM and surface sediments, produced important spatial gradients in Pu concentrations in the water column and in surface sediments.

The spatial distribution within the lake body of sedimentary material supplied by the main inflows largely depends on the water circulation and the characteristic settling velocities of SPM with different grain sizes. Thus, Michel et al. (2002) found in Blelham Tarn, Cumbria, UK (with a length of 0.65 km and mean depth of 6.8 m), that the catchment inputs of Pu and Am were localised around the mouths of the input streams, with the remaining sediment records being dominated by direct atmospheric fallout, modified by the influence of sediment focussing. Similarly, Bindler et al. (2001) found in Lake Härsvatten, Sweden (with a length of 1.0 km), that the highest inventories of Pb and flyash particles were generally localised at shallow sites (<4 m water depth) and not in the three deep basins of the lake (10, 12 and 24 m deep). This was in agreement with the predictions of the hydrologic modelling of the transport of transuranic elements in Härsvatten (El-Daoushy et al. 1999). Although these examples correspond to small lakes, the basic physico-chemical laws can be applied to Ichkeul Lake, although other sources of complexity may be relevant, such as lake resuspension.

There is observational evidence that the internal redistribution of sediments plays an important role in the sedimentary dynamics of this shallow wind-stressed lake. It is likely

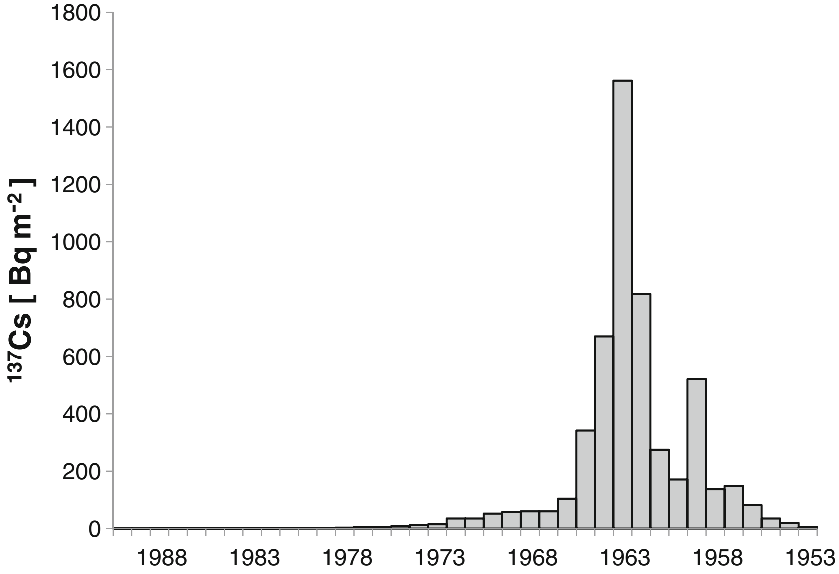


Fig. 5 Historical record of ^{137}Cs atmospheric deposition at Gibraltar (36° 08′ N, 5° 21′ W) (data from Wright et al. 1999)

that the sedimentary material supplied by Oueds Sejnane, Ghezala and Joumine will be primarily deposited in a limited area of influence around the mouth of these inlets, after which it may be subject to further resuspension and transport. Finally, the expected counter clockwise water circulation pattern (Emery and Csanady 1973) could lead to areas of differential SAR. The available data show a strong linear relationship ($R^2=0.955$)—although not statistically significant at 90% confidence limit—among the inventories of the three cores and their respective mass thicknesses. Thus, different areas receive, on average, higher amounts of matter and scavenged excess ^{210}Pb than others; with inputs being composed of fresh atmospheric deposition and by an additional fraction coming from other areas within the lake. Within the typical time scale and time resolution involved in the ^{210}Pb-based radiogeochronology, it seems reasonable to assume the preservation of the wind-driven water circulation pattern, and that, on average, the local unsupported ^{210}Pb fluxes onto the sediment remain almost constant with time, therefore allowing the application of the CRS model.

The ratio between ^{137}Cs inventories (decay corrected to 2009) associated with cores 2009 and 1997 was 1.34±0.06, slightly higher but comparable to those found for unsupported ^{210}Pb. We note that because the ^{137}Cs radioisotope can follow the same basic transport mechanisms (with a different uptake kinetics and equilibrium k_d), and as the atmospheric deposition diminished after its 1963 maximum, the contribution from other areas within the lake and/or the catchment can lead to a significant input into the net sedimentation areas. Thus, when comparing these inventories against the integrated ^{137}Cs atmospheric deposition, they are higher by a factor 1.6 and 2.1 for cores 1997 and 2009, respectively.

3.3 CRS chronology

Application of the CRS model requires an accurate estimation of the total unsupported ^{210}Pb inventory. Given the low ^{210}Pb activities and large uncertainties, a better approach to calculating the excess ^{210}Pb flux was to use the relatively well-defined ^{137}Cs peak fallout date, i.e. the reference point method of Appleby (2001). A clear ^{137}Cs peak appears in the 30–35 cm depth interval (see Table 2), and was assigned a date of 1963 (i.e. when atmospheric fallout reached its maximum value). This method leads to an estimated annual flux of excess ^{210}Pb into the sediment of 192± 20 Bq m^{-2} yr^{-1}, with a corresponding total inventory of 6120±650 Bq m^{-2}. Figure 6 shows the CRS chronology estimated by this approach along with the ^{137}Cs time marker. For the sake of comparison, the chronology obtained from the CRS model without the point reference method is also depicted.

Sediment accumulation rate was plotted against dates derived from the CRS model, using the reference point method (Fig. 7). For comparison, the same information is depicted for the 1982 and 1997 cores, to which the CRS model was also applied. Within the propagated uncertainties, results are comparable, and SAR shows an increasing trend in the last three decades, following increasing human impact on lake hydrology, as will be discussed in detail below.

3.4 Cesium-137 profile

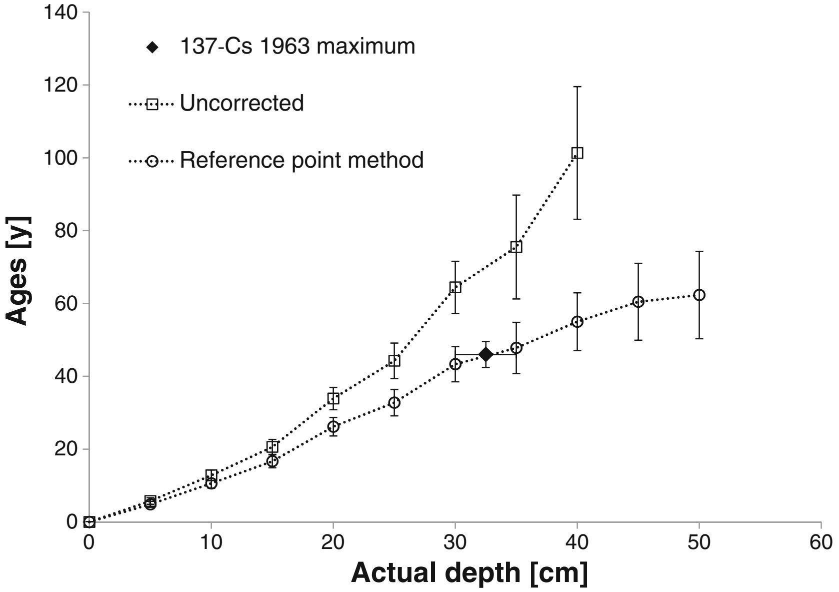
^{137}Cs activity was plotted against cumulative mass in the profile (Fig. 8). For comparison, the same information is depicted for the 1997 core, after applying a correction for radioactive decay and adjusting the sediment water interface (SWI) accordingly using the estimated mean SAR for the last 12 years. For this last calculation, a value of 0.56 g cm^{-2} yr^{-1} was adopted, a compromise between the trends shown by the time series of SAR in Fig. 7. The maximum penetration depth of ^{137}Cs (see Table 2 and Fig. 8) is compatible with the CRS chronology (see Fig. 6) but it is worth noting that neither follows the atmospheric deposition pattern (see Fig. 5). Because of the potential for sediment mixing, there may be some limitations on use of the CRS model, as well as the ^{137}Cs peak as a time marker (Abril 2004). Furthermore, it has been suggested that ^{137}Cs could be remobilized under conditions of increasing salinity in the pore-water, thus lowering the inventories and perturbing their depth profiles (Foster et al. 2006). To support the self-consistency and applicability of the CRS model to the present data, it should be necessary to give a quantitative interpretation of the whole ^{137}Cs profile, within the framework of the assumptions involved in the CRS model and, particularly, without need to invoke post-depositional mixing.

The depth distribution patterns of ^{137}Cs similar to that of the 2009 core (see Fig. 8) have been explained by the Integrated-Atmospheric-Flux Effect model (Abril and García-León 1994), which is equivalent to the System Time Averaged (STA) model of Robbins et al. (2000). The basic idea of these models is that the input of radionuclides to the sediment is not governed solely by direct atmospheric fallout, but rather that these atmospheric fluxes are integrated (mathematically in the catchment and/or in the water column) and then transferred to the sediments at a constant rate, or with a constant residence time; which is a site-specific parameter. Thus, in the STA model (Robbins et al. 2000), the flux to the sediment, F_s [Bq L^{-2} T^{-1}], is given by:

$$\frac{dF_s}{dt} = k_r F_a - (\lambda + k_r) F_s, \tag{1}$$

where F_a is the atmospheric deposition rate of the studied radionuclide, $\lambda=\ln 2/T_{1/2}$ [T^{-1}] is the radioactive decay

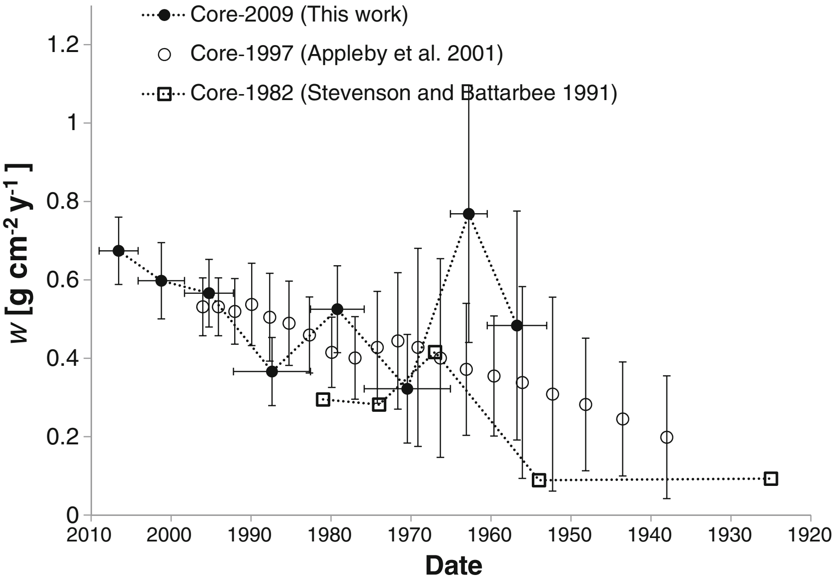
Fig. 6 Chronology for the Ichkeul core (2009) using the CRS model without correction and using the reference point method, from the ^{137}Cs time marker (with its maximum activity, associated with 1963) also depicted



constant, and k_r=1/T$_s$ [T^{-1}], where T$_s$ is the residence time. Other more sophisticated models have been proposed to explain similar ^{137}Cs depth distributions in sediment cores, with the combined contributions from direct atmospheric deposition and from the catchment (including distinguishing behaviour in different soil types), and taking into account post-depositional diffusion (He et al. 1996). Nevertheless, the available data in our present study do not justify such a degree of complexity, and the SAT model, with a single parameter, will be able to roughly explain the main effects from the catchment (in its "expanded" sense, including erosional areas within the lake).

The measured ^{137}Cs profile for the 2009 core could be reasonably explained using the STA model, assuming non post-depositional mixing, and for simplicity, a constant SAR (which is a mean value for the chronology). Results are shown in Fig. 8 (STA model 1), with parameter values k_r=0.0390± 0.008 yr^{-1} (a residence time of 25.6±0.6 yr), and a SAR of w= 0.538±0.06 gcm^{-2} yr^{-1}. Associated uncertainties arise from the typical fitting procedures. The residence time governs the shape of the input function (^{137}Cs fluxes onto the sediment) and thus it can be found by inverse modelling. In the relatively few applications of the STA model, residence times ranging from 6.7 to 23 years have been reported (Abril and García-León 1994; Robbins et al. 2000; Abril 2004). Moderate variations in SAR around the mean value will produce moderate distortions of the line in Fig. 8, but will maintain the position of the peak and overall shape of the ^{137}Cs profile. Thus, Fig. 8 includes two additional modelling exercises using the time series of SAR produced by the CRS model (see Fig 7, after

Fig. 7 Sediment accumulation rates versus CRS-dates for the Ichkeul cores sampled in 2009 (this work), using the CRS model with the reference point method, 1997 (data from Appleby et al. 2001) and 1982 (data from Stevenson and Battarbee 1991). Vertical error bars correspond to 1σ, propagated errors (data not available for core 1982). Horizontal bars relate to the thickness of the measured sediment slices



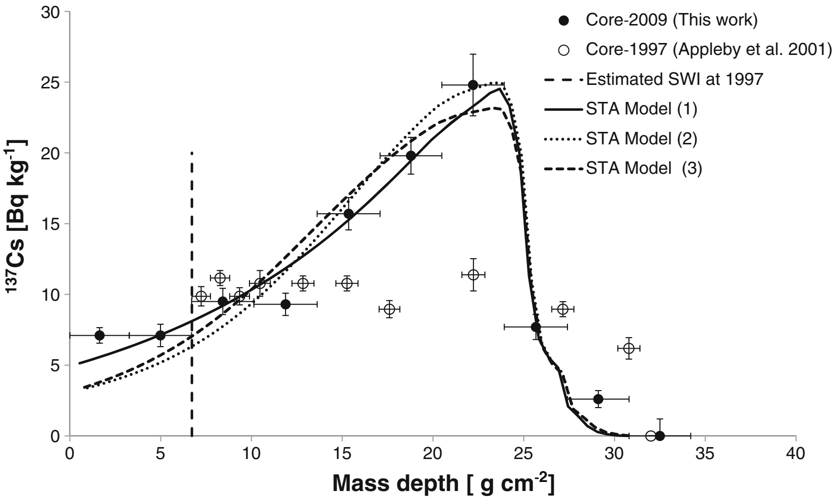


Fig. 8 Measured ^{137}Cs activity (dots, with 1-sigma error bars) versus cumulative mass in the Ichkeul cores: 2009 (this work); and 1997 (from Appleby et al. 2001). For comparison, data for the 1997 core were corrected for radioactive decay to 2009, and the position of the SWI was adjusted by an averaged w=0.56 gcm^{-2} yr^{-1}. The continuous line corresponds to the STA model (1), assuming non post-depositional mixing and constant SAR. The best fit provided parameter values k_r= 0.0390±0.008 yr^{-1} and w=0.538±0.06 gcm^{-2} yr^{-1}. STA-Model (2) uses SAR produced by the CRS model (Fig. 7, after being smoothed by a third order polynomial) with a constant k_r=0.039 yr^{-1}; and STA-Model (3) includes time-dependent $k_r(t) = k_{r,0}w(t)/ < w >$, where <$w$> is the averaged value of SAR and $k_{r,0}$=0.039 yr^{-1}

being smoothed by a third order polynomial) with k_r being either (i) constant (STA model 2, k_r=0.039 yr^{-1}); or (ii) time-dependent (STA model 3). The latter is proportional to the time-dependent SAR:$k_r(t) = k_{r,0}w(t)/ < w >$, where <$w$> is the averaged value of SAR and $k_{r,0}$=0.039 yr^{-1}. As underlined by Fig. 8, the basic structure of the profile is preserved and the overall description of ^{137}Cs data was acceptable. It suggests that there is no need to include mixing, thus preserving this basic assumption of the CRS model.

From the STA model, the contribution of the catchment area to the inventory during the last 12 years was 417 Bq m^{-2}. This value, if added to the inventory of the core sampled in 1997, changes the previous ratio between ^{137}Cs inventories to 1.16±0.04, still comparable, and closer to the one derived from the excess ^{210}Pb inventories.

Previous results suggest that atmospheric fluxes of ^{137}Cs are firstly concentrated in the catchment and/or in marginal areas of the lake, after which they are transferred to sediments in the central region of the lake. Given the shallow water depths, the residence time in the water column is thought to be negligible. Pre-depositional integration of atmospheric fluxes does not necessarily violate assumptions of the CRS ^{210}Pb model. If atmospheric deposition of ^{210}Pb is constant, and the geological processes governing the behaviour of the catchment are at a steady state, then the resulting fluxes to the lake sediment will be also constant (Eq. (1)).

3.5 Environmental implications

Variation in sediment discharges in aquatic environments are related to catchment characteristics, climatic conditions, anthropogenic influences (i.e. dams and reservoirs) and can be evidenced by the temporal dynamics of sedimentation rates (Robbins and Edgington 1975; Mahmood 1987; Vaidyanathan 2011). Due to sedimentation processes, in half a century the world's water storage in reservoirs—especially in arid and semi-arid environments—will be half of the current storage capacity, which will have large economic and environmental consequences (de Vente et al. 2005).

Despite the site-to-site variability, the three time series of SAR in Ichkeul Lake (see Fig. 7) follow a common trend of increase over time, within which other major events can be identified. Taking into account the large uncertainties, in the early 1950s there was an increase in SAR, as recorded in cores 1982 and 2009. This can be linked to modifications in the course of the Oued Joumine, carried out in 1948 in order to reclaim a large amount of marshland (Stevenson and Battarbee 1991). Prior to 1947, the sediment load from Oued Joumine was deposited on the marshland to the south of the Jebel Ichkeul. In 1948 a new canal connecting the Oued Joumine to Ichkeul Lake became operational, allowing the river's sediment load to be deposited directly into the lake during the winter.

As documented by Stevenson and Battarbee (1991), this canal was closed in 1963, when a new channel connected the upper course of the Joumine with the eastern plain of the Jebel Ichkeul, being reconnected to the lake water body in 1982. Two years later, the dam at Joumine became operational, reducing the freshwater inflow. A decline in SAR after 1963 is recorded in cores 1982 and 2009 (see Fig. 8), while a slight peak can be recognized in the early 1980s in core 2009.

After 1996, with the construction of the dam at Sejnane and the regulatory sluice at Tinja, SAR remains almost constant, with a slight increasing trend. As discussed previously, the major events in the sedimentological history of the Ichkeul Lake appear to be superposed on a continuous trend of increasing SAR, as recorded in the three cores. Most likely this increase in SAR is linked to changes in land use and the intensification of agriculture.

A decline in the SAR following the reduction of water inflow after the construction of the dams was expected, but the sluice at Tinja also altered the exchange of matter with the Bizerte Lagoon. Other inputs from the catchment could be increasing following intensification of agriculture. Sediment redeposition and focusing still contribute to the SAR in the central part of the lake; meanwhile the system tries to adjust to new base-line sedimentological conditions.

The construction of dams and the diverting of an important fraction of the freshwater inflow could produce other major ecological impacts, such as the flow of nutrients, the salinity, the vegetal bed cover, and the population of migratory birds; which cannot be directly inferred from our present data.

From our results on SAR, at present, the filling of the central area of Ichkeul Lake takes place at a rate of ~0.7 g $\mathrm{cm}^{-2}\ \mathrm{yr}^{-1}$. Consequently, its depth could be drastically reduced during this century, which will likely have a noticeable impact on the ecology of this aquatic ecosystem. Also, as highlighted by Knox (1993), even small changes in climate can cause major impacts in arid areas, and sedimentation in the Ichkeul would likely be significantly affected by global warming.

Excess sedimentation impacting shallow lacustrine areas can be reduced through the concept of "watershed management" that allows for the control of sediment deposition in these waterbodies. This sustainable approach, combines the management of agro- and hydro-systems at the watershed scale, and includes soil bioengineering techniques, afforestation, grassed filter strips, revegetation and the development of sustainable agricultural practices which reduce runoff and soil erosion from agricultural lands (e.g. Goldman et al. 1986; Mabit et al. 1999; 2007). In order to further improve our understanding of sediment dynamics and processes, conventional methods (i.e. hydrographic survey, inflow-outflow approaches) coupled with agro-environmental investigations (e.g. to assess sediment contributions from agricultural lands) should be initiated as soon as possible to establish sediment origins and determine a sediment budget, thus allowing efficient corrective actions. Moreover, the observed spatial variability in bulk densities and radionuclide inventories makes it difficult to determine solid general conclusions, and thus it would be desirable to undertake another multi-core survey to better estimate the siltation pattern in the whole basin.

4 Conclusions

Annual water inputs into Ichkeul Lake are partially controlled by the management of dams, but they are still governed largely by precipitation and unregulated runoff from the catchment, with very large inter-annual variability. Radionuclide inventories of excess $^{210}\mathrm{Pb}$ in the core collected from the lake in 2009 were comparable to those measured in a core sampled in the same area in 1997, but significantly higher than those reported for a core sampled in 1982 in the central-eastern part of the lake. There was a strong linear relationship among these inventories and their respective mass depths. Concerning the $^{210}\mathrm{Pb}$ fluxes onto the sediment derived from these inventories, the value from core 1982 (48.1 Bq $\mathrm{m}^{-2}\ \mathrm{yr}^{-1}$) was much lower than the estimated local $^{210}\mathrm{Pb}$ atmospheric deposition (123 ± 12 Bq $\mathrm{m}^{-2}\ \mathrm{yr}^{-1}$; García-Orellana et al. 2006) while fluxes from cores 1997 and 2009 were comparable or higher than this latter value.

The ratio of $^{137}\mathrm{Cs}$ inventories (decay corrected to 2009) between cores 2009 and 1997, was 1.34 ± 0.06, slightly higher but comparable to those found for unsupported $^{210}\mathrm{Pb}$. When compared against the integrated $^{137}\mathrm{Cs}$ atmospheric deposition (1674 Bq m^{-2}; Appleby et al. 2001), these inventories were higher by a factor 1.6 and 2.1 for cores 1997 and 2009, respectively.

There is observational evidence that internal redistribution of sediments plays an important role in the sedimentary dynamics of this shallow wind-stressed lake. The above observed spatial variability can be understood from the kinetic reactive transport of pollutants in these lacustrine environments.

The excess $^{210}\mathrm{Pb}$ profile for the core sampled in 2009 yielded comparable concentrations and trends with the one collected in 1997 (Appleby et al. 2001). The $^{137}\mathrm{Cs}$ profile, however, showed a distinct peak, but the distribution trend did not follow the atmospheric deposition pattern. Application of the CRS model with the reference point method produced a chronology and SARs consistent with those reported by Appleby et al. (2001) and Stevenson and Battarbee (1991), with an increasing trend in the last three decades.

The whole $^{137}\mathrm{Cs}$ profile can be reconstructed quantitatively from historical records of atmospheric deposition using the STA model without the need to invoke mixing. The STA model, which postulates integration in the catchment and/or other lake areas of atmospheric fallout, and subsequent transfer to the sediments, does not necessarily contradict the assumption of constant $^{210}\mathrm{Pb}$ flux to the sediments, particularly considering the time resolution of the chronology (~6 years) and analytical uncertainties.

Despite the site-to-site variability, the radiometric results from cores sampled in 1982, 1997 and 2009, reveal a common trend of increasing SAR over which other major events can be identified related to river canalizations and the construction of dams. SAR increased from ~0.25 g cm^{-2} yr^{-1} in the early 1940s to ~0.67 gcm^{-2} yr^{-1} today, far greater than the value of ~0.1 gcm^{-2} yr^{-1} for the early 1920s reported by Stevenson and Battarbee (1991) for the east-central part of Ichkeul Lake. Thus, after 13 years of the operation of the sluice at Tinja, SAR in the central Ichkeul Lake has not been reduced. Lake sedimentation, if it were to continue at the present rate, would seriously alter the hydrology and ecology of this shallow lake in the coming decades.

Acknowledgements The authors gratefully acknowledge the support provided by the International Atomic Energy Agency. The work reported in this paper was undertaken as part of the IAEA Technical Cooperation Programme (Project RAF7/008). The authors would like as well to thank the editors and reviewers for their comments, which substantially improved the initial submitted manuscript.

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