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Reconstruction of the Evolution of the Hydro-Sedimentary Signal to the Sea from the Study of the Sedimentary Archives: Case of the Wadi Cheliff, Algeria

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Abstract

This work focuses on the study of several fluvial cores to help better understand the contribution of rainfall and large dams in the decline of sedimentary inputs of the Wadi Cheliff at its outlet. Therefore, three sediment cores, sampled in the lower Cheliff valley, downstream of dams, were studied through the paleohydrological approach. Then, the granulometric and geochemical profiles obtained were correlated with ^{137}Cs profiles, hydrological data of the Wadi Cheliff at the station closest to the Sea, Sidi bel Attar, the evolution of the rainfall signal and the data on the large dams. Such an examination aims, on the one hand, to establish a chronology of depositional accumulation and, on the other hand, to evaluate the ability of the information contained in the sedimentary archive to transcribe the evolution of the hydro-sedimentary signal and the fluctuations of the controlling factors. The results reveal a strong variation in the granulometric distribution of the deposits and a progressive decline in the rate of sediment accumulation. Thus, the upper part of the core is mainly made of particles belonging to the silt and clays granulometric classes that have accumulated with an average rate of about 1.31 $cm.y^{-1}$, contrary to the deposits in the lower part of the core composed of a succession of sand and finer sedimentary layers, and showing an accumulation rate much more superior, which value is evaluated to 16 $cm.y^{-1}$. However, the fluctuations observed in the granulometric composition, and the accumulation rate of the deposits correlated strongly with the evolution of the rainfall signal and/or the multiplication of the number of large dams. Indeed, frequent sand deposits and a higher accumulation rate correspond to the wet period before 1980. Then, the decrease in rainfall has been accompanied by a lower accumulation rate, and deposits composed mainly of clay and silt particles. In addition, the recently built dams have a drastic effect on the deposition process. Thus, the accumulation rate has been strongly slowed, and the deposits are short of the sand fraction. This study shows that the deposition process is closely linked to the hydro-sedimentary yield of the Wadi Cheliff to the sea, as it shows that the information present in the sediment archive accurately reflects the evolution of rainfall signal and the effect of large dams on the decline of sedimentary inputs from the Wadi Cheliff to the sea.

Keywords: sedimentary archive; paleohydrological approach; Wadi Cheliff; rainfall; dam; granulometric profile

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1. Introduction

Traditionally, sediment yield in watersheds is assessed through the measure of sediment load at the watershed outlet or at key points along the river [1]. The results of such an approach provide a general assessment of the intensity of land degradation and offer a spatially clustered representation of the different components of the sediment record and the resulting changes, as well as monitoring the temporal evolution of the sediment production of the catchment [2]. Nevertheless, the absence or scarcity of continuous sediment load monitoring in many rivers around the world limits investigations related to sediment transport and is a disability for any attempt to assess, understand and document sediment dynamics [3–6]. More recently, the growing awareness on the environmental and socio-economic role of river sediment loads combined with the concerns related to the impact of climate change and intensification of anthropogenic activities on the different components of the sediment budget has shown the need to have sediment information over a long time period [2,7]. To this end, the exploitation of the sediment archive via appropriate techniques is a very promising area to address the many issues related to the absence or the lack of instrumental information related to the hydro-sedimentary yields of watersheds. Thus, Walling [8] demonstrates the interest of combining more traditional monitoring techniques with techniques related to the study of the sedimentary archive, in particular the use of environmental radionuclides. Today, there are many identified areas of application of these environmental radionuclides either as a tracer [9–11] and important timers for the determination of sediment accumulation rates [12]. One particular group of environmental radionuclides stands out from the others, namely fallout radionuclides. These originate from atmospheric testing of nuclear weapons, which occurred during the period 1940 to 1980 [13]. These tests introduced many radionuclides into the atmosphere on a global scale, which have been deposited and accumulated on the Earth's surface since the mid-1950s [14]. Cesium-137 (^{137}Cs) is the most widely used fallout radionuclide by environmental scientists as a sediment tracer and timer [2,7,12,13,15–20]. The latter (^{137}Cs) is characterized by its strong binding to the surface of silt and clay particles and its presence indicates that the sediments or soil has been exposed to atmospheric nuclear fallout [13,21]. ^{137}Cs dating is present in many multi-proxy approaches aimed at either reconstructing flood depositional history [12] or identifying sediment sources and establishing the relative contribution of these sources to the total sediment yield [1,2,11,22,23] as it is employed in the estimation of erosion and deposition rates and sediment budget of a watershed [7,24]. Furthermore, this technique is highly responsive in reconstructing extreme paleo-events and paleo-environments in lagoon [25] and lake environments [26,27]. More recently Kotti et al. [28] have attempted to document the sedimentation rate in floodplains and back-waters of rivers via this technique. Similarly, ^{137}Cs is involved in confirming the dating of sediment cores established by lead-210 (^{210}Pb) geochronology [29,30].

Dating with ^{137}Cs and ^{210}Pb is an important step in a concept for the analysis of flood and low-flow sediment deposits accumulated in caves, lakes, lagoons, river oxbows and floodplains [12,31–33]. This recent theme, called paleo-hydrology, brings together many proxies to reconstruct the history of floods and document the chronology of sediment accumulation. Indeed, the difficulty in using this approach differs according to the nature of the environment studied, e.g., the sedimentary archive preserved in closed environments (lakes, lagoons, etc.) is generally more complete and easier to interpret compared to flood deposits in floodplains and low valleys. Thus, the erosion/conservation phenomenon conditioned by the amplitude and frequency of river flows generally hinders the conservation of previously deposited sediments in depositional areas [12]. However, the change in fluvial conditions for some rivers and wadis favors the formation ^{137}Cs of sediment depositional areas over a long period of time. For example, rivers draining North African

catchments show a great shrinkage for decades as a result of the combined effect of large dams and decreasing rainfall [28,34]. This has promoted the stabilization of vegetation, providing a means of protection against erosion during subsequent large flood events [12]. The palaeohydrological approach is applied via the use of an array of tools and methods. It combines granulometric study, geochemical analysis and dating techniques. Other proxies are added according to the studies, such as flow records and rainfall measurements, as well as the inventory of anthropogenic actions [12,25,28].

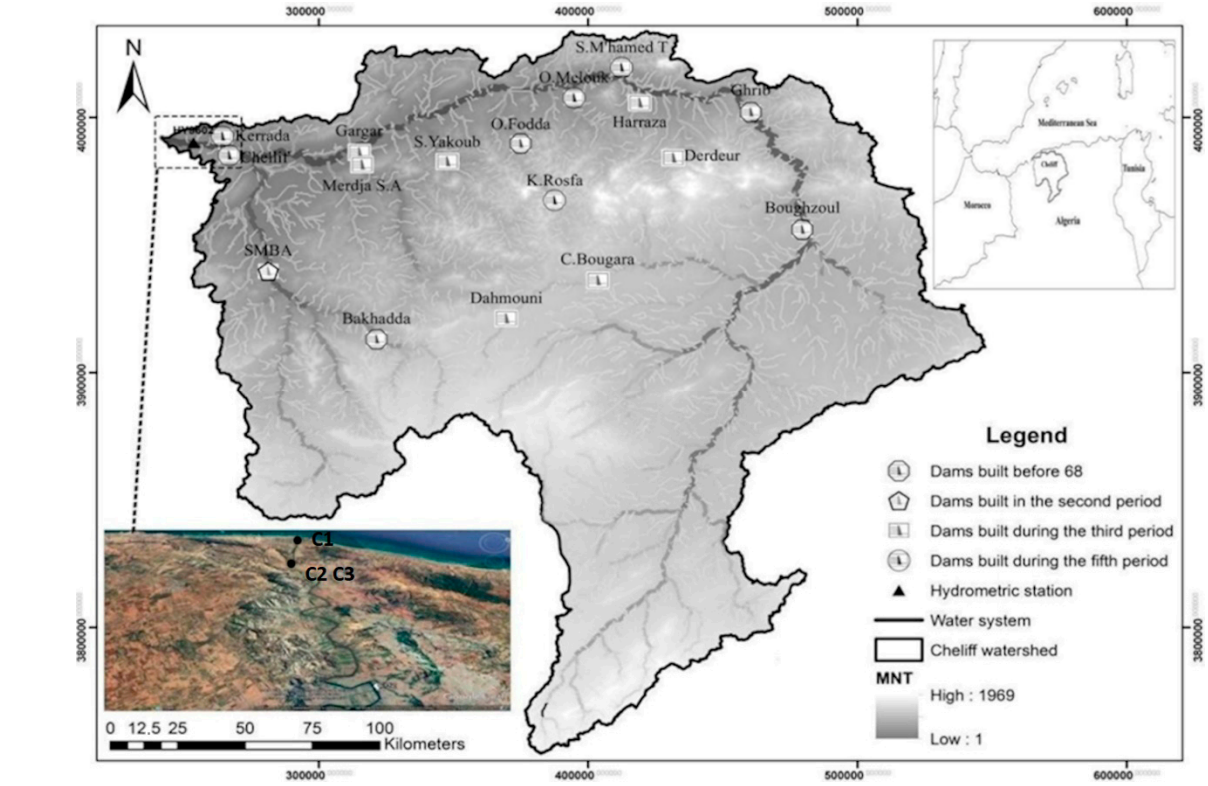
The literature includes few works relating to the study of artificial radionuclides in Algerian soils. In total, three campaigns of sampling and evaluation of the content of artificial radionuclides in the soil have been carried out since 1986. The first survey was carried out during the first half of 1986. It was launched with the aim of assessing the environmental impact of the Chernobyl accident on the entire northern land strip of Algeria. Other works followed this pioneering experience, namely the 1993 campaign carried out over the entire administrative territory of Algeria and the 1999 campaign carried out along the Algerian coast. If the 1993 work sought to evaluate the radionuclide contents in the upper layers of the soil (0 to 15 cm), that of 1999 aimed to define a reference level of natural and artificial radionuclides in water and marine sediments [35]. We also highlight the work performed by Nadri et al. [36] on the estimation of depth profile of ^{137}Cs and ^{210}Pb activity in the regions of Ghardaïa and Reggane, located in southern Algeria. In terms of results, ^{137}Cs activity was clearly identified in soil and sediments with more or less marked variations. Thus, the highest ^{137}Cs concentration recorded was (41 $\pm$ 4) Bq. kg^{-1} dry mass. The surface distribution of ^{137}Cs activity shows a strong inhomogeneity between regions, depending on the physico-chemical characteristics of the soils (e.g., grain size, organic matter content, etc.) and the importance of rainfall.

The problem of the decrease in terrestrial sediment supply to the oceans is real and concerns most of the world's rivers [4]. Scientists point to the combined effect of climate change and anthropogenic action [8,37–40]. Indeed, the recent environmental change has strongly modified the erosion and sedimentation mechanisms, consequently the sedimentary inputs to the sea. Nevertheless, the absence of measurement chronicles, in many rivers of the globe, constitutes a hindrance for any investigation aiming at quantifying and documenting the evolution of the contribution of these catchments [4,5]. In the case of the North African countries, for example, except for Algeria, no other country has continuous measurements on the supply of terrestrial sediment to the Mediterranean Sea. Attempts have been undertaken by Kotti et al. [28] and Aoula et al. [41] to assess the contribution of dams and climate in the decline of sediment supply to Wadi Mejerda and Bouregreg, respectively. This was performed through the paleohydrological approach. Nevertheless, we question the reliability of the information incorporated in the sedimentary archive to transcribe the evolution of the hydrosedimentary signal, on the one hand, and its correlation with the evolution of the climatic signal and the anthropogenic action, on the other hand. In an attempt to provide answers to these questions, the present study attempts to document the sedimentary archive of the Wadi Cheliff. Then, to compare it with the instrumental information relating to the evolution of the hydro-sedimentary contributions of the Wadi Cheliff to the Mediterranean, to the evolution of the pluviometric signal and to the history of the dams [34]. It includes: (1) A granulometric, geochemical and chronological analysis of the deposits accumulated in the lower Cheliff valley; (2) A comparison between the information incorporated in the sedimentary archive and the instrumental information related to the hydro-sedimentary regime, climate and the evolution anthropogenic action; (3) A discussion of the contribution of the sediment archive documentation to the reconstruction of the hydro-sedimentary signal and its ability to transcribe fluctuations in controlling factors related to climatic and anthropogenic action.

2. Framework of the Study

Located in the north-west of Algeria, the Cheliff watershed has an area of about 44,900 km^2. It is geographically delimited by the Dahra Mountains in the North, by the Saharan Atlas in the South, by the Oranese watershed in the West and by the Algerian watershed in the East (Figure 1A). The morphology of the Cheliff shows a succession of four types of relief which follow one another from north to south. These are the coastal zone, the valleys of the Cheliff, the mountainous chains of the Tellian Atlas and the high lands. The most important wadi is 250 km long and bears the same name of the watershed. From the exit of the Boughzoul dam, where it originates, the Cheliff winds its way through the Atlas mountain range, the Cheliff valleys, and the coastal area before flowing into the sea. Along its course, many tributaries join it, especially in the Atlas Mountains. The watershed is endowed with a very dense hydrographic network in the Tell part; on the other hand the high lands are characterized by a weak density of drainage.

The climate of the Cheliff is of the semi-arid Mediterranean type [42], which is associated with a very irregular rainfall pattern in time and space. Precipitation is concentrated on only a few days per year, with low frequency and high intensity. Summers are generally hot and dry, while winters are mild and wet. The dry period succeeded the wet period since 1980 [43–45]. This resulted in a rainfall deficit, between periods, of about 100 mm [45]. Similarly, rainfall shows a strong spatial disparity, with rainfall in the northeastern part, about 600 $mm/year^{-1}$, being twice as high as in the northwestern region. The slopes of the Cheliff are highly vulnerable to water erosion and runoff [46–49]. Such vulnerability is the combined effect of low vegetation cover and relatively soft lithology. Thus, marl and clay formations predominate in the mountain ranges, while the plains are mainly composed of limestone and alluvium. However, the forest area is very small compared to the agricultural land. In the Cheliff, the interactions between humans and the landscape take many forms. Amongst these are those linked to soil conservation and those corresponding to the mobilization of water resources. The results of the various mechanical and biological techniques used in erosion control have been disappointing and their impact is less well known. The alterations introduced by the large dams into the Cheliff landscape are very remarkable. There are 17 of these reservoirs with a total capacity of about 2284 Hm^3, intercepting more than 70% of the total runoff from the Cheliff. These stored volumes are then generally diverted out of the watercourse. In terms of silting, these reservoirs currently intercept an annual mass of more than 20 million tons of sediment. The decrease in rainfall combined with the multiplication of actions related to the mobilization of water resources have strongly modified the hydro-sedimentary regime of the lower Cheliff river. The latter is endowed with an irregular regime, characterized by alternating periods of high and low water, where the major part of the liquid and solid flows at the outlet is associated with flash floods, occurring on a few days of the year. Nevertheless, climate and anthropogenic action have strongly decreased the magnitude and frequency of floods, the yields of liquid and solid flows to the sea and have led to a modification of the morphology of the river [34]. Thus, a strong narrowing of the flow section and a strong vegetation of the banks have been observed along the downstream river [34].



(**A**)



(**B**)

Figure 1. (**A**). Presentation of the study area, monitoring and sampling sites. (**B**). Detail of sampling sites locations: CH1 near the shore, CH2 and CH3 some km upstream. Sidi Bel Attar hydrometric station further upstream (S).

3. Sampling, Data and Methods

Sediment cores are the basic data for a paleohydrological study of the fluvial or other sedimentary archive. A prerequisite for any analysis is the collection of cores from sites of potential interest. Therefore, the choice of site must meet many criteria related to the hydro-sedimentary regime of the river and the objective of the study. Thus, when choosing the site, we favored relatively protected and occasionally flooded depositional areas. The identification of these zones was performed through an understanding of the hydro-sedimentary dynamics and the documentation of the morphological evolution of the watercourse, as well as an assimilation of the extent of the floods. However, the approach of this study introduced other constraints related to the representativeness of the site in

terms of total sediment flow towards the sea, and its location, which must be close to the hydro-sedimentary measurement station of interest. The various favorable sites were validated following a field mission, dated 10 May 2018, accompanied by a team of experts in morphology and hydrology. A total of three sediment cores were collected in the lower Cheliff valley, downstream of the last dam before the sea and near the hydrometric station of Sidi Bel Attar (Figure 1A,B). The first sediment core (CH1) 1.6 m long was sampled in June 2018 near the mouth of the Wadi Cheliff (Figure 1B), where it can be noticed that the sandy delta at the mouth of the river is reversing. The second core (CH2) measuring 5 m long was sampled in November 2019 in a meander located halfway between the Cheliff dam and its outlet. In addition, the third core (CH3) measuring 4.04 m in length was sampled in December 2020, from a meander located below the second core collection site.

The collected cores were sent to the laboratory for particle size, geochemical and chronological analysis. Thus, the particle size analysis was carried out in the wet state on every two centimeters of the sedimentary profile, the range of analysis of the sedimentary particles is included between 0 and 2 mm. In order to ensure a better deflocculation of the particles, especially those of clays, a deflocculant solution, based on sodium silicate, and ultrasound were used before and during the measurement, respectively. The apparatus used was Beckmann Coulter LS13 320 laser diffraction (Geoscience laboratory, Montpellier and Continental and Coastal Morphodynamics laboratory, Caen, France) [12,25,28,41]. Then, geochemical analyses were performed using a Nikon XL3t and XL5t+ portable spectrometer (X-ray fluorescence; Geoscience Montpellier laboratory and Continental and Coastal Morphodynamics laboratory, Caen, France). The protocol for preparing the samples for measurement consisted of placing each 2 cm sedimentary layer in an oven at 40 °C for at least 48 h to dry. Then, the sedimentary layers were finely crushed and put in boxes covered with a plastic film. The measurement was carried out, at the fixed stand, according to two different modes; namely, the Soil mode and the Manning mode, with a duration of 180 s for each measurement and for each mode.

For the time series analysis, representative subsamples with a weight ranging from 27 to 35 g were carefully selected for the measurement of ^{137}Cs, ^{210}Pb and ^{226}Ra activity. Then, each subsample was packed in a small tube or a small airtight box and stored for 3 weeks before the radiometric assay, in order to ensure the equilibration between ^{226}Ra and its ephemeral descendant ^{222}Rn [2,7,12,28,41]. The activity of the nuclides of interest was measured by gamma ray spectrometry, using a Canberra BEGe 3825 well detector, coupled to a PC-based digital analysis system with CANBERRA GENIE 2000 software. A counting time of at least 222.55 s was adopted for each measurement. Similarly, the reliability of the measurements was verified by comparing the results obtained with those of an internal standard, for which the activity of the various radionuclides was already known. All analyses were carried out at Laboratoire Géosciences, Montpellier, France. The content of each subsample in total ^{210}Pb, ^{226}Ra and ^{137}Cs radionuclide was obtained through the integration of the peak air corresponding to the 46.5 Kev, 351.9 Kev and 661 Kev energy of the gamma spectrum, respectively. The ^{210}Pb concentration exassociated with a subsample was the difference between the total ^{210}Pb activity and the ^{226}Ra concentration measured [2,12,13,24]. The uncertainty associated with the measurement of ^{137}Cs, $^{210\ total}$ Pb and ^{226}Ra did not exceed 6%, 4% and 1.5% for the three nuclides, respectively. The decrease in activity of excess ^{210}Pb (^{210}Pbex) in soils is by radioactive decay following the radioactive decay law [25]. From this decay law, three models were developed to determine the timing and accumulation rate of sediments, through measurement of ^{210}Pb activity [25].

Firstly, a comparative study was carried out between the distribution and accumulation rate of sedimentary deposits and the evolution of liquid and solid flows at the Cheliff

outlet. For this purpose, the instrumental archive collected at the Sidi Bel Attar station was used. Indeed, this station is located downstream of the last dam and 11 km from the Che-liff outlet. It offers a chronicle of liquid and solid flows over a period of 32 years, from 1968 to 2001 [34]. This instrumental information relating to the hydro-sedimentary yield of the Wadi Cheliff to the sea informs us on the temporal distribution of extreme events and their amplitudes. The methodology consisted of verifying, on the one hand, the presence of a concordance between the hydro-sedimentary signal and the evolution of the deposits accumulated at the outlet and, on the other hand, the presence of a possible link between the most energetic events and the coarsest and thickest sedimentary layers. However, instrumental information will be able to refine the accuracy of the depositional chronology established by radioactive chronometers. The hydro-sedimentary regime of the Cheliff is closely linked to climatic variability and anthropogenic actions. Hadour et al. [45] underline the strong decrease in the Cheliff's contributions to the sea following the combined effect of the decrease in rainfall and the multiplication of large dams. In this changing context, the effect of these modifications on the sediment accumulation process at the Cheliff outlet is questionned, as it is asked whether the information incorporated in this analyzed archive is able to transcribe these modifications alone. However, the rainfall information relating to the intensity and magnitude of the events, as well as the temporal location of the dry and wet periods, could be indications that help to have a chronology of sediment accumulation that is as precise as possible. Average annual rainfall data over a 42-year period, from 1968 to 2010, were used in this study. This average annual rainfall was calculated by [34] based on the records of 50 rain gauge stations. As we used the records of station 3002 offering the longest period of record, 1930–2010. In terms of anthropogenic action, large dams remain by far the structures that most alter watershed hydrology and related processes. In the present study a wide range of information on the characteristics of the dams, their conditions and their management methods was used. The history of dams in the Cheliff began in 1932 with the construction of the first structure; at present, there are 17 large dams with a total capacity of about 2284 Hm^3 (Table 1).

Table 1. Summary of the characteristics of the various reservoirs on the Cheliff.

Barrage	Lat	Long	Y *	IC *	AI *	AS *	SV *	D *
Koudiet Rosfa	35.843986	1.752254	2004	75	44.58	1.15	12.41	SD **, IR **
Boughzoul	35.748648	2.775432	1934	55	82.8	0.66	42.65	FC **
Colonel Bougara	35.566364	1.937242	1989	13	9	0.3	5.28	IR **
Chellif	35.983530	0.412956	2009	50	61	7.5	—	SD **, IN **
Dahmouni	35.426159	1.563480	1987	41	13.3	0.4	6.28	SD **, IN **, IR **
Derdeur	35.998898	2.241917	1985	114.95	45	0.83	19.79	SD **, IR **
Bakhadda	35.345470	1.036586	1936	56	72	0.27	19.30	SD **, IR **
Gargar	35.960972	0.961746	1988	450	185	4.5	145.47	SD **, IR **
Ghrib	36.163019	2.561064	1939	280	148.5	3.2	203.08	SD **, IR **, T **
Harraza	36.193561	2.100654	1984	70	30.8	0.28	3.36	IR **
MERDJA SIDI ABED	36.001157	0.955489	1984	55	40	0.59	13.68	IR **
Oued Fodda	36.045583	1.611526	1932	228	120	2.66	157.07	SD **, IR **, T **
Sidi M'hamed Ben AOUDA	35.573387	0.586883	1978	235	148.5	1	93.30	SD **, IR **

Table 1. *Cont.*

Barrage	Lat	Long	Y *	IC *	AI *	AS *	SV *	D *
sidi M'hamed Taiba	36.318590	2.024604	2005	75	76	0.4	5.98	SD **, IR **
ouled melouk zedin	36.208873	1.829678	2003	127	47.5	1.4	24.76	SD **, IR **
SIDI YAKOUB	35.976003	1.313246	1986	280	98	0.17	29.19	SD **, IR **
Barrage de Kerrada	36.050290	0.381021	2010	70	1.47	—	—	SD **

Note: Y *: Year the dam was impounded. IC *: initial capacity. AI *: Annual input. AS *: Annual siltation. SV *: Silted volume up to 2017. D *: destination. SD **: Supply of drinking water. IR **: Irrigation. IN **: Industry. T **: Transfer. FC **: Flood control.

The chronology of the equipment of the Wadi Cheliff in reservoir shows that the construction of all the works was performed in three distinct periods (Table 1). These are the periods 1932–1939, 1978–1989 and 2003–2010. The dams of the first period, four in number, were built on the upstream tributaries of the Cheliff. On the other hand, the eight dams of the second period intercept the inflows of the various tributaries of the Tell. The downstream part of the Cheliff is equipped with works, five in total, during the third period.

4. Results

4.1. Particle Size and Geochemical Analysis

The results of the analysis of the first CH1 and second CH2 cores are shown in Figures A1 and A2 in Appendix A. In this paper the discussion is limited to the third core CH3. This is due to the insufficient length of the first core and the interference of the global signal of the Cheliff by the contributions of a secondary tributary, located near the sampling site of the second core.

The particle size and geochemical composition of the CH3 core is shown in Figure 2, which includes a stratigraphic log, the evolution with depth of the median diameter and the iron (Fe) and zirconium (Zr) content. The stratigraphic logo includes a first column corresponding to the results of the dominant sediment type based on the observation, and a second column summarizing the results corresponds to the granulometric composition of each sample, obtained via a laser granulometer.

The analysis of all the results shows that the sedimentary contributions of the CH3 core present a succession of sandy, silty and clayey deposits. However, the particle size composition, thickness and distribution of the accumulated layers, combined with the results of the Fe and Fr profile along the core, reveal five distinct accumulation phases. These are distributed as follows: from the base to 29 cm, the sedimentary layers of the CH3 core consist mainly of fine sand and silts. It is noted that the sand layers are thick and very recurrent, while the presence of silt is more important than that of clay. The median diameter distribution (D50) shows fluctuations ranging from 3 to 73 µm. Furthermore, at the fine element optima (clay and silt) a high Iron (Fe) content is associated. In contrast to the sandy peaks which show low Zirconium (Zr) content, from 291 to 230 cm depth, the grain size composition of this fragment is predominantly silt with the presence of a few fine layers of sand, which are spaced out. The increase in clay content of this fragment compared to the one below is highlighted. D 50 varies along this segment, between 2 and 61 µm. Fe shows a strong affinity to clay deposits. However, the sandy deposits are very rich in Zr, from a depth of 230 to 129 cm, there is a strong accumulation of sandy deposits, whose successions are interfered by some silty and clayey layers. The sandy deposits were

characterized by relatively large thicknesses and the presence, even, of coarse sand. The fluctuations of D50 oscillate between 2 and 213 µm. The geochemical composition of the sandy layers shows a high concentration of Zr and a low content of Fe, from 129 to 75 cm depth, a progressive decline of the sand content is observed, with a simultaneous increase in the clay percentage while the amount of silt present in the different samples is relatively stable. The D50 reaches a maximum of 34 µm. The content of geochemical elements (Fe and Zr) confirms this signal change, of which the curve of Zr shows a bearish slope, in contrast, to that of Fe presenting an ascending profile, from a depth of 75 cm to the top, the particle size composition is characterized by a strong presence of fine elements, particularly clay. However, sandy deposits are almost non-existent. Small fluctuations are associated with D50, whose values oscillate between 2 and 11 µm. The Fe content reaches its maximum, while the Zr concentration is the lowest ever recorded.

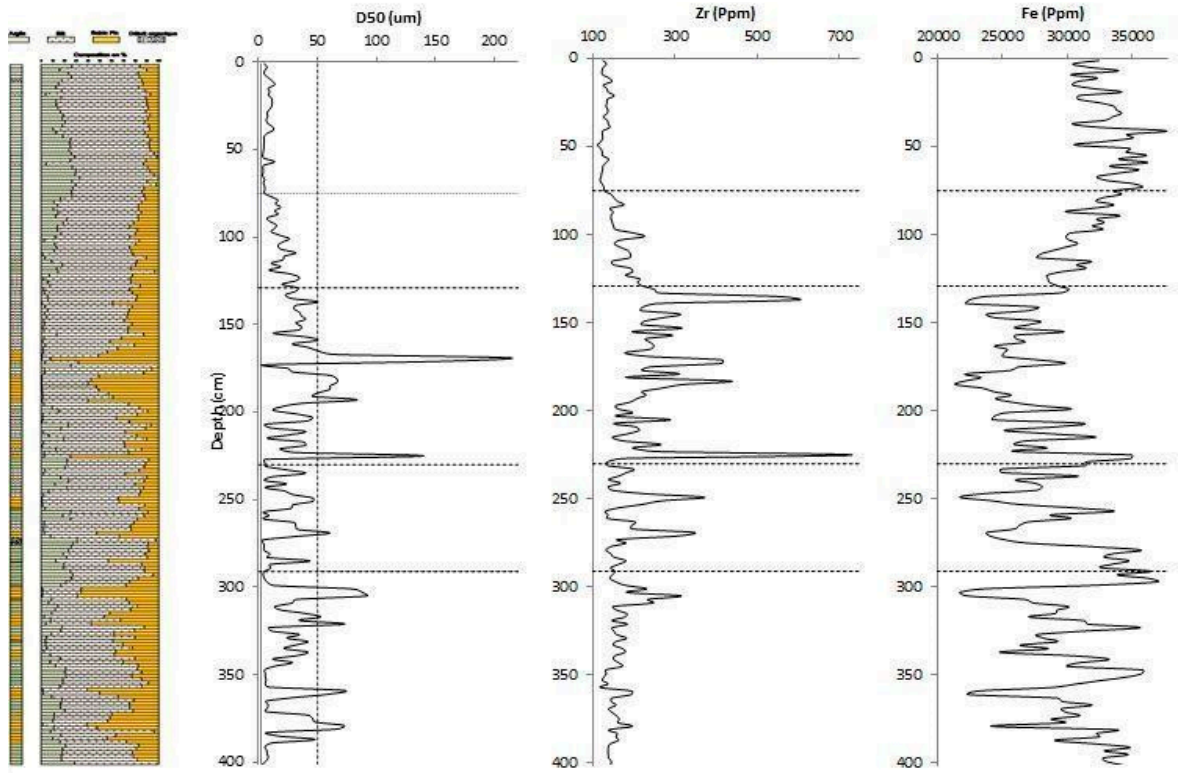


Figure 2. Granulometric distribution l and content in Zr and Fe in the sediments of the CH3 core.

At the end of these analyses, the strong variability of the granulometric nature of the deposits is underlined and the presence of more or less striking trends. Moreover, the geochemical composition depends, relatively, on the granulometric nature of the deposits. Thus, sandy deposits are associated with a high concentration of Z, whereas the clayey deposits are very rich in Fe. In addition, we observe a concentration of sandy deposits, more or less thick, in the lower part and the medium part of the core. Then, sand is almost non-existent from 129 cm depth to the top. This change in particle size distribution, marked by a very low coarse particle content, reflects the low frequency of energetic events, during the period of accumulation of surface deposits, from a height of about 129 cm. In fact, these exceptional events of the river have a significant transport capacity, ensuring the transit of sand to the outlet.

4.2. Chronological Analysis

The ^{137}Cs and ^{210}Pbex activity profiles were used to establish an age model. This is to reconstruct the temporal evolution of sediment accumulation at the Cheliff outlet. Then,

the age model ^{137}Cs activity has been clearly identified in the deposits contained in the CH3 core with more or less marked variations. Referring to the work of [13] on the first year of ^{137}Cs detection in soil and sediments, all deposits in the CH3 core are post-dated to 1950. The distribution of ^{137}Cs activity along the sediment core shows a succession of three radioactive anomalies. These anomalies correspond to activity peaks identified at the top, center and bottom of the core. The first peak is about 5 mBq.g^{-1} and is identified at 45 cm depth. Then, a second peak appears at about 227 cm depth, with an estimated ^{137}Cs activity of 6.75 mBq.g^{-1}. However, the largest peak of about 8 mBq.g^{-1} is identified at the bottom of the core at a depth of about 349 cm (Figure 3). An approach has been adopted in attributing the origin of these radioactive anomalies, observed in the accumulated sediments in the lower Cheliff valley, by considering three major events [28,36,41]. These are mainly the Chernobyl accident (1986), the global fallout of nuclear weapons tests (1963) and the French atmospheric nuclear tests in the Algerian Sahara (1960). Thus, the surface peak probably corresponds to the fallout associated with Chernobyl. The radio-cesium anomaly identified at 227 cm depth can be attributed to the maximum fallout from the atmospheric tests. However, there are major difficulties in identifying the origin of the largest peak, located at 349 cm depth. This is due to its restricted spatial distribution and the lack of documentation regarding the best candidate to explain such a peak. Indeed, the work carried out in the region, notably in Tunisia and Morocco, testifies to the presence of only two radioactive anomalies attributed to the Chernobyl accident and to the maximum of the fallout from atmospheric tests, respectively [28,41]. On the other hand, work on the distribution of caesium-137 in soil and sediments in Algeria shows the presence of such a peak. French atmospheric testing has been identified as a potential candidate for the origin of this anomaly. Nevertheless, the lack of documentation of these tests is a major obstacle to validating such a hypothesis [36,50]. The sediment accumulation rate, projected according to ^{137}Cs age model results, shows a progressive decline. Thus, for the period 1952–1963, the sedimentation rate is estimated at 16 cm/y^{-1}. Then, sediments were accumulated with an average annual rate of about 7.9 cm during the period 1963–1986. On the other hand, the most recent period (1986–2021) has seen a drastic decrease in the sediment accumulation rate with only an annual rate of about 1.31 cm.

However, the CH3 core samples show a low ^{210}Pbex content, with values that did not exceed 0.8 mB./g^{-1}. This may be due to the fact that ^{210}Pb adsorbs less on medium-coarse samples, contrary to the fine elements where the adsorption is better.

4.3. Correlation with Liquid and Solid Flows at the Outlet

The flood history recorded at the Sidi Bel Attar station over a period of 32 years, from 1969 to 2001, was compared simultaneously with the granulometric and ^{137}Cs dating re-sults (Figure 4). Based on the assumption of a relationship between flood magnitude and grain size/deposit thickness, such a comparison aims at refining the chronological framework of sediment accumulation. The chronicles of the floods at the Cheliff outlet (Figure 4) show that the events exceeding 1000 m^3.s^{-1} are very frequent (occurring once every 2 or 3 years), during the period 1969 to 1979. Thus, in 1969 a flood of about 1100 m^3.s^{-1} was recorded, with an estimated solid flow of 65,600 kg.s^{-1}. Then, the year 1972 was marked by a major event, the largest ever recorded, with a discharge of about 2400 m^3.s^{-1} carrying a sediment load estimated at 106,800 kg.s^{-1}. Three major floods followed this major event. They occurred in 1974, 1976 and 1979, respectively. The liquid and solid flows correspond-ding to each flood were approximately 1280, 1090, 1540 m^3.s^{-1} and 56,000, 62,000 and 88,000 kg.s^{-1}, respectively.

However, from 1981 to 2001, major floods were less frequent. Only two events, with a flow rate close to 1000 m^3.s^{-1}, were recorded. One was recorded in 1996 and the other

in 1997. The liquid and solid flows associated with these two events are estimated at 945 $m^3.s^{-1}$, 1312 $m^3.s^{-1}$ and 39,500 $kg.s^{-1}$, 91,600 $kg.s^{-1}$, respectively.

The stratigraphic logo combined with the median diameter profile (Figure 4) shows a strong accumulation of sandy deposits between 157 and 194 cm depth. The median diameter in this sedimentary sequence reaches a very large peak, never recorded, of about 213 µm at 169 cm depth. The succession of many major floods could be the origin of this thick layer of sandy deposits. The chronicle of liquid and solid flows at the outlet shows that the period from 1969 to 1979 is the only one that recorded a high frequency of energetic events. Therefore, the sandy deposits with a thickness of about 37 cm, recorded between 157 and 194 cm deep, could be attributed to the floods occurring between 1969 and 1974. On the other hand, the 1972 flood, the largest ever recorded, could be the origin of the granulometric peak of about 213 µm observed at 169 cm depth. Contrary to the floods observed during the period between 1969 and 1979, those occurring in 1996–1997 did not leave sands, at least in the coring area. This can be explained by the hydro-sedimentary conductivity of the watercourse and the modification of the morphology of the Cheliff.

The CH2 core (Figure A2) gives roughly similar results to the CH3 one, with some perturbations due to lateral influxes from local small tributaries, bringing more sand all along the core. The CH1 core (Figure A1) is a shorter one (145 cm) and shows only clays and silt except for the top with thick sand deposits. The ^{137}Cs peak of at the bottom of the core cannot be associated for sure with the maximum of 1963, which does not allow us to correctly date the deposits. Clays and silts could refer to the most recent decades where it has been shown, from the CH3 core and sediment transport records from the Cheliff river (Ha-dour et al. [34]), that silts and clays transport and deposit where largely predominant. The top layer of sand is associated with large marine intrusions into the estuary which tend to become more frequent since the deficit of river sediment outputs to the sea increases with time.

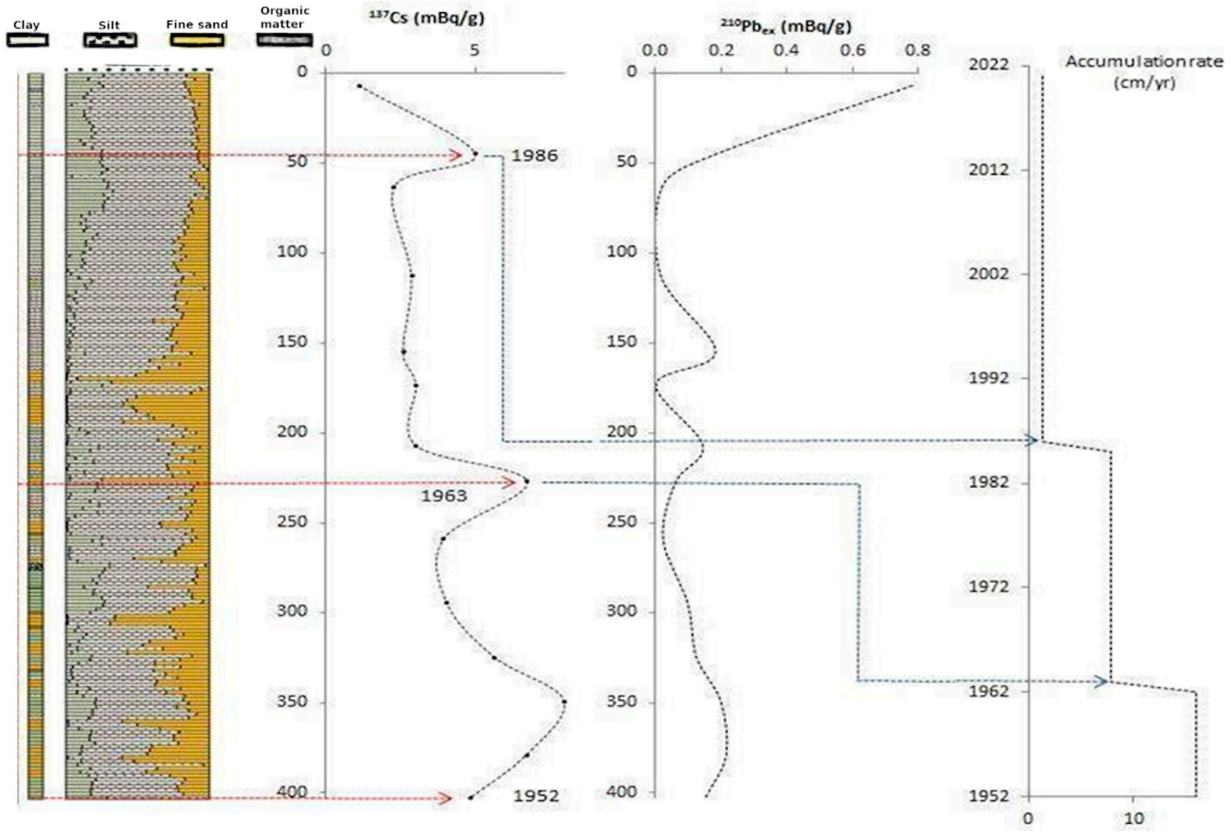


Figure 3. ^{137}Cs and $^{210}Pb_{ex}$ profile and accumulation rate of deposits in the lower Cheliff valley CH3.

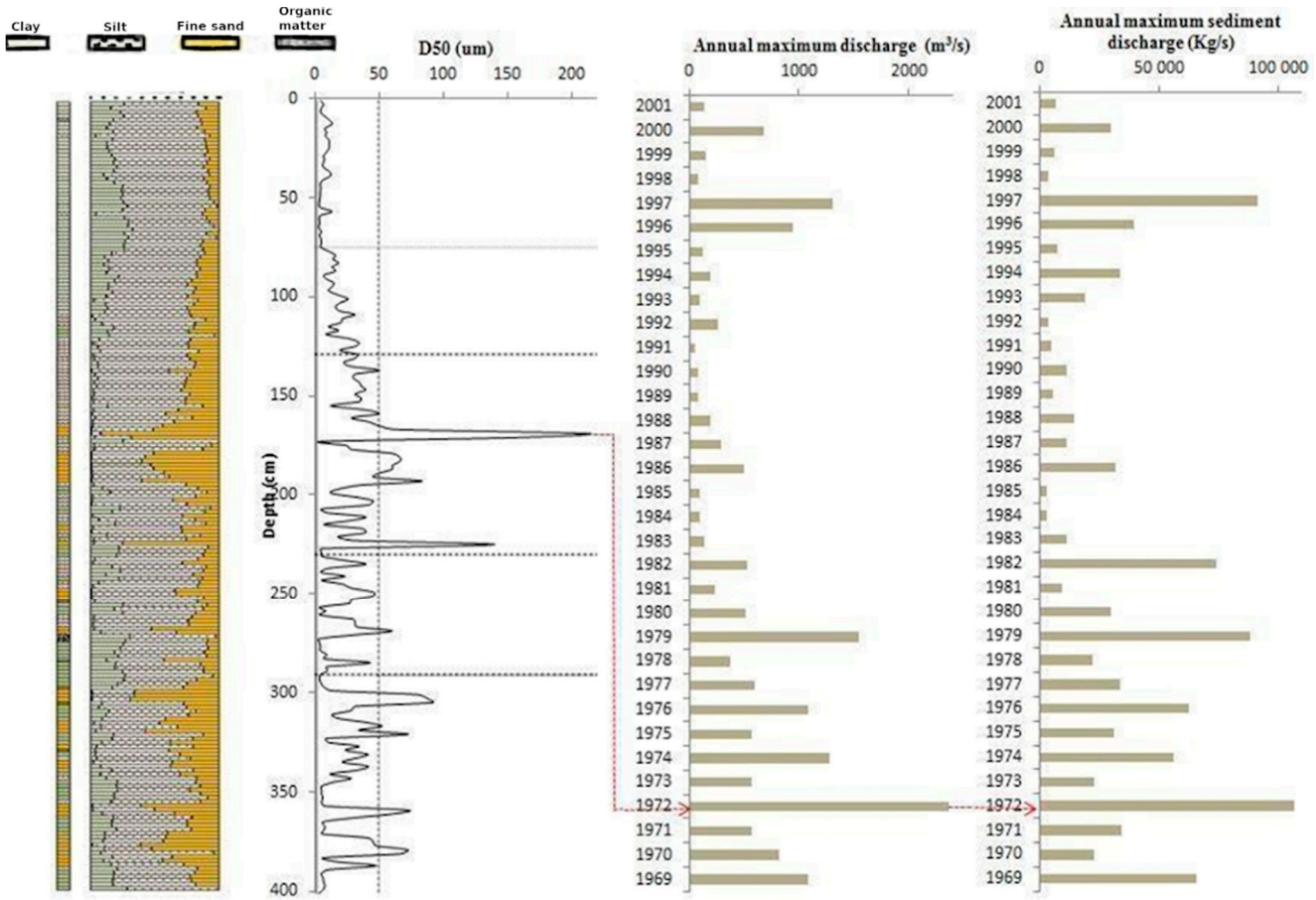


Figure 4. The particle size distribution of the deposits and the record of historical floods and their associated solid flows, CH3 core.

5. Discussion

5.1. Impact of Climate on the Accumulation Rate of Deposits

In a previous study, Hadour et al. [34] demonstrated the close link between climatic fluctuations, especially the temporal variability of rainfall, and the hydro-sedimentary yields of the Cheliff at its outlet. In fact, the rainfall regime in the study area is characterized by alternating dry and wet periods. For wet sequences, abundant hydro-sedimentary fluxes were associated, while dry periods showed less transport capacity. Thus, the chronicle of the rains on the Cheliff, from 1968 to 2012, showed the superiority of the rainfall volumes received during the period 1968–1980 compared to the volumes precipitated during the period 1980–2012. This was due to a rainfall decline which spread throughout the watershed from 1980 onwards. The latter resulted in a rainfall deficit of about 26%, compared to the average rainfall of the wet sequence (1968–1980), estimated at 443 mm. The authors note that the dry period (1980–2012) includes a succession of years of extreme deficit from 1980 to 1995. Then, more or less humid years have been observed since 1995, especially the years 1996, 1997 and 2001. About the link between rainfall and the liquid and solid supply to the outlet of the Cheliff, the study shows that rainfall was the main factor controlling the magnitude and fluctuations of hydro-sedimentary, with a contribution of approximately 89% and 81% in liquid and solid streams, respectively. In contrast, in the dry period, when rainfall conditions decrease the inputs to the sea are lower. Moreover, the contribution of the unit rainfall in liquid (solid) contribution to the seadecreased from 1.75 to 7.78 hm^3 (3.12 tons to 0.69 tons), a decrease of about 77% (78%) during the dry period compared to the wet sequence. This translates concretely into small contributions to the outlet of the Cheliff, even during intense rain events. They conclude that the effect of rainfall on liquid

and solid flows at the Cheliff outlet is highly dependent on its variability. For long and intense droughts, sediment supply is low, while the sediment load associated with wet sequences or rainy events is considerable. In the end, they estimate the contribution of rainfall in the decline of sedimentary inputs from the Cheliff to the sea at about 40%. The simultaneous study of the temporal evolution of rainfall and the particle size distribution of sedimentary deposits (Figure 5) shows a concordance between the evolution of the rainfall signal and the particle size distribution of sediments, especially in the core of the core. On the basis of the results of the chronological markers (^{137}Cs and the chronicle of floods and associated solid flows) it is possible to correspond the accumulated deposits between 0.73 and 2 m, 0.3 to 0, and 0 to 0.3 m of depth, in the period 1968–1980, 1980–1995 and 1995–2021, respectively. Deposits in the period 1968–1980 are characterized by the frequent presence of sand and silts, whose median diameter fluctuates between 5 and 213 µm. This testifies to the recurrence of rainy events, relatively important, providing the stream with the capacity necessary to make transit of coarse particles until the Cheliff valley decline. The recorded floods and the associated sediment load recorded during this period confirm this observation. Then, the deposits between 0.73 and 0.3 m show a gradual decrease in the median diameter of the grains, going from the bottom to the top, with values of the D50 which do not exceed 0.3 µm. This coincides with the succession of many dry years accompanied by a hydrological respite and a drastic decrease in the hydro-sedimentary yield of the Cheliff. However, the period 1995–2010 was marked by a recovery in rainfall, with direct impacts on the Cheliff hydro-sedimentary regime. Indeed, there is an increase in liquid and solid inputs to the outlet of the Cheliff following the increase in rainfall. Nevertheless, the grain size distribution profile shows that the D50 characterizing the top of the core (0 to 0.3 m deep) is relatively low, with values ranging from 5 to 11 µm. This is probably due to the low control exerted by rainfall on the flows exported to the outlet during this period and the decrease in its contribution, as well as the modification of the hydro-sedimentary continuity of the Cheliff following the presence of many large dams.

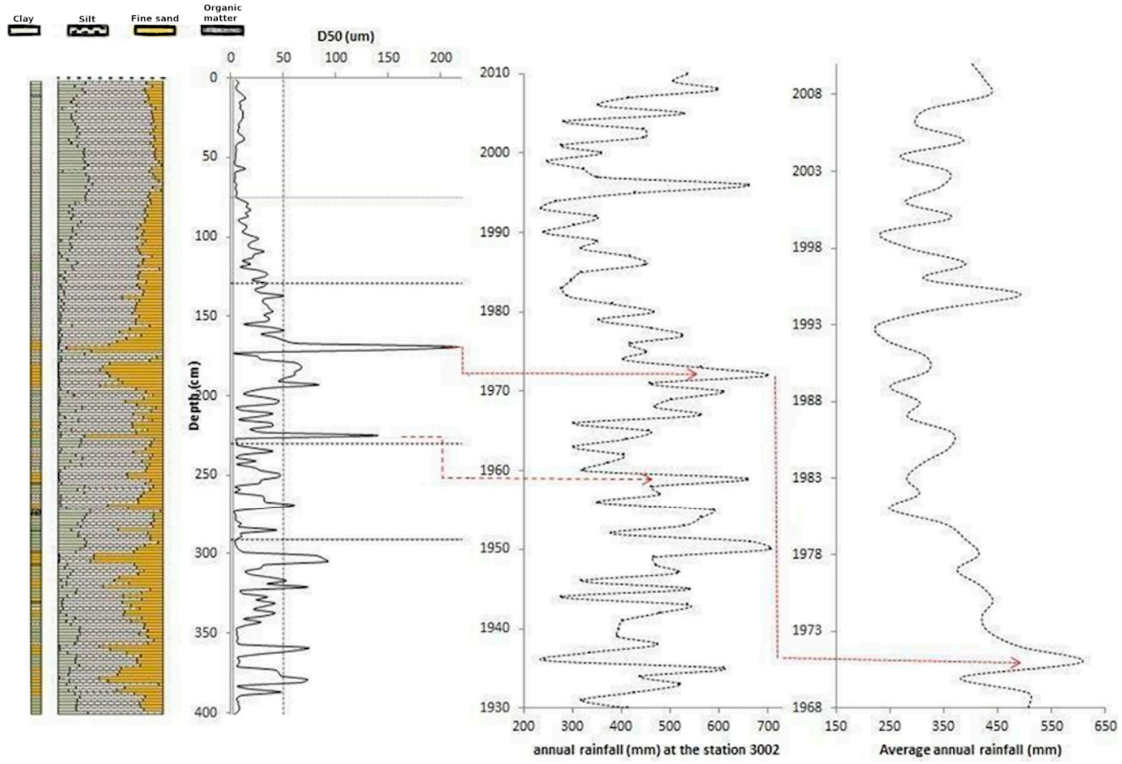


Figure 5. Sedimentary profile of deposits for CH3 core, evolution of the average annual rainfall on the Cheliff and the rainfall chronicle at the station bearing the code 3002.

Using only average rainfall as an age marker of accumulated deposits is a full stage of hiring, which is associated with many uncertainties. Nevertheless, the temporal distribution of rainfall can be combined with other proxies to confirm assumptions and results already established. Thus, the chronicle of the rains shows that the year 1972 is the rainiest ever recorded. This confirms what has already been observed in the liquid and solid flow surveys at the outlet of the Cheliff and reinforces the hypothesis that the optimum of the D50 observed at 169 cm of depth may correspond to the events of 1972.

Furthermore, the use of the records of the station 3002, which provides the longest record over an 80-year period, from 1930 to 2010, confirm that 1972 is indeed the rainiest year in the entire instrumental recording period. On the other hand, it makes it possible to analyze the correlation of deposits post-dated to 1968 accumulated between 2 and 4 m of depth. Thus, the evolution of rainfall between 1930 and 1968 shows the presence of many rainy years and relatively abundant rainfall. This period can be described as wet compared to previous decades. In the Cheliff, the hydro-sedimentary regime is closely linked to the rainfall regime. Thus, the heavy rains, surely, were associated with exceptional events, and the numerous layers of sandy deposits, identified between 2 m and 4 m of depth, could be attributed to these possible high energy events generated by the abundance of rainfall.

5.2. Impact of Dams on the Granulometric Distribution and the Accumulation Rate of Deposits

Social-economic changes coincide with a long period of rainfall decline, directly impacting the hydrological regime and water resources. The multiplication of many of the large dams was an inevitable fact in the Algerian context, especially in the Cheliff watershed. In a recent study [34], the effect of these large reservoirs on hydro-sedimentary continuity and on Cheliff's discharges and sediment yield was highlighted. Indeed, the results point out an accentuation of the decline in sedimentary inputs from the Wadi Cheliff to the sea, which coincides with the construction of new dams, precisely during the periods 1932–1939, 1978–1989 and 2003–2010, while the volumes of sediment trapped in the various dams show a gradual increase, as new works come into service. Thus, the amount of sediment intercepted by large dams increased from 74 million tons to 195 million tons, then to 269 million tons during the periods 1968–1980, 1981–1995 and 1996–2010, respectively. The total volume of sediment retained by large dams until 2010 is about 695 Hm^3. Furthermore, the volumes retained at the various dams far exceed the volumes returned to the downstream river. Similarly, the volumes diverted out of the river represent 68.4% of the total liquid input. Numerous observations show the repercussions of the dams on the landscape and the morphology of the lower Cheliff river. These are mainly a strong vegetation of the banks, a reduction in the flow section and a fattening of the watercourse. They conclude that the effect of the dams on the yields of the Cheliff in liquid and solid flows to the sea continues to increase. As they underline that the contribution of dams to the reduction in sedimentary contributions to the sea is more important than that of the decrease in rainfall in the Cheliff region.

The combined analysis of the particle size distribution of the accumulated deposits and the evolution of the annual sedimentation rate in the dams (Figure 6) highlighted the sensitivity of nature and the accumulation rate of the deposits in face of the multiplication of reservoir structures. Indeed, the effect of the first four dams, installed between 1932 and 1939, is difficult to assess because of the distance of these works from the outlet and the small contribution of the drained area in the total yield of the Cheliff in liquid and solid contribution to the sea. However, the estimated age of deposits, relatively between 1930 and 2021, does not allow us to have information on the accumulation process at the time when the Cheliff was devoid of any reservoir dam. Then the eight reservoirs that were built between 1979 and 1989 increased the annual siltation rate by a factor of 4 at the end

of 1989. This increase in the interception of sediments by dams coincides with deposits belonging mainly to the granulometric class of clays and silts, with a D50 of little more than 11 µm. In addition, a drastic decrease in rainfall was observed during the same period. This makes it difficult to attribute the modification of the granulometric distribution of the accumulated deposits in the lower Cheliff valley, only, to the growth of the number of dams. Nevertheless, to hinder the inflow of eight tributaries from the central part of the Cheliff (the Tell), the most contributing liquid and solid to the outfall, necessarily impacted the nature of the deposits and their accumulation rate in the lower Cheliff valley. This impact is evident from 1996 onwards. Indeed, the post-1996 period was marked by a resumption of increased rainfall and the commissioning of five new dams, in the downstream part of the Cheliff, between 2003 and 2010. Nevertheless, despite the return of rainy years, the deposits accumulated during this period are mainly composed of fine elements (clay and silt) and no sandy layer was recorded. This could be attributed to the high number of dams built in the Cheliff basin which shows an annual siltation rate of around 20 million tons per year.

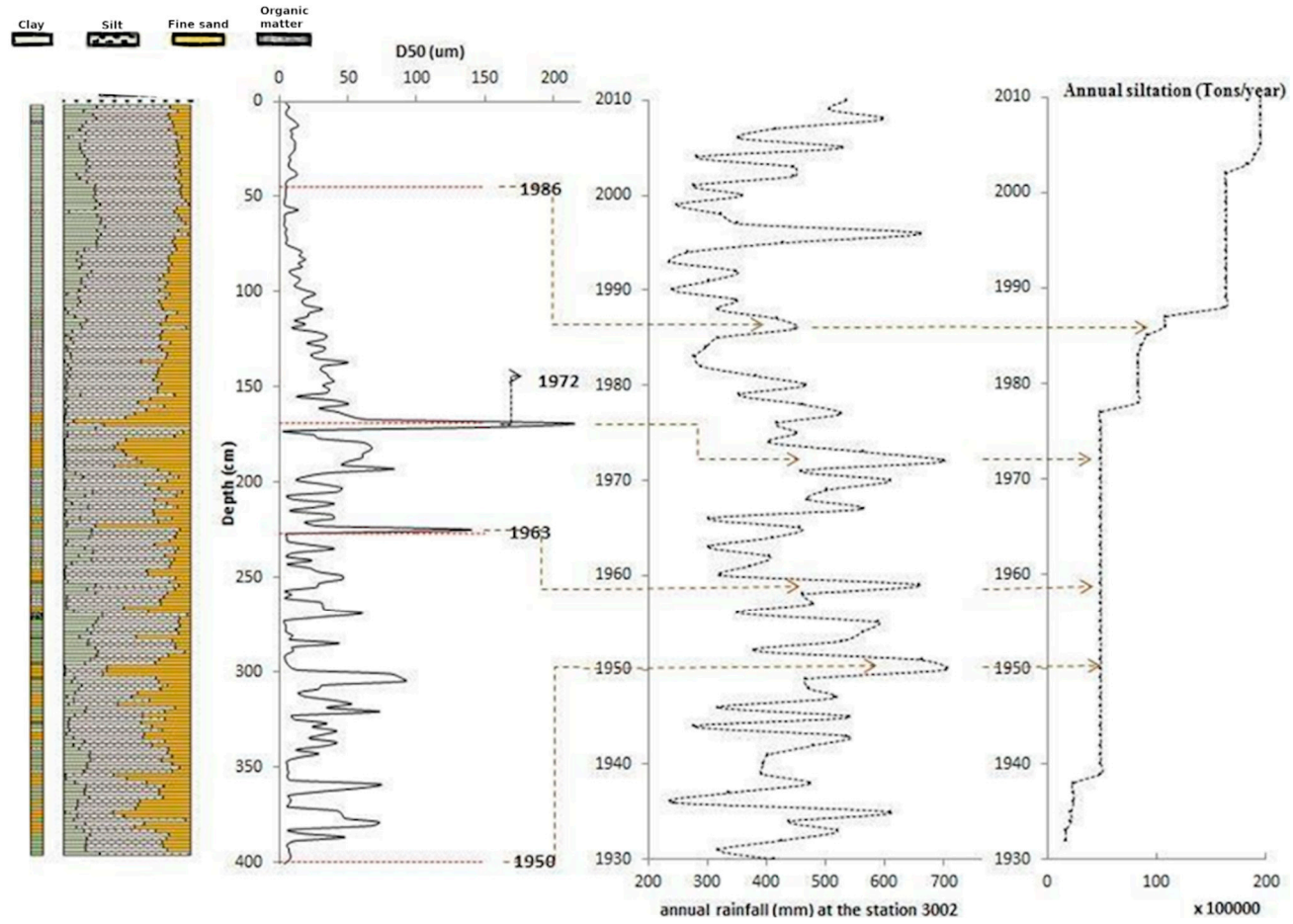


Figure 6. Particle size profile of deposits on CH3 core, temporal distribution of mean annual rainfall on the Cheliff and evolution of sediment accumulation rates in large dams.

However, the accumulation rate of deposits has strongly slowed down since 1986. Thus, the sedimentation rate has gone from 16 cm.y^{-1} to 7.9 cm.y^{-1}, then to 1.31 cm.y^{-1} during the periods 1952–1963, 1963–1986 and 1986–2021. Such a regression finds its explanation in the strong interception exerted by the many dams and the reduction in the transport capacity of the lower river Cheliff. Indeed, the multiplication of the reservoirs and the adopted management mode fragmented the hydro-sedimentary conductivity of the Cheliff and hindered the outflow of liquid and solid contributions from many tributaries [34]. In addition, the importance of the volumes stored and then diverted, compared to those

returned to the river, combined with the decrease in rainfall, have strongly impacted the flow of the lower river and consequently its capacity for sediment transport.

5.3. Information Content of the Sedimentary Archive Versus Instrumental Information

The objective of the palaeohydrological approach is the documentation of the sedimentary archive, through the study of particle size composition, geochemical composition and the establishment of a chronology of the accumulation of deposits. The value of such an approach is to restore the absence of instrumental information on climate variability and the hydro-sedimentary regime. The results of this study show that the particle size distribution of the deposits and their accumulation rates are closely linked to the variability of the Cheliff hydro-sedimentary yields at the outlet. These yields in liquid and solid flow at the outlet are constantly fluctuating, due to the variability of the controlling factors, particularly those related to climate and anthropogenic action. Thus, the distribution of the granulometry of the deposits transcribed, on the one hand, the internal variability of the rainfall and the evolution of the climatic signal. On the other hand, the intensification of the anthropogenic action, corresponding, in the present study, to the multiplication of the reservoir dams. The confrontation between the granulometric and geochemical composition of the sedimentary deposits and the instrumental information relative to the hydro-sedimentary flows at the outlet and the evolution of the rainfall signal brings out the following observations:

Large and intense rainfall events give rise to energetic hydrological events associated with strong sedimentary loads. In terms of deposits, such events generally correspond to relatively thick layers and a medium coarse particle size. In contrast, fine deposits, which are generally associated with low rainfall and smaller flows, which provided low carrying capacity to the stream.

The rainfall signal characteristics are relatively well recorded in the sediment archive contained in core CH3. Changes in the particle size distribution and the rate of sediment accumulation coincide with climatic signal variations. Thus, during the wet sequence characterized by a strong recurrence of extreme events and abundant rainfall, we observed a succession of numerous thick sedimentary layers and a relatively coarse particle size, while the rainfall decline accompanied by a hydrological respite led to an immediate impact on the particle size nature of the deposits. This modification into a gradual decrease in the median diameter of the deposits was made up mainly of clay and silts. However, the control exerted by the reservoir dams on the granulometric distribution and the accumulation rate of deposits is a function of their number, their distribution, their location and the importance of the contribution of the drained tributary to the outlet. Thus, the effect of large dams is all the more important and visible as the number of reservoirs is high and their locations are near the outlet. In the case of the Cheliff, the effect of the first dams is less visible, because of their positions far from the outlet and the low contribution of the drained part in liquid and solid flow to the outlet. On the other hand, recent dams have a drastic effect on the accumulation rate and the particle size distribution of deposits. Thus, the accumulation rate has been reduced to 1.31 cm/y^{-1} and the deposits are of a fine nature. Such an effect can be explained by the high number of dams in place, by the importance of the drained tributaries and by their locations which are getting closer and closer to the outlet.

The results of the present study show that the information content incorporated in the sedimentary deposits accurately reflects hydro-sedimentary fluctuations. Similarly, the particle size distribution of the deposits is intimately linked to climate variability and anthropogenization of the watershed. Therefore, the study of the sedimentary archive through the paleohydrological approach could contribute to the reconstruction of rainfall

trends and/or anthropogenic disturbances, as well as the fluctuations of the hydrosedimentary regime. Such a contribution is of paramount importance in catchments without any measurement records. It can also be a source of additional information in watersheds that are already monitored. Contrary to the instrumental information which informs us on the characteristics of each event and allows us to study the evolution of the signal as a whole. The information incorporated in the sedimentary archive shows limitations and strong difficulties in going beyond the reconstruction of global trends characterizing the different processes. The work carried out by [12,28,41], on the chronology of floods via a hydrological approach, highlights the difficulty of associating each flood with the deposits that correspond to it. This is due to numerous uncertainties related to the high variability characterizing the hydro-sedimentary processes, the constant adjustment of the river morphology and the temporal and spatial variability of the erosion and accumulation processes, as well as the difficulty related to the complete preservation of the sedimentary deposits in a given place over a long period.

6. Conclusions

The analysis of the sedimentary archive collected in the lower Cheliff valley shows a strong variability in the granulometric distribution of the deposits and a progressive decline in the rate of sediment accumulation. The lower half of the core consists of a succession of sand and clay/silts deposits, with more or less significant thicknesses. This is in contrast to the upper half, which is mainly made up of clay and silts deposits. Moreover, the accumulation rate has reduced from an average of about 16 cm/y^{-1} during the period 1952–1963 to only 1.31 cm/y^{-1} for the period 1986–2021. These changes in the composition and process of deposits are directly related to the decrease in the hydro-sedimentary yields of the Wadi Cheliff to the sea, particularly the decrease in the magnitude and recurrence of floods. This is due to the combined effect of the decrease in rainfall and the multiplication of the number of large reservoirs.

The sediment accumulation process at the outlet was mainly affected by the rainfall pattern and the density and location of large dams. Previously, rainfall was the main factor controlling the accumulation process. Thus, the wet period is associated with significant transport and coarser deposits. In contrast, transport is less important, and deposits are mostly clays during the dry sequence. Nevertheless, recently, the control exerted by the large reservoirs on the deposition process is more important than that of rainfall. In-deed, these structures deprived the outlet of a large part of the liquid and solid flows produced by the Cheliff, especially the sand fraction. As a result, the deposition rate at the outlet has slowed down considerably and recent deposits are composed mainly of clay and silt particles.

In the Cheliff, the sediment accumulation process is closely linked to the hydro-sedimentary yields of the rivers at the outlet. In addition, the rainfall regime and the large dams were the main factors affecting the variability of liquid and solid inputs to the sea. As a result, the granulometric profile and the accumulation rate of deposits accurately transcribed the different fluctuations of the controlling factors. With regard to the evolution of the rainfall signal, the implementation of a dry sequence since 1980 has directly translated into a decrease in deposits belonging to the sand granulometric class and a slowdown in the accumulation rate. This is in contrast to the previous wet sequence where deposits accumulated more rapidly and the sand fraction was more abundant. However, the effect of large dams is all the more important as the number of reservoirs is high and their locations are near the outlet. Such a situation has been observed in the Cheliff since 1980 and has had a drastic effect on the accumulation rate and has deprived the outlet of sand deposits.

At the end of this study, it can be concluded that the documentation of this sediment archive will be able to contribute to the reconstruction of the hydro-sedimentary signal and to detect the tendencies of the controlling factors, that is to say, those related to the climatic signal and/or to anthropogenic actions, as can also be concluded from other studies Mississippi [51,52]. This could be a solution for the study of the evolution of hydro-sedimentary yields, under the effect of climate and anthropogenic action, in many rivers with little instrumental information.

Author Contributions: G.M.: (Principal supervisor) Assisted with manuscript compilation, editing and co-author of manuscript. M.M.: (Research supervisor) Supervised and Assisted with manuscript compilation, editing and co-author of manuscript. L.D.: (Research supervisor) Analysis sediment cores, assisted with manuscript compilation, editing and co-author of manuscript. A.H. (Candidate) Established methodology, data analysis, analysis sediment cores writing, editing and co-author of manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to national regulation.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

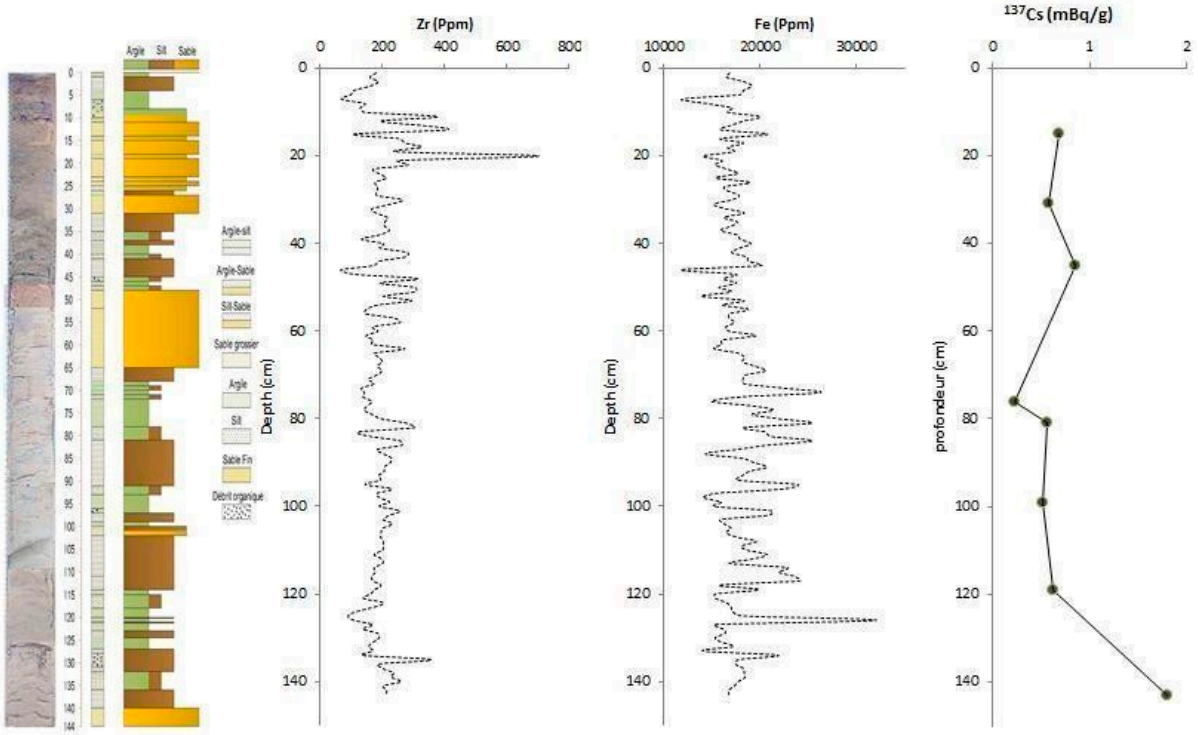


Figure A1. Size profile, Zr and Fe content and ^{137}Cs profile of the CH1 core.

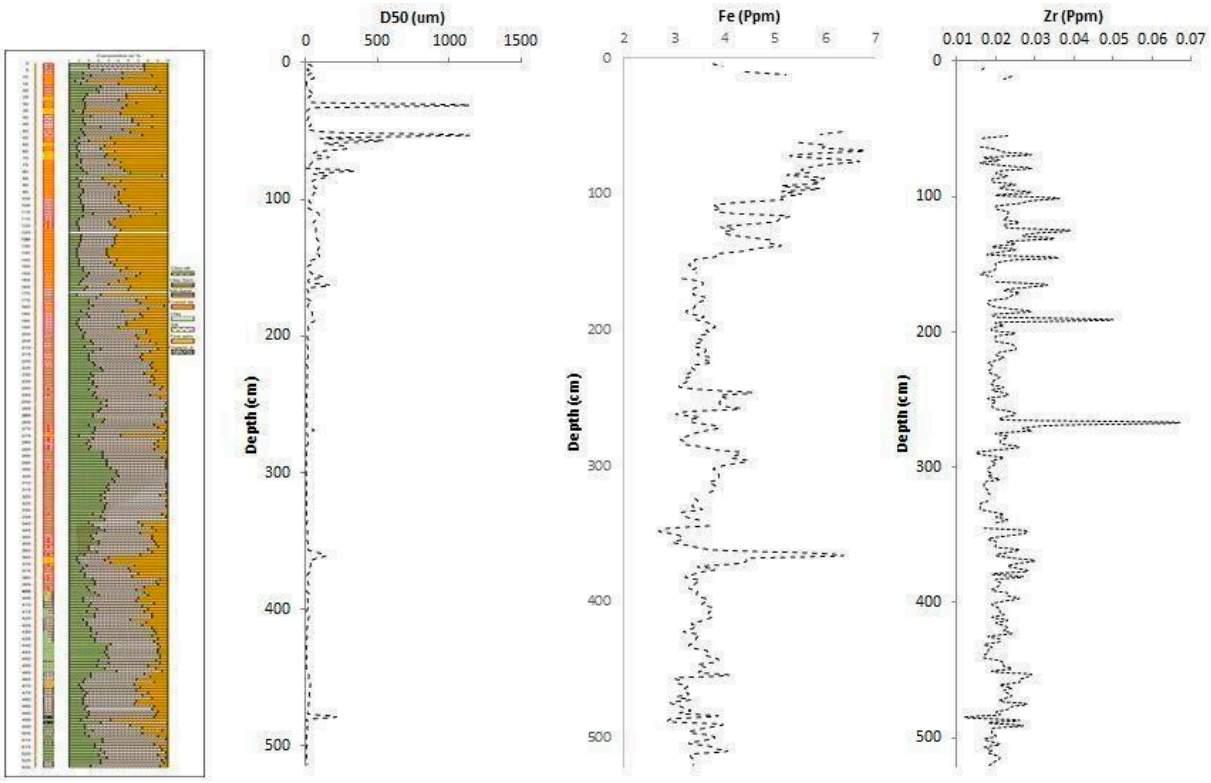


Figure A2. Size profile, Zr and Fe content of deposits and D50 profile of the CH2 core.

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