Transport of dissolved and suspended solids from three coastal rivers (North Central Algeria)

Belhadi Youcef, Aicha B. Amira

Department of Marine Science, Faculty of Science, Laboratory of Biogeochemical and Ecological Analysis of Aquatic Environments, Badji Mokhtar Annaba University, Box 12, Annaba 23000, Algeria. Corresponding author: B. Youcef, belhadiy@yahoo.fr

Abstract. The Soummam, Isser and Sebaou river catchments occupied together 16 000 km^2; they are regulated by several dams intercepting over one billion m^3 of freshwater. The catchments are heavily populated (3 million inhabitants) and mainly submitted to agricultural and household wastes. The objectives of this work were to estimate the loadings in dissolved (TDS) and suspended (TSS) materials into the receiving coasts and to assess the dam effects on their retention, to better understand soil erosion, salinization and shoreline sedimentation. The TDS and TSS were measured two times a month during the period March 2010-February 2011 at the entrances and exits of the dams and at respective river outlets. The TSS was found largely removed in the dams at high rates reaching 60 to 99%. Also, the TDS was highly retained (46 to 81%) depending on the dams. The specific erosion rates reach (28 to 59 t km^{-2} yr^{-1} for the TSS and 0.1 to 2.3 t km^{-2} yr^{-1} for the TDS according to the river). Even if the TDS were removed in the dams at high rates, their specific loadings were paradoxically very elevated indicating a large soil salinization in lower basins. Despite the great masses introduced into the adjacent coasts, the soil fertility is expected to large alteration.
Key Words: coastal river, dam, TSS, TDS, Mediterranean.

Introduction. Rivers represent the major link between land and the ocean. Presently rivers annually discharge about 35 000 km^3 of freshwater and 20-22x10^9 tones of solid and dissolved sediment to the global ocean (Milliman 2001; Liu et al 2006). Moreover, several studies noticed that both water and sediment discharge of North American and European rivers spans 50 years or longer, many rivers in Central and South America, Africa and Asia are poorly documented, despite the fact that many of these rivers have large water and sediment inputs and are particularly susceptible to natural and anthropogenic changes (Milliman 2001; Ludwig et al 2009; Jarsjö et al 2012; Jaramillo & Destouni 2014; Yang et al 2015; Pietroń et al 2017). This problem might be due to dam construction, water abstraction, and soil conservation. The Yellow River in northern China, for example, is considered to have one of the highest sediment loads in the world, 1.1 billion tonnes y^{-1} (Ma et al 2017). In recent years, however, its load has averaged < 100 million tons, in response to drought and increased human removal of river water. Both water and sediment discharge of the Huanghe (Yellow River) have shown progressive decrease during the last 50 years, which is partly due to climate change (particularly, reduced precipitation) and more primarily, due to a series of human activities (particularly reservoir construction, water abstraction, and soil conservation) (Milliman 1997; Xu 2003; Walling 2006; Wang et al 2006). It has been reported that the completion of the Three Gorges Dam on the Yangtze River, the world largest dam, has already caused significant decrease in sediment discharge (Yang et al 2006; Chu & Zhai 2006; Zhang et al 2016). Decreasing of sediment load was reported to coincide with decreasing trends of some major ions and total dissolved solids (TDS) in the Dongjiang, one of the three main rivers in the Zhujiang Basin (Zhang et al 2007). The impacts of land use change on water discharge and sediment load, mainly afforestation and deforestation, have been known for small river basins (e.g. Chen et al 2004). On the other hand, effects of land use change may be difficult to identify or detect in large basins due to the existence of other human disturbances (such as reservoirs/dam construction, water extraction) and hydrological time lags (Lu 2004).

In some basins, such as the Colorado and Nile, sediment is trapped completely due to large size of the reservoirs and flow diversion (Vörösmarty et al 2003; Walling & Fang 2003). According to Williams & Wolman (1984) and Graf (2005) the trapping efficiency of large reservoirs (Volume > 10^7 m^3) is commonly greater than 99%, depending on the characteristics of the sediment, inflow, and the reservoir. Trapping efficiency for smaller dams ranges between 10 and 90% (Kummu & Varis 2007; Kondolf et al 2014).

The dams are trapping a large portion of the sediments, which in turn may decrease the biological productivity as parts of nutrients are attached to the sediment (Kummu & Varis 2007). In the rivers, sediment played in influencing structural and functional aspects of aquatic ecosystems (Håkanson 2005). Insufficient amounts of total solids affected the primary production of phytoplankton, benthic algae and macrophytes, the production and biomass of bacterio- plankton, and hence also the secondary production of, e.g., zooplankton, zoobenthos and fish (Håkanson 2006; Taamalah et al 2016; Bougdah & Amira 2017). It is possible that the feeding and spawning conditions would be disturbed and lead to declining biodiversity and productivity (Blake 2001). The effect of dams on bed load transport is even more dramatic because it is fully trapped by reservoirs (e.g. Kondolf 1997).

The objective of the present work is to describe the kinetic of the water out-flows, of the transportation of dissolved and suspended solids from three coastal rivers in north central Algeria.

Material and Method

***Sampling sites**.* The Soummam, Isser and Sebaou rivers catchments occupied together 16 000 km² with a population of about three millions and are mainly submitted to household and agricultural wastes (Figure 1). They are heavily managed by several dams that retain more than the half of the precipitation wealth. The largest dams are Koudiat Acerdoune (640 million m^3 storage capacity) built on the Isser River (Is) and Tilesdit (167 million m^3) built on the Soummam River (Sm). The catchment of the Sebaou River (Sb) is populated with about 1 million and 200 thousands inhabitants. The catchments receive an annual precipitation yield of about 400-800 mm inducing large fluctuation in river flow. In summer period all rivers fall dry at the entering of dams while at the exit the dams continue to deliver low flows. Being irrigated from dams and near-river mouths, the northern areas sustain large intensive agricultural activities and the land use becomes mainly dominated by intensive agricultural practices and forests occupied always less than 30%.

***Analytical methods**.* All hydrological parameters were measured twice a month from March 2010 to February 2011 in three stations for Soummam and Isser Rivers and one station in Sebaou catchment (Figure 1). Measurements in the Sebaou River were performed monthly because of some practical constraints. Stations were located at the entrances and exits of dams and at the outlets of the respective rivers. Velocities of the streams, at the moment of water sampling, were assessed with the current meter CM-2 (Toho Dentan Co. Ltd, Tokyo). The flow rate (m^3 s^{-1}) was calculated by multiplying the water velocity (m s^{-1}) by the total surface area (m^2) of the rivers' transecting at the sampling stations. In the laboratory the total suspended solids (TSS) were measured following the method described in Aminot & Chaussepied (1983). Volume water of 500 mL were filtered on pre-combusted (450°C for 1 h) and pre-weighed Whatman GF/C glass filters for TSS weight measurements. These filters were dried at 110°C for 1 hour by an oven dryer and then weighed with a Mettler microbalance which provides a precision of 0.10 mg. For each filter, the TSS was obtained by subtracting the final filter weight (filter + TSS) from the initial weight of the filter, and the results were expressed in milligram per liter (mg L^{-1}). The total dissolved solids were measured with a multi-parameter probe WTW Cond 1970i. The instantaneous and annual TSS and TDS fluxes were assessed using the method of average instantaneous loads (Preston et al 1989).

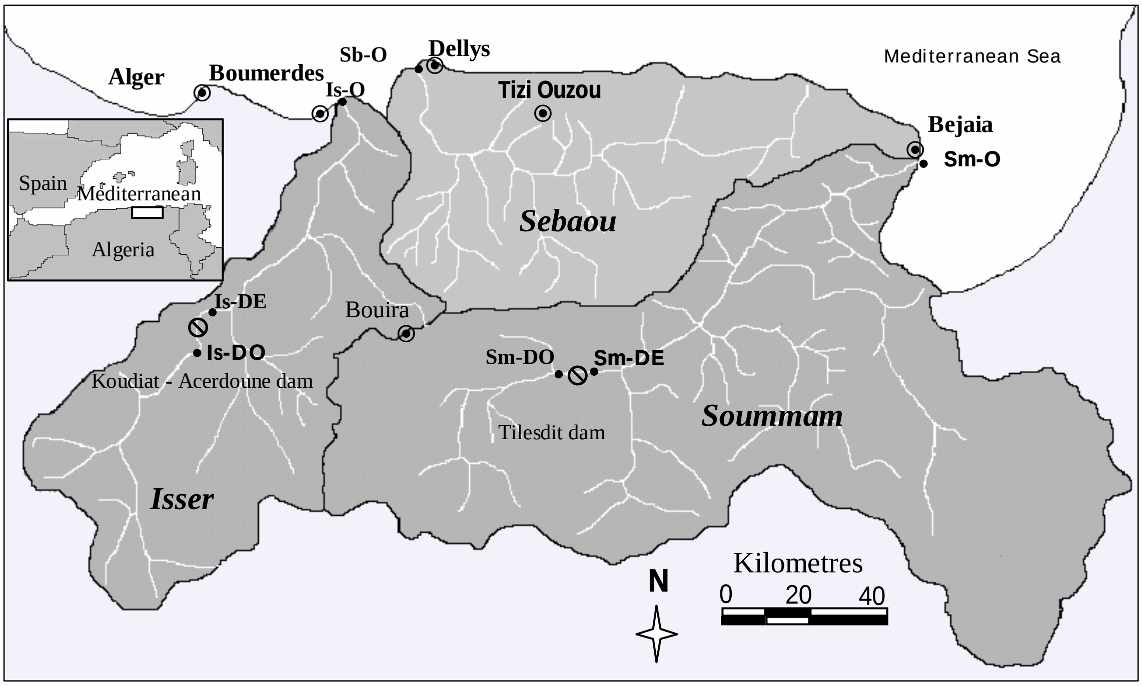

Figure 1. Sampling stations in the coastal rivers of Soummam (Sm), Isser (Is) and Sebaou (Sb). ⊘- Dam; Sm-DO: Soummam dam opening; Is-DO: Isser dam opening; Sm-DE: exit of Sm dam; Is-DE: exit of Is dam; Sm-O: outlet of Sm River; Is-O: outlet of Is River; Sb-O: outlet of Sb River.

Results

Freshwater discharge. River discharge is a function of meteorological runoff (precipitation minus evaporation) and drainage basin area. The annual precipitations at the different catchments were as follows 617 mm at the Soummam, 834 mm at the Isser and 827 mm at the Sebaou. The Soummam River has both a large basin and a high runoff; the catchment area of the Isser River is twice of that the Sebaou River with which has similar runoff (Table 1). On the whole of the rivers the discharges at the river outlet are equals 0.32-0.34 10^9 m^3 y^{-1}.

Table 1

Catchment area, catchment rainfall, catchment runoff, and discharge at river outlet

River	*Catchment area (km²)*	*Catchment rainfall (10^9 m^3 y^{-1})*	*Catchment runoff (10^9 m^3 y^{-1})*	*Discharge at river outlet (10^9 m^3 y^{-1})*
Soummam	9.125	5.6	0.95	0.32
Isser	4.149	3.4	0.71	0.34
Sebaou	2.500	2.1	0.70	0.32

TSS and TDS levels. Hydrological parameters recorded in the three rivers are given in the Figure 2. Water flow at the respective rivers varied according to the precipitation yield and control of reservoir. During the year at the entrance of the Tilesdit dam the average of water flow was 12.8 m^3 s^{-1} reaching 14 m^3 s^{-1} in wet period and decreased to 12 m^3 s^{-1} in the dry period. The exit was characterized by low river flow compared to the other stations. As at the exit of Tilesdit dam the annual average of water flow was 3.4 m^3 s^{-1} and reached 5 m^3 s^{-1} in the wet period and did not exceed 1 m^3 s^{-1} in the dry period. At the outlet of the Soummam River the water flow varied between 0.7 and 13.5 m^3 s^{-1} according to the period and it is of 10 m^3 s^{-1} during the year. At the entrance of Koudiat Acerdoune dam the average of the annual water flow was 10 m^3 s^{-1} and it is increased in the wet period, reaching 16 m^3 s^{-1} but in the dry period it does not exceed 1 m^3 s^{-1}. Following the dam effect, at the exit, the average values are less important, reaching 6 m^3 s^{-1} during the year and 10 m^3 s^{-1} in the wet period, in dry period the values are about only 0.2 m^3 s^{-1}. At the outlet of the Isser River the average annual value is of 11 m^3 s^{-1}, reaching 0.1 and 19 $m^3 s^{-1}$ respectively in the dry and wet period. At the outlet of the Sebaou river water flow varied between 1 and 16 $m^3 s^{-1}$ according to the period. And it was 10 $m^3 s^{-1}$ during the year. At the entrance of the Tilesdit dam the average annual level in TSS was 9.2 mg L^{-1} where the maximal levels were found in wet period reaching 13.3 mg L^{-1} and decreased to only 3.5 mg L^{-1} in the dry period. At the opening of the Koudiat Acerdoune dam the average annual level in TSS is more important than the one of Tilesdit and it reached 24 mg L^{-1}, 33 mg L^{-1} in wet period and 12 mg L^{-1} in dry period. The average annual levels of TSS were mainly decreased at the exit of the dam and did not exceed 3.6 mg L^{-1} in Tilesdit dam explained by retention of 36% and only 13 mg L^{-1} in Koudiat Acerdoune dam which expressed a retention of 46% of TSS. Even if TSS were retained in the dam, at the outlet of the river the average annual level was significantly increased to reach 36.6 mg L^{-1} at the outlet of Soummam River, and 26 mg L^{-1} at the outlet of Isser River. At the outlet of the Sebaou River the average annual level was 35 mg L^{-1}, and the maximal level was found in wet period reaching 44 mg L^{-1} and decreased to 29 mg L^{-1} in the dry period. The TDS or dissolved salts levels at the studied stations were changed from a station to another. At the entrance of the Tilesdit dam the average annual level in TDS was 685 mg L^{-1}, reaching 730 mg L^{-1} in wet period and 652 mg L^{-1} in dry period, more elevate at the entrance of the Koudiat Acerdoune dam as reaching 1103 mg L^{-1} during the year where the maximal levels was found in wet period reaching 1326 mg L^{-1} and decreased to only 943 mg L^{-1} in the dry period. The dissolved salts levels at the exit of the dam are always weak compared to the entrance dam levels. The TDS levels were increased when reaching the outlet. At the outlet of the Soummam River the average annual levels in TDS was 1128 mg L^{-1}, reaches 1130 mg L^{-1} in the wet period and 1126 mg L^{-1} in the dry period. At the outlet of the Isser river the average annual levels does not exceed 996 mg L^{-1} and reaches 1083 mg L^{-1} in the wet period and decreased to 874 mg L^{-1} in the dry period. The variation of the average seasonal levels in TDS was very clear at the outlet of the Sebaou River where the average annual levels was 979 mg L^{-1} where the maximal level was found in wet period reaching 1155 mg L^{-1} and decrease to only 853 mg L^{-1} in the dry period.

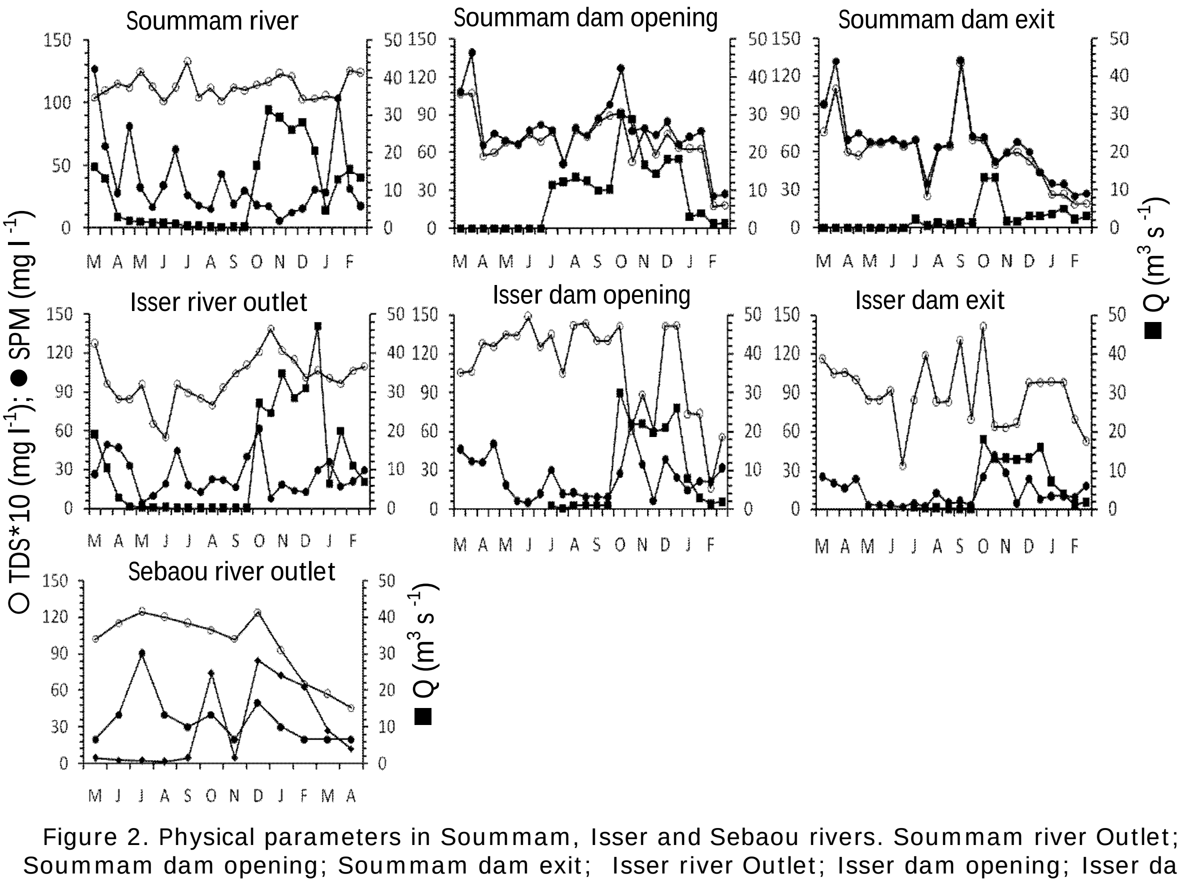

Figure 2. Physical parameters in Soummam, Isser and Sebaou rivers. Soummam river Outlet; Soummam dam opening; Soummam dam exit; Isser river Outlet; Isser dam opening; Isser dam exit and Sebaou river Outlet.

Discussion. This work aims mainly to estimate the transfer of dissolved and suspended solids from three coastal rivers north central Algeria, Soummam, Isser and Sebaou to the inshore waters, and to determine the effects of the dam on this suspended and dissolved solids since the upstream of the dam until the river mouths.

During the study period, both Tilesdit and Koudiat Acerdoune Dams received about 0.7 10^9 m^3 of freshwater. Adding Sebaou dam, the three rivers delivered together 0.99 10^9 m^3 of continental water. This discharge represented about half the average value reported by UNEP/MAP (2013), Ounissi & Bouchareb (2013), Taamalah et al (2016).

The amount of water entering the reservoirs was very charged in TSS and TDS. Due to the significant role of dams, total solids were remarkably reduced downstream and trapped in the dams. Tilesdit dam trapped more solids and salts than Koudiat Acerdoune Dam (Table 2). Retention of solids (TSS) was 99% in Tilesdit Dam, which is 1.5-fold higher than Koudiat Acerdoune Dam. Tilesdit dam trapped 81% of salts (TDS), which is 1.8-fold elevated than Koudiat Acerdoune dam (46%). These elevated total solids retention was also observed in the North East Algeria dams (Ounissi et al 2013; Taamalah et al 2016; Bougdah & Amira 2017). Due to geoclimatic conditions, Algerian surface waters are known to be more salty than those of Northern Mediterranean countries (Aubert 1976; Taamalah et al 2016; Bougdah & Amira 2017). The storage capacity (640 10^6 m^3) of Koudiat Acerdoune dam was about 4 times higher than that of Tilesdit dam and it trapped about 91 800 tons of TSS. Koudiat Acerdoune dam was immensely affected by sediment deposition. This sediment deposition of TSS might lead to grave and rapid clogging of dam. The similar problem was also observed in several contiguous Algerian dams (UNEP/MAP 2003; Remini 2010; Taamalah et al 2016; Boughdah & Amira 2017). Sediment loss reached about 55.5 t km^2 yr^{-1} in Isser and Sebaou outlets, this sediment loss was 1.8-fold higher than that of Soummam River outlet. In Algerian and Mediterranean costal watersheds and their dams, the sediments yields are highly variable (Taamalah et al 2016; Boughdah & Amira 2017), varying between 4 to 2780 t km^2 yr^{-1} depending on the river as seen in Table 3.

Table 2

Annual nutrient fluxes from and into the different reservoirs and at the respective river outlets (specific fluxes are given between parentheses)

		Flow *(m^3 s^{-1})*	*Volume* *(10^9 m^3 yr^{-1})*	*TSS* *(t yr^{-1})*	*TDS* *(t yr^{-1})*
Soummam Dam	Opening	12.8	0.39	79120	4597
	Exit	3	0.09	86	876
	R/P (%)		-76	-99	-81
Soummam River	Outlet	10	0.30	253616 (28)	8619 (1)
Isser Dam	Opening	10	0.30	156140	5374
	Exit	6.3	0.19	64372	2924
	R/P (%)		-36	-59	-46
Isser River	Outlet	11	0.33	215654 (52)	9625 (2.3)
Sebaou River	Outlet	10	0.30	146560 (59)	2862 (1.1)

R/P(%): retention rate.

Table 3
Sediment loading (TSS, *t km² yr⁻¹*) for some Mediterranean and Algerian rivers and dams

River/dam opening	*t km² yr⁻¹*	*References*
Mediterranean rivers	251	UNEP/MAP/MED POL (2003)
Ebro River, Spain	214	UNEP/MAP/MED POL (2003)
Têt stream, France	40	Serrat et al (2001)
Rhône River, France	324	Pont et al (2002)
Italian rivers	780	UNEP/MAP/MED POL (2003)
Greece rivers	1140	UNEP/MAP/MED POL (2003)
Albanian rivers	2780	UNEP/MAP/MED POL (2003)
North African catchments	800	Fox et al (1997)
Maghreb catchments	397	Probst et al (1992)
Majrda, Tunisia	963	UNEP/MAP/MED POL (2003)
Moulouya, Morocco	250	UNEP/MAP/MED POL (2003)
Nile, Egypt	42	UNEP/MAP/MED POL (2003)
Cheliff, Algeria	78	UNEP/MAP/MED POL (2003)
Isser, Algeria	193	UNEP/MAP/MED POL (2003)
Kebir west, Algeria	200	UNEP/MAP/MED POL (2003)
Seybouse, Algeria	333	UNEP/MAP/MED POL (2003)
Soummam, Algeria	513	UNEP/MAP/MED POL (2003)
Tafna, Algeria	143	UNEP/MAP/MED POL (2003)
Cheffia dam, Algeria	2700	Touaibia (2010)
Charf dam, Algeria	300	Touaibia (2010)
Beni-Haroun dam, Algeria	64	Bouchareb (2013)
Zit El-Amba dam, Algeria	374	Bouchareb (2013)
Zerdaza dam, Algeria	192	Bouchareb (2013)
Chaffia dam, Algeria	143	Taamalah et al (2016)
Mexa dam, Algeria	371	Taamalah et al (2016)
Mafragh catchment' outlet,	1974	Taamalah et al (2016)
Zit Amba dam	20	Bougdah & Amira (2017)
Kebir Ouest Rivers	4	Bougdah & Amira (2017)
Soummam River	28	This study
Isser River	52	This study
Sebaou River	59	This study

Meybeck & Moatar (2012) reported that the average sediment yield of 86 river watersheds of semi-arid and temperate regions, which were daily surveyed for a long term was about 61 t km^2 yr^{-1}. Considering this world average catchment value, Algeria river catchments were among the most eroded catchment. Because of intensive dam building the actual sediment flux is reduced to 251 t km^2 yr^{-1} compare to 580 t km^2 yr^{-1} calculated by UNEP/MAP (2003).

Annual retention of TDS was 2450 and 3729 t yr^{-1} in Koudiat Acerdoune and Tilesdit dams respectively, even if Tilesdit dam received highly salty waters. Soil salt loss was also important in the Tilesdit dam, representing 81% of TDS. In Algerian and Mediterranean costal catchment and their reservoirs, the dissolved solids yields are highly variable (Milliman 2001; Bouchareb 2013; Taamalah et al 2016), ranging between 6 to 228 t km^2 yr^{-1} depending on the river as shown in Table 2. The TSD specific flux in the Soummam and Sebaou rivers was comparable (1.1 t km^2 yr^{-1}), which is 2-fold lower than that of the Isser River (2.3 t km^2 yr^{-1}), but these levels are still very low compared to those of Mediterranean and Algerian rivers (Table 4).

Table 4

Total dissolved solids loading (TDS, t km^2 yr^{-1}) for some Mediterranean and Algerian rivers and dams

River/dam opening	*t km^2 yr^{-1}*	*References*
World average value	61	Meybeck & Moatar (2012)
Ebro River, Spain	104	Milliman (2001)
Evros Rivers, Greece	50	Milliman (2001)
Rhone River, France	175	Milliman (2001)
PO Rivers, Italy	228	Milliman (2001)
Beni-Haroun dam, Algeria	8.6	Bouchareb (2013)
Zit El-Amba dam, Algeria	6.3	Bouchareb (2013)
Zerdaza dam, Algeria	40	Bouchareb (2013)
Chaffia dam, Algeria	82	Taamalah et al (2016)
Mexa dam, Algeria	218	Taamalah et al (2016)
Mafragh catchment' outlet	224	Taamalah et al (2016)

Conclusions. This paper describes the sediment and salts transport observed in three rivers in the North Central Algeria, assessing the influence of the reservoirs on their hydrosedimentary regimes. Sediment trapping by reservoirs has negative consequences for the reservoir and for the downstream and coastal zones. Sediment accumulates in reservoirs, and it can perturb reservoir functions and ultimately reduce storage capacity and affect biological productivity. The main findings of the study can be summarised as follows:

- Tilesdit and Koudiat Acerdoune dams, reduced the water flow at the downstream by 76-36% respectively;
- Tilesdit dam built on Soummam River trapped more the sediment (99%) and salt (81%), which is equivalent to 7900 t of TSS and 3700 of TDS;
- significant retention of salts in reservoirs lead to very low specific flux (1-2.3 t km^2 yr^{-1}) in outlets of the three rivers.

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Authors:
Belhadi Youcef, Department of Marine Science, Faculty of Science, Laboratory of Biogeochemical and Ecological Analysis of Aquatic Environments, Badji Mokhtar Annaba University, Box 12, Annaba 23000, Algeria, e-mail: belhadiy@yahoo.fr
Aicha Beya Amira, Department of Marine Science, Faculty of Science, Laboratory of Biogeochemical and Ecological Analysis of Aquatic Environments, Badji Mokhtar Annaba University, Box 12, Annaba 23000, Algeria, e-mail: amira.aichabeya@yahoo.com

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