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DAMMING EFFECTS ON RIVER SILICON BIOGEOCHEMICAL CYCLE IN A SOUTH MEDITERRANEAN BASIN (SEYBOUSE, NORTHEAST ALGERIA)

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Abstract: Silicon (Si) is the most abundant element in the earth's crust after oxygen; it is found in aquatic environments as orthosilicic acid. This study concerned for the first time the distribution and flux of dissolved silicates (SiO_4) in strategic sites (Charef dam, Bouhamdane dam, and estuary) from the upstream of the Seybouse basin to its mouth to understand silicon biogeochemical transformations under dams and estuarine effects. Surface water sampling was taken and analyzed in the dry (September 2016) and wet (April 2017) seasons. In parallel to sampling dates, physical parameters, and water discharge data were recorded. The highest SiO_4 levels were recorded upstream and weakened towards the mouth. It was reduced between 32% and 54% for the Charef and Bouhamdane dams respectively, while the retention rate of the estuary was on average 44%. In terms of flux, the Charef and Bouhamdane dams produced 2 t/yr and 17 t/yr respectively, whereas the estuary produced only 54 t/yr to the coastal zone. Dams and estuarine part play a crucial role in changes in the biogeochemical silicon cycle and are expected to have severe impacts on the river system and the receiving coastline functioning.

Keywords: silicon, dam, Charef, Bouhamdane, Seybouse basin, biochemical cycle

1. INTRODUCTION

Silicon is a key element for the aquatic ecosystem being one of the necessary and specific nutrients for diatoms. It accumulates in biogenic silica particles to form the frustule (Martin-Jézéquel et al., 2000). Diatoms are the basis of the food chain contributing to more than 60% of primary productivity (Ragueneau et al., 2006) and can play an important role in the archiving of atmospheric CO_2 in the deep ocean (Tréguer and Pondaven, 2000).

Besides, the Mediterranean has experienced rapid changes in its chemistry directly linked to inputs from agricultural, domestic, and industrial activities (Dali et al., 2023; Haridi et al., 2012). Moreover, the construction of dams on rivers and water extractions for irrigation have evolved since the 1960s and have largely reduced the river flow by at least 20% (Humborg et al., 2008), which has profoundly modified the natural functioning of the Mediterranean rivers (Lehner et al., 2011; Ludwig et al., 2009).

In addition, dams trap a large part of sediments and therefore nutrients linked to them (C, N, P, and Si), which reduces the number of nutrients available downstream (Billen and Garnier, 2007; Ziouch et al., 2023). Further, the transfer of nutrients to the sea plays a key role in the hydrological balance of carbon, dissolved nutrients, sediments, and biodiversity of surface waters (Li et al., 2021; Meybeck, 2003).

Along with the reduction in flow rates and silicon retained in large proportions in dams, nitrogen (N) and phosphorus (P) fluxes have increased 3 to 5 times (Dürr et al., 2011; Ludwig et al. al., 2009; Meybeck, 2003) and the Si/N/P ratios are thus modified. These biogeochemical modifications are responsible for numerous negative impacts: increase in the proliferation of harmful phytoplankton species, eutrophication, hypoxia, and loss of habitat and biodiversity (Bao et al., 2022; Billen and Garnier, 2007; Turner et al., 2003; Ounissi et al., 2021). These biogeochemical changes have repercussions on the entire coastal system, including the decline in coastal fisheries resources. This study aims to evaluate the dissolved silicate contents and fluxes delivered to the sea and focuses on the effects of dams and estuarine part on the biogeochemistry of this nutrient.

2. MATERIALS AND METHODS

2.1. Presentation of the Study Area

The Seybouse basin is an exoreic basin hosting more than 1,5 million inhabitants (Ziouch, 2014). It is located in the North-Eastern of Algeria occupying an area of 6471 km² and extending South-West–North-East layout over 240 km (Ounissi et al., 2014). The rainfall in the Seybouse basin is characterized by a high intensity in winter and low rainfall amplitudes in summer; it varies considerably between the north (735 mm/yr) and the south (450 mm/yr) (ABH, 2013).

The Seybouse River is the second largestriver in Algeria after the ChelifRiver, it has an average annual flow of 15 m^3/s, which corresponds to a flow rate of about 500 million m^3/yr (UNEP/MAP, 2013). In addition to 64 hill reservoirs, the Seybouse basin contains two large dams, namely the Bouhamdane dam and the Charef dam built respectively on Bouhamdane and Charf branches, they have a total capacity of 377 hm³ and can regulate 110 hm³ (AHB, 1999). Cereals and market gardens are the main crops grown in irrigated areas reaching about 14 hectares (ABH, 1999). The basin has experienced very significant industrial development with the consequences of abundant, untreated discharges into the waters of Seybouse (Ziouch et al., 2020).

2.2. Sampling and Analytical Methods

To evaluate the distribution and flux of silicates across the Seybouse basin, sampling was carried out during two campaigns: September 2016 for the dry season and April 2017 for the wet season. This work involved seven sampling sites, with three replicate samples collected from each site during each campaign.Hydrological variables and dissolved silicates were measured at 07 stations (Figure. 1; Table 1). Readings of temperature (°C), salinity (PSU), and electrical conductivity (µS cm^{-1}) were taken in situ using a WTW 197i multiparameter. Analyzes of silicates were carried out according to the protocols of Aminot and Chaussepied, (1983). The flow rate at each station was determined according to the following equation:

$$Flow\ rate\ (m^3 s^{-1}) = width\ (m) \times depth\ (m) \times current\ speed\ (ms^{-1})\ (1)$$

The current speed was measured with a CM-2 type current meter (Toho Dentan Co. Ltd., Tokyo). The silicates instantaneous fluxes were calculated by multiplying their respective concentrations by the River discharge to obtain g s^{-1} and then converted to kg d^{-1}. The annual silicates flux was estimated using the average of instantaneous flow rates (Preston et al., 1989):

$$F = K \sum_{i=1}^{n} \left(\frac{CiQi}{n}\right)\ (2)$$

Where F is the annual flow rate (t/yr), Ci is the concentration of Silicates (µM, converted to kg m^{-3}), Qi is the concomitant instantaneous flow rate (m^3 s^{-1} converted in m^3 d^{-1}), n is the number of days of concentration data and K is the conversion factor taking into account the study period (365 days) and the estimation unit.

Table 1. Sampling stations and their characteristics.

	Coordinates	Altitude (m)
St 1	36°03’10.90”N7°19’41.52”E	754
St 2	36°04’28.33”N7°29’39.34”E	753
St 3	36°06’57.90”N7°22’56.84”E	712
St 4	36°28’14.52”N7°08’35.83”E	378
St 5	36°27’59.50”N7°15’46.98”E	272
St 6	36°47’55.87”N7°46’27.60”E	7
St 7	36°51’56.00”N7°46’10.90”E	1

St 1: Upstream 1Charef dam; St 2: Upstream 2 Charef dam; St 3: Downstream Charef dam; St 4: Upstream Bouhamdane dam; St 5: Downstream Bouhamdane dam; St 6: Upstream estuary; St 7: Downstream estuary (Mouth station).

The retention rate (R%) is calculated as follows:

$$R\% = -\ (E - S)/E \times 100\ (3)$$

Where E is the content at the entrance to the dam/estuary and S is the content at the exit of the dam/estuary.

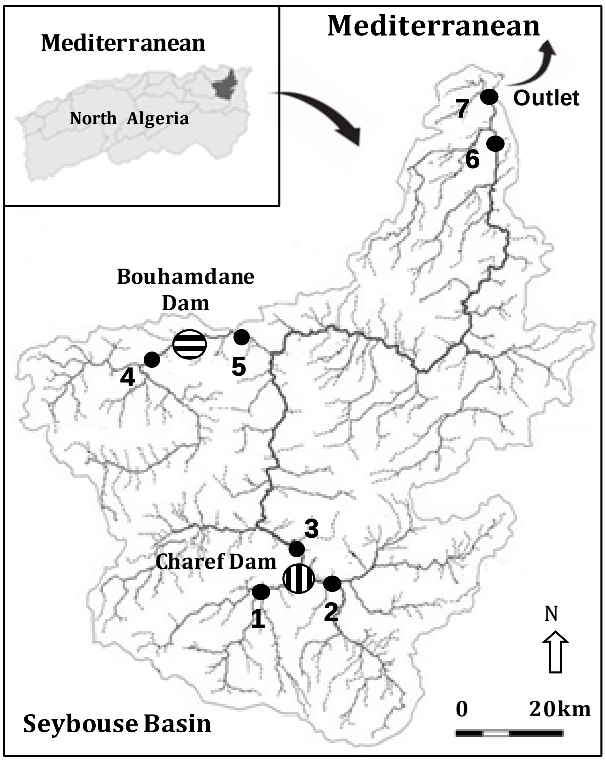

Figure 1: Geographic map of the Seybouse basin and sampling stations; ●: Stations, 1: Upstream 1 Charef dam, 2: Upstream 2 Charef dam, 3: Downstream Charef dam, 4: Upstream Bouhamdane dam, 5: Downstream Bouhamdane dam, 6: Upstream estuary, 7: Downstream estuary (Outlet).

3. RESULTS AND DISCUSSION

3.1. Physical environment

This work mainly aims to estimate the transfer of dissolved Silicates from the Seybouse basin to coastal waters and determine the effects of dams and the estuarine part on the SiO_4 biogeochemical transformations from the upstream of the basin to its mouth.The measurement results of the different parameters are configured in Figure 2 and Table 2. Water temperatures of the SeybouseRiver varied considerably throughout the aquatic continuum. It fluctuated in the range 12.9-26.7°C, with an average of 20.2°C and 16.8°C for dry and wet seasons, respectively (Figure 2A). It is recognized that water temperature is subject to substantial changes through the aquatic continuum, and it is also dependent on airtemperature (Zaidel et al., 2021); More interestingly, dams have been demonstrated to change riverine thermal regimes (Zhang et al., 2022).

The salinity of Seybouse waters varied on average between 1.51 PSU in the dry season and 1.17 PSU in the wet season. The highest salinities of about 1.9 PSU (wet season) and 4.6 PSU (dry season) were observed at the mouth station (Figure 2B).

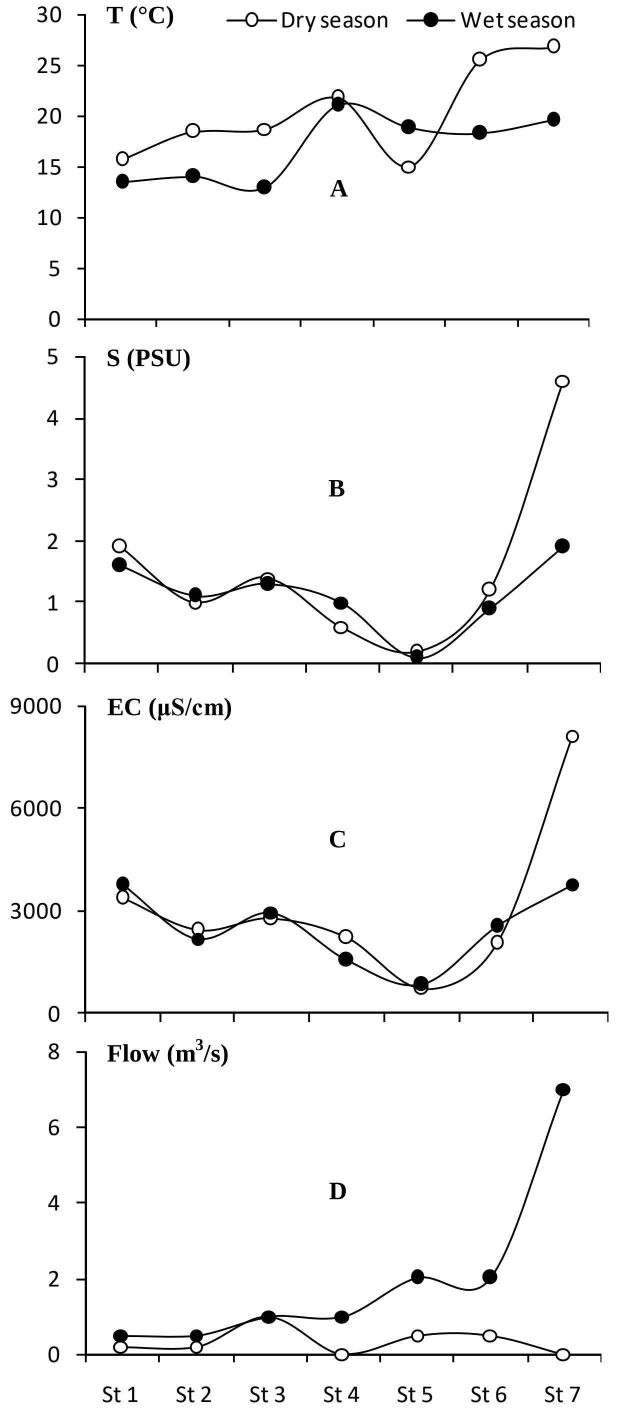

Figure 2.Hydrological parameters variations at the upstream and the downstream of the dams andat the upstream and the downstream of the Seybouse estuary during the study period.Values are averages of three replicate samples.

The water's electrical conductivity values behaved the same way as salinity (Highly significant correlation; Table 4) and fluctuated in the interval 735 - 8120 µS/cm with an average of 2810 µS/cm during the study period (Figure 2C). Before reaching the sea, salts pass through the aquatic continuum and undergo physical, chemical and biological modifications (transformation, retention, and immobilization) (Ziouch et al., 2020). In this context, Milliman (2001) revealed that nearly 200 dams along the Mississippi River, for example, have reduced salt discharge to the Gulf of Mexico by 60%.

During the study period, the flow of the Seybouse River varied greatly with extreme values of 0 $m^3 s^{-1}$ in the dry season and up to 7 $m^3 s^{-1}$ during the wet season. Also, it should be noted that the water flow upstream of the dams and the estuarine part is always higher than that of their respective downstream whatever the season (Figure 2D). According to Meddi et al. (2010), the total annual rainfall has decreasedby at least 20% from the mid-1970s. River discharges with their loads of nutrients into the Mediterranean Sea were then doubly affected by the climatic variability and by the dam's retention.

Table 2. Physical parameters measured in dry and wet seasons, minimums, maximums, and averages are also given.

		T (°C)	S (P.S.U)	EC (us/cm)	Flow (m^3/s)
Dry season	St 1	15.7	1.6	3380	0.2
	St 2	18.4	1.1	2440	0.2
	St 3	18.7	1.3	2780	1
	St 4	21.7	1	2210	0
	St 5	15	0.1	735	0.5
	St 6	25.4	0.9	2050	0.5
	St 7	26.7	4.6	8120	0
	Min.	15	0.1	735	0
	Max.	26.7	4.6	8120	1
	Mean	20.22	1.51	3102	0.34
Wet season	St 1	13.4	1.9	3740	0.5
	St 2	14	1	2190	0.5
	St 3	12.9	1.4	2950	1
	St 4	21	0.6	1554	1
	St 5	18.8	0.2	858	2
	St 6	18.3	1.2	2560	2
	St 7	19.5	1.9	3780	7
	Min.	12.9	0.2	858	0.5
	Max.	21	1.9	3780	7
	Mean	16.84	1.17	2519	2
Study period	Mean	18.53	1.34	2815	1.17

3.2. Distribution of Silicates in the Seybouse Basin

3.2.1. Silicates Levels at Entrance and Exit of Dams

SiO_4 contents showed a pronounced variation in Charef and Bouhamdane dam's waters on the spatio-temporal scale. Figure 3 and Table 3 show that Silicate contents in the dry season were higher than those recorded in the wet season for the two dams. Also, SiO_4 contents were always lower downstream than upstream of the dams. The retention rate oscillated in the range 15-49% for Charef dam and between 33-75% for Bouhamdane dam. The Charef sub-basin waters seem to be richer in silicates than Bouhamdane ones. Also, the retention rate at the Charef dam was higher than that of the Bouhamdane dam, which can be explained by its relatively long residence time.

3.2.2. Silicates Levels at Entrance and Exit of the Estuary

At the Seybouse estuary, SiO_4 ions fluctuated remarkably with the hydrological cycle, they varied in the dry season between 82 µM at its entrance and only 40 µM at the mouth station. In wet season SiO_4 contents were about 68 µM upstream and dropped to only 43 µM at the mouth station. Silicate ions were subjected to strong retention (37-51%) in the estuary, ultimately resulting in low contents (42 µM) at the mouth (Figure 3; Table 3).

3.3. Approximation of Silicates Flux in the Seybouse Basin

3.3.1. Silicates Flux Upstream and Downstream of dams

Table 3 indicates that SiO_4 flux did not show a clear trend. Thus, the Charef dam acts as a producer of 16 t/yr (29%) in the dry season and a consumer of 13 t/yr (15%) of silicates in the wet season. In contrast, the Bouhamdane dam acts as a silicon producer whatever the period. The Bouhamdane dam produced large silicate fluxes compared to the other dam due to water releases happening regularly during dry periods for irrigation purposes.

3.3.2. Silicates Flux Upstream of the Estuary and at the Mouth

The Seybouse estuary received silicate flux in the range 36-120 t/yr and it discharged fluxes ranging from 0 to 264 t/yr. It acts as a producer of 144 t/yr (121%) in the wet season and a consumer of 36 t/yr (100%) of silicates in the dry period (Figure 3; Table 3).

SiO_4 contents and fluxes were strongly modified throughout the aquatic continuum before reaching the sea. At the dam's entrance, the waters appear moderately loaded with Silicates with an average of 120 µM. Moving towards the sea, this quantity was reduced to 1/2 downstream of the dams and to only 1/3 at the mouth. The masses of SiO_4 are already reduced naturally in our rivers by the low water flow (Meddi et al., 2010) and by the geological nature of rocks and sediments poor in Si (Dürr et al., 2011) (world average 150 µM, Tréguer et al., 1995) were further eliminated in dams at rates varying on average between 24% and 62%. Furthermore, the SiO_4 in Seybouse River waters have also been sequestered (44%) within the estuary.

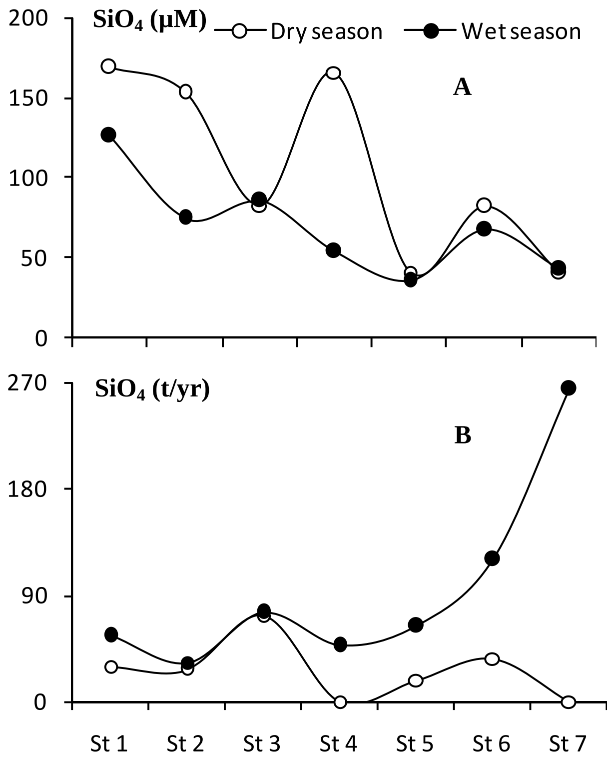

Figure 3.Silicates contents (A) and fluxes (B) variations at the upstream and the downstream of the dams, the upstream and the downstream of the Seybouse estuary during the study period.

Table 3. Silicate SiO_4 contents (µM) and loads (t/year; between brackets) upstream and downstream of the dams, upstream and downstream of the estuary, and retention rate; R%: Retention (-) or production (+).Ups.: Upstream. Dow.: Downstream; Char.: Charef; Bouh.: Bouhamdane; Pr/Ret: Procuction/retention; Pr/Ret (%):Procuction/ retention rate.

Season	Site	Ups.	Dow.	Pr/ Ret	Pr/Ret (%)
Dry season	Char. dam	161	83	**-78**	**-49**
		(57)	(73)	(16)	(29)
	Bouh. dam	166	41	**-125**	**-75**
		(0)	(18)	(18)	(100)
	Estuary	82	40	**-42**	**-51**
		(36)	(0)	(**-36**)	(**-100**)
Wet season	Char. dam	100	85	**-15**	**-15**
		(89)	(75)	(**-13**)	(**-15**)
	Bouh. dam	54	36	**-18**	**-33**
		(47)	(64)	(16)	(35)
	Estuary	68	43	**-25**	**-37**
		(120)	(264)	(144)	(121)

In terms of flux which seems to be closely related to water flow, the adjacent coast received low silicate fluxes (0-264 t/yr). This is evidenced by the highly significant correlation between water and Silicate fluxes (Table 4). According to Romero et al. (2013), the SiO_4 annual mean level for the Seybouse River estuary was about 1/2 the European and Mediterranean rivers, with a flux three times lower. UNEP/MAP, (2013) reported that of the Mediterranean rivers, the Seybouse River had the lowest levels and fluxes of SiO_4. Silicate levels in Algerian rivers decreased as a result of reservoir retention, which can remove more than half of the incoming flux (Aounallah., 2015; Ounissi and Bouchareb, 2013). Within the River system in watersheds, dams are known for trapping and recycling nutrients (Howarth and Marino, 2006; Humborg et al., 2008). However, little work has been devoted to the retention of Si compared to nitrogen (N) and phosphorus (P) but clearly shows that a substantial fraction of Si is retained in dams (Li et al., 2021). If the retention of N and P in dams can be compensated downstream of the dams by anthropogenic inputs (agricultural fertilizers, domestic discharges), Si is trapped in dams and remains dependent on hydrology. Marine waters consequently receive waters with a completely unbalanced Si/N/P ratio (Redfield et al., 1963).

Table 4. Pearson correlation matrix displaying the interrelationships between the physicochemical parameters of water of the Seybouse basin. Pearson correlation tests are given as correlation coefficient values with asterisks indicating the level of statistical significance. The levels of statistical significance are denoted as ***: $p < 0.001$, **: $p < 0.01$, and *: $p \leq 0.05$.

	SiO_4 (t/yr)	SiO_4 (µM)	Flow (m^3/s)	EC (µS/cm)	S (PSU)
T (°C)	-0.11	-0.2	3.49×10^{-4}	0.37	0.43
S (PSU)	-0.01	-0.10	-0.02	0.98***	
EC (µS/cm)	0.01	-0.03	2.23×10^{-4}		
Flow (m^3/s)	0.97***	-0.43			
SiO_4 (µM)	-0.35				

According to Turner et al. (2003), Si can not only reduce productivity but also alter phytoplankton populations, resulting in the dominance of non-siliceous hazardous species. Likewise, Cloern (2001) illustrates that the decline in diatom and copepod populations in coastal regions correlates with diminished silicon imports from rivers. The construction of dams on upstream rivers obstructs water flow and associated nutrients, adversely impacting fishery production and contributing to the decline and extinction of species in rivers, estuaries, and marine ecosystems (Marmulla 2001). Numerous research examining nutrient levels and stoichiometry or primary production with fish production or fisheries yields indicate that a correlation may exist (Ounissi et al., 2008; Chassot et al, 2010; Bao et al., 2022).

Some restoration practices that focus on managing water levels and discharges from dams can guarantee an environmental flow and significantly minimize negative environmental impacts. This management concept corresponds to the quantity or volume of water required over time to maintain river health in a particular state (Acreman and Dunbar 2004). The initial methods for assessing environmental flow concentrated solely on the lowest flow, predicated on the notion that all river health issues are linked to low flows. In this context, it is widely recognized (Postel and Richter 2003; Li et al., 2021; Ziouch et al., 2020) that not only the volume of water discharged is critical, but also the timing and dynamics of the discharge play essential roles in maintaining and preserving the diversity of native species and the ecological integrity of rivers.

Successful applications of restoration practices in various river systems demonstrate their effectiveness in improving ecosystem health. For instance, the Murray-Darling Basin in Australia has adopted a range of water management strategies, including increasing environmental water allocations during crucial periods. As a result, there has been a reduction in salinity and enhanced habitat conditions for aquatic species (Murray-Darling Basin Authority 2018). Another example, the Housatonic River in Massachusetts has seen a restoration of aquatic communities due to increased river flows and enhanced riparian buffer zones achieved through dam management (Housatonic River Commission 2019).

These hydrological studies should constitute a crucial element in decision support for the integrated management of continental and coastal environments and their renewable resources.

4. CONCLUSIONS

Within the Seybouse basin, dissolved silicates showed very variable levels and fluxes in space and time. The highest levels were recorded upstream of the basin and weakened towards the mouth. SiO_4 was reduced between 32% and 54% by the Charef and Bouhamdane dams respectively, while the estuary retention rate was on average 44%. Silicates were subjected to strong retention in the dams and also in the estuary, ultimately resulting in minimum values of around 42 µM at the mouth. In terms of flux which is closely related to the water flow, the Charef and Bouhamdane dam produced on average 2 t/yr and 17 t/yr respectively while the estuary produced 54 t/year to the coastal zone. These moderate fluxes were considered among the lowest ones compared with those of Mediterranean rivers. These hydrological and biogeochemical conditions are expected to have severe impacts on the River system and the functioning and production of renewable resources of the receiving coastline. Some of our understanding of the water inflows and silicate biogeochemical changes in the Seybouse basin has improved as a result of this study. However, it is important to note that the number of samples collected is not sufficient. Further investigations are required, including a larger number of sampling sites and extended monitoring over a longer period. Additionally, biogeochemical studies encompassing nitrogen and phosphorus dynamics across the entire Seybouse River basin are essential to provide a more comprehensive understanding of the system.

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Data availability

The data collected and analyzed for this study can be shared upon request.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the study's design, the collection, analyses, or interpretation of data, the writing of the manuscript, or the decision to publish the results.

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