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Article

Anthropogenic Reservoirs of Various Sizes Trap Most of the Sediment in the Mediterranean Maghreb Basin

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Abstract: The purpose of this study is to obtain a spatially explicit assessment of the impact of reservoirs on natural river sediment fluxes to the sea in the Mediterranean Maghreb Basin (MMB), a region where both mechanical erosion rates and the anthropogenic pressure on surface water resources are high. We combined modeling of riverine sediment yields (sediment fluxes divided by the drainage basin area) and water drainage intensities in a 5' × 5' grid point resolution (~10 km × 10 km) with a compilation of existing reservoirs in the area, and calculated sediment trapping based on average water residence time in these reservoirs. A total number of 670 reservoirs could be assembled from various sources (including digitization from Google maps), comprising large-scale, small-scale and hillside reservoirs. 450 of them could be implemented in our modeling approach. Our results confirm that natural sediment yields are clearly above the world average, with the greatest values for Morocco (506 t km⁻² year⁻¹), followed by Algeria (328 t km⁻² year⁻¹) and by Tunisia (250 t km⁻² year⁻¹). Including dams in the downstream routing of suspended sediments to the sea reduces the natural sediment flux in the entire MMB to the sea from 96 to 36 Mt km⁻¹ year⁻¹, which corresponds to an average sediment retention of 62%. Trapping rates are highest in the Tunisian basin part, with about 72%, followed by the Algerian (63%) and the Moroccan basin parts (55%). Small reservoirs and hillside reservoirs are quantitatively important in the interception of these sediments compared to large reservoirs. If we only considered the dams included in the widely used Global Reservoir and Dam (GRanD) database which comprises mainly large reservoirs sediment retention behind dams would account for 36% of the natural suspended particulate matter (SPM) flux to the Mediterranean Sea. Our data reveal negative correlation between sediment retention and natural erosion rates among the three Maghreb countries, which can be explained by the greater difficulties to build dams in steep terrains where natural sediment yields are high. Although the lowest sediment retention rates are found in the Moroccan part of the MMB, it is probably here where riverine sediment starvation has the greatest impacts on coastline dynamics. Understanding the impact of dams and related water infrastructures on riverine sediment dynamics is key in arid zones such as the MMB, where global warming is predicted to cause important changes in the climatic conditions and the water availability.

Keywords: Mediterranean Maghreb Basin; water fluxes; sediment fluxes; reservoirs; hillside reservoirs; sediment retention

1. Introduction

Because of the strong seasonal and inter-annual variability of flow regimes in inland waters, water stress is endemic in most parts of the Mediterranean drainage basin. Water is relatively scarce throughout most of the year, whereas high flows threaten lives and property on a small number of days per year or decade. Under such conditions, the rising demand for water is met by steadily increasing reservoir constructions to store seasonal or annual water surpluses [1]. These reservoirs impact the natural transfer and cycling of water, sediments and associated elements in the corresponding drainage basins. They retain considerable amounts of riverine nutrients and suspended sediments [2,3], preventing them to be supplied to the coastal waters in order to sustain biological productivity and to allow geomorphological edification of beaches and deltaic systems.

Sediment starvation in rivers through damming has been recognized as a major environmental problem in the Mediterranean area, as it exacerbates coastal erosion and sea level rise in relation to global warming [4,5]. In Mediterranean rim countries most of the population is concentrated in the coastal areas, which also represent the dominant economic resources via tourism and fishery. Erosion in these areas is hence a major threat. Rapid sediment accumulation in the reservoirs has also negative economic impacts as it reduces their performance and lifetime. Detailed knowledge on the riverine sediment dynamics in relation to the natural and anthropogenic forcings is therefore mandatory for sustainable development strategies. This is particularly true in the Mediterranean area because natural riverine sediment fluxes are high in its drainage basins [6] and environmental conditions respond rapidly to anthropogenic alterations.

The impact of reservoir construction on riverine sediment fluxes to the Mediterranean Sea was examined in a recent study [7]. By combining spatially explicit modeling of natural sediment and water fluxes with the precise locations and properties of dams as they are documented in the GRanD database (Global Reservoir and Dam, [8]), they calculated that about 35% of the natural sediment discharges should nowadays be retained in reservoirs. This underlines their significant impact on the basin-wide budgets, although the percentage is comparable to what has been estimated at the global scale [9,10], which questions the idea of the Mediterranean being a hot spot area for anthropogenic perturbations. Nevertheless, Mediterranean rivers are often small in size [11] and GRanD is far from being complete in this area.

We therefore attempted to go a step further and to examine the role of the “missing dams”. We selected the Maghreb region of Northern Africa as a regional focus and intended to assemble a much more complete database from various sources, also including small-scale and hillside reservoirs. This allowed us to produce for the first time a detailed regional assessment on dams in the area, which is not only useful for general budget considerations, but which may also serve as a management tool for the evaluation of potential environmental risks in terms of coastal erosion and/ or reservoir silting. Our method may further be applied to other regions of the Mediterranean drainage basin in order to put together a more complete picture of human perturbations in this key environment for global change studies.

2. Data and Methods

2.1. Study Area

The Maghreb in northwestern Africa, also known as the small Maghreb, is a mountainous region including the countries of Morocco, Algeria and Tunisia. In particular, the Mediterranean Maghreb basin (MMB) covers the northern part of Morocco excluding the terrains that are drained to the Atlantic, Algeria, and the northern and eastern parts of Tunisia (Figure 1). The Maghreb is among the regions that are most vulnerable to erosion in the world. Several researchers [12–14] have attempted to explain the mechanisms of solid transport in this region, and Probst and Suchet proposed an overall estimate for the riverine sediment fluxes in the Maghreb basin of 100 Mt year^{-1} [15], corresponding to a specific

sediment flux (sediment yield) of about $400 \text{ t km}^{-2} \text{ year}^{-1}$. These are probably among the highest values in Africa.

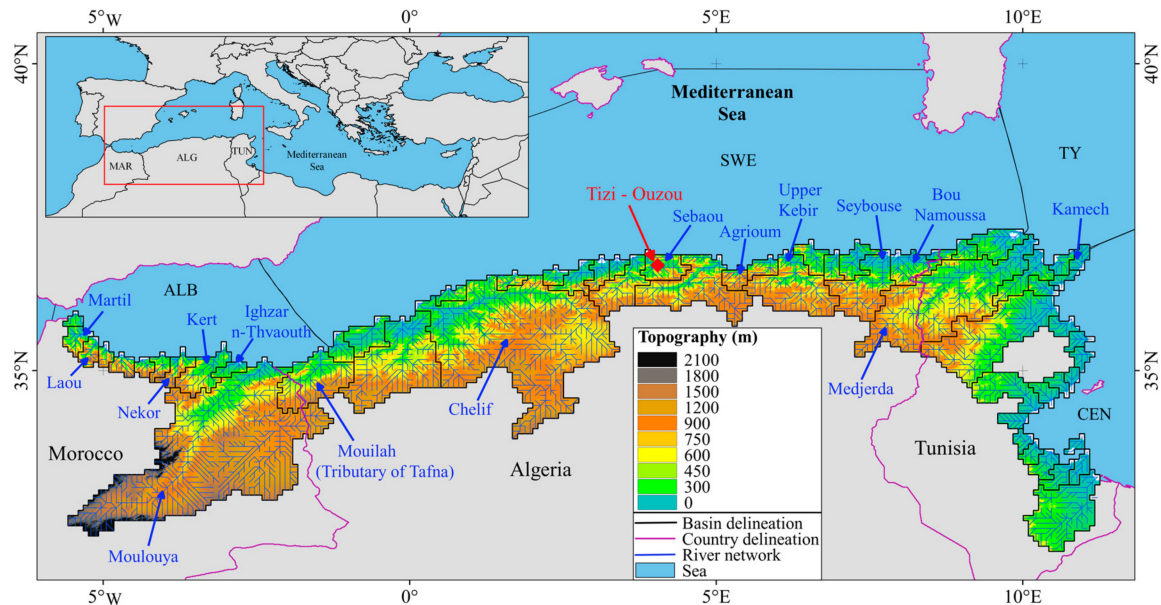


Figure 1. Location map of the Mediterranean Maghreb Basin (MMB) and delimitation of its drainage basins at a spatial resolution of 5 arc-minutes. Topography was extracted from the digital elevation model of [16]. All rivers and locations which are mentioned in the text have been included in this figure. Abbreviations: ALB: Alboran sub-basin, CEN: Central sub-basin, SWE: Southwestern sub-basin, TY: Tyerrhenian sub-basin.

These average values, however, cannot be transposed locally because their spatial variability can be significant. For example, rather moderate sediment yields of $165 \text{ t km}^{-2} \text{ year}^{-1}$ have been reported for the Mouilah basin [17] in Algeria; intermediate values of about $600 \text{ t km}^{-2} \text{ year}^{-1}$ for the Medjerda basin [15] in Tunisia and $884 \text{ t km}^{-2} \text{ year}^{-1}$ for the Upper Kebir basin in Algeria [18]; high values of 1500 and $2000 \text{ t km}^{-2} \text{ year}^{-1}$ for the Kamech basin in Tunisia [19] and the Martil basin in Morocco [20], respectively; and peak values of 5000 to $5900 \text{ t km}^{-2} \text{ year}^{-1}$ for the Agrioum basin [21] in Algeria and the Nekor basin [22] in Morocco. Several factors combine in order to explain these high erosion rates. The Maghreb is a fragile mountainous area. The mountains extend over large areas and are characterized by high altitudes as well as steep slopes. Lithology is often made of soft sedimentary rocks susceptible to erosion and the Maghreb is subject to contrasted climatic conditions. In summer, climate is dominated by Saharan aridity with high temperature and low precipitation. In winter, climate is colder and wetter due to the oceanic influence [23]. Hence, climate is irregular and characterized by a strong contrast between dry and wet years, with often intense and devastating rains [24].

Due to the aridity of the climate, water is an important factor for economic development and the construction of dams represents a major issue for the Maghreb countries. North Africa (here considered as including the totality of these three countries: Morocco, Algeria and Tunisia) has currently over 230 large dams with a total storage capacity of 23 km^3 [25]. Large dams serve in general to store drinking water and for industrial and electrical energy production. In addition, many small dams and hillside reservoirs exist and serve to mitigate floods, contribute to water table recharge and improve water storage for irrigation and livestock watering and domestic uses. A detailed census of the different reservoir categories is nevertheless difficult. The only existing database is the GRanD database [8], which includes 53 dams in the Maghreb basin with a total storage capacity of about 6.5 km^3 [7].

Anthropogenic degradation in MMB is very high, increasing erosion and enhancing early silting of reservoirs in Morocco [20,26], in Algeria [24,27] and in Tunisia [28]. According to [25], who monitored

and evaluated silting in the 230 dams of North Africa, the average capacity loss in these dams can be estimated to about $0.54\% \text{ year}^{-1}$. Silting of these dams poses many problems at the level of the reservoir itself, but also in the basin parts upstream and downstream the reservoir. The authors of [25,29] cite several dams in North Africa where major degradations occurred, such as the reduction of the dam capacity, the destabilization of the structure (e.g., Oued El Fodda, Algeria), the filling of drainage ditches (e.g., Zardézas dams, Algeria), the silting of irrigation channels (e.g., bypass channel, Morocco) and the degradation of water quality (e.g., El Khattabi Dam, Morocco).

2.2. Modeling Framework

The modeling framework we used to calculate river sediment fluxes in the MMB and their retention in dams was set up in the study by [7]. It is based on the numerical definition of the drainage basin delineations and hydrological networks around the Mediterranean Sea in a $5' \times 5'$ grid point resolution ($\sim 10 \text{ km} \times 10 \text{ km}$), and was produced by aggregation of the Hydrosheds digital elevation model of [30] with manual corrections of the resulting hydrological networks (for further details, see [7]). A total of 549 river basins could be distinguished for the entire Mediterranean drainage basin. In each basin all internal grid points are linked to one single mouth point that represents the river estuary according to a realistic river routing scheme (multi-branch estuaries that often exist for large river systems cannot be reproduced this way).

Quantification of specific riverine suspended matter (SPM) and specific water (Q) fluxes was obtained through empirical modeling relating these parameters at the grid point scale to a series of environmental factors that are considered to represent their major controls. The corresponding multi-regression models could be established on the basis of the average long-term basin characteristics from a large data set of 126 (Q) and 80 (SPM) Mediterranean rivers [7]. In short, specific water discharge (Q) was produced as a combination of annual precipitation, potential evapotranspiration, seasonal variability of precipitation (all climatic parameters were taken from [31]) and grid point slope [30], whereas specific SPM fluxes could be linked to specific water discharge, grid point slope, the percentage of sedimentary rocks in altitudes above 600 m [32] and the percentage of erodible land use classes (agriculture, grasslands and bare soils—[33]).

Both the produced Q and SPM fluxes represent average long-term values that do not account for temporal fluctuations in relation to climate variability and/or recent climate change, although we are aware that seasonal and inter-annual variability of SPM fluxes can be very important in the Mediterranean area and short and violent floods may represent more than 90% of the annual sediment load [34]. Moreover, the SPM fluxes are considered to represent natural (i.e., “pre-damming”) values, since most of the literature estimates that were used to fit the regressions correspond to the pre-1950–1980 period, when human impoundments on rivers were not as frequent as today. This allowed simulating the impact of the dams constructed along the river courses through conservative routing of the grid-point SPM fluxes into the reservoirs and retaining them as a function of the average water residence time according to the equation initially proposed by [35]. The whole method has been described with more detail in [7].

2.3. Inventory of Dams

We started our inventory with the geo-referenced dams included in the GRanD database of [8]. It contains 53 dams in the Maghreb basin (6 for Morocco, 28 for Algeria and 19 for Tunisia). To this, 48 dams could be added from repertoires from various national agencies in the Maghreb, including 36 dams from the ANBT (National Agency for Dams and Transfers, [36]) in Algeria, 7 dams from the ABHL (Loukkos Hydraulic Basin Agency, [37]) in Morocco and 5 dams from the DGBGTH (General Directorate for Dams and Major Hydraulic Works, [38]) in Tunisia. Generally, these agencies provide information on storage capacity, water discharge and the year of reservoir construction, but no digitized files in a GIS format for the location of the dams. Manual location of these dams from Google satellite maps was necessary (consulted in June 2016). A total of 101 dams were consequently assembled

(Table 1). The majority of these dams were constructed in recent decades. More than 30% were built after 2000, and 60% between 1950 and 2000. Less than 10% were erected over the period from 1860 to 1950.

Table 1. Characteristics of the 101 dams of the Mediterranean Maghreb Basin (MMB) considered in this study.

NB	Dams	Country	Year of Construction	CAP (Mm ³)	S (km ²)	H (m)	Source
1	Ain Dalia	Algeria	1987	82	3.4	24	GRanD
2	Ain zada	Algeria	1986	125	6.9	18	GRanD
3	Ajras	Morocco	1969	3	0.4	8	GRanD
4	Al Thelat-Laou	Morocco	1934	30	0.9	33	GRanD
5	Asmir	Morocco	1991	43	2.6	17	ABHL
6	Bakhada	Algeria	1935	56	3.5	16	GRanD
7	Barbara-Zoutina	Tunisia	1999	58	3.9	15	GRanD
8	Beni Amrane	Algeria	1988	12	1.0	12	ANBT
9	Beni Bahdel	Algeria	1946	63	1.2	53	GRanD
10	Beni Boussaid	Algeria	2007	1	0.2	7	ANBT
11	Beni Haroune	Algeria	2003	998	44.4	22	ANBT
12	Beni metir	Tunisia	1954	73	1.8	41	GRanD
13	Beni zid	Algeria	2000	40	3.5	12	ANBT
14	Bezrik	Tunisia	1959	7	0.7	9	GRanD
15	Bir M'Cherga	Tunisia	1971	160	4.3	37	GRanD
16	Bou Hanifa	Algeria	1948	73	2.7	27	GRanD
17	bou heurtna	Tunisia	1976	118	7.1	17	GRanD
18	Bou Roumi	Algeria	1985	188	1.7	111	GRanD
19	Boughzoul	Algeria	1934	55	16.3	3	GRanD
20	Bougous	Algeria	2010	65	2.8	24	ANBT
21	Boukourdene	Algeria	1992	110	3.1	36	ANBT
22	Boussiaba	Algeria	2000	120	10.3	12	ANBT
23	Cap Djinet	Algeria	1990	13	0.4	34	ANBT
24	Cheffia	Algeria	1965	171	7.0	24	GRanD
25	Chelif	Algeria	2009	130	7.2	18	ANBT
26	Cheufra	Algeria	1935	14	1.3	11	GRanD
27	Chiba	Tunisia	1963	8	1.1	7	GRanD
28	Colonel bougara	Algeria	1988	13	2.3	6	GRanD
29	Dahmouni	Algeria	1987	41	3.4	12	GRanD
30	Deurdeur	Algeria	1984	115	4.8	24	ANBT
31	Djoumine	Tunisia	1983	130	5.4	24	GRanD
32	Douera	Algeria	2014	87	1.3	65	ANBT
33	Draa Diss	Algeria	2016	151	0.5	80	ANBT
34	El Abid	Tunisia	2002	10	1.4	7	DGBGTH
35	El Agrem	Algeria	2002	34	2.3	15	ANBT
36	El Djomoaa	Morocco	1992	7	0.5	12	ABHL
37	El habib-ouareb	Tunisia	1988	110	5.0	22	GRanD
38	El Hamiz	Algeria	1990	16	0.9	17	ANBT
39	El hamma	Tunisia	2002	12	0.6	21	DGBGTH
40	El Masri	Tunisia	1968	6	0.7	8	ANBT
41	Ennakhela	Morocco	1961	13	0.6	22	GRanD
42	Erraguen	Algeria	1961	200	11.0	18	ANBT
43	Fergoug	Algeria	1970	18	0.7	26	GRanD
44	Gargar	Algeria	1988	450	19.0	24	GRanD
45	GHrib	Algeria	1938	280	7.1	39	GRanD
46	GuenitraOumToub	Algeria	1984	125	1.3	96	GRanD
47	H.M.Bouhemdene	Algeria	1987	220	5.1	43	GRanD
48	Hammam Grouz	Algeria	1987	45	2.3	20	GRanD
49	Harreza	Algeria	1984	70	1.0	70	GRanD
50	Hassan II	Morocco	2000	400	11.0	36	ABHL
51	Hassan II Midelt	Morocco	2006	400	11.8	34	ABHL
52	Ighil Emda	Algeria	1953	156	2.9	53	ANBT
53	kasseb	Tunisia	1969	81	4.0	20	GRanD
54	Kebir	Tunisia	1925	26	1.6	16	GRanD
55	Keddara	Algeria	1990	142	5.6	26	ANBT
56	Kef Eddir	Algeria	2015	150	0.5	77	ANBT
57	Kerrada	Algeria	2010	70	3.6	19	ANBT
58	Kissir	Algeria	2010	68	3.6	19	ANBT
59	Koudiat Acerdoun	Algeria	2009	400	16.5	24	ANBT
60	Koudiat resfa	Algeria	2007	75	3.7	20	ANBT
61	Kramis	Algeria	2005	45	2.1	21	ANBT
62	Ladrat	Algeria	1988	10	0.5	20	GRanD
63	Lakhmess	Tunisia	1966	8	0.7	11	GRanD

Table 1. Cont.

NB	Dams	Country	Year of Construction	CAP (Mm ³)	S (km ²)	H (m)	Source
64	Lekhal	Algeria	1985	30	0.9	33	GRanD
65	Iepna	Tunisia	1986	30	6.6	5	GRanD
66	M.B.A.L.khattabi	Morocco	1981	43	2.1	20	GRanD
67	Mahouane	Algeria	2014	148	0.3	76	ANBT
68	Martil	Morocco	2014	100	0.8	118	ABHL
69	Mechra Hammadi	Morocco	1955	42	1.2	35	GRanD
70	Mefrouch	Algeria	1960	15	1.8	8	ANBT
71	Merdja sidi abed	Algeria	1984	55	7.0	8	GRanD
72	Meurad	Algeria	1860	0.2	0.1	26	ANBT
73	Mexa	Algeria	1998	47	5.4	9	ANBT
74	Mlaabi	Tunisia	1967	4	0.8	4	DGBGTH
75	Mohammed V	Morocco	1967	730	16.3	45	GRanD
76	M. Bouchta	Morocco	2014	13	0.7	18	ABHL
77	Nabeur-Mellegue	Tunisia	1954	300	8.5	24	GRanD
78	Nebhana	Tunisia	1965	86	2.6	33	GRanD
79	Oued Cherf	Algeria	1995	157	10.2	15	ANBT
80	Oued el hajar	Tunisia	1999	6	2.0	3	DGBGTH
81	Oueder mel tunis	Tunisia	1999	22	7.8	3	DGBGTH
82	Oued Fouda	Algeria	1932	228	2.9	79	GRanD
83	Oued Rmel	Morocco	2008	25	1.1	22	ABHL
84	Ouzert	Algeria	1985	100	2.0	50	GRanD
85	S.M.B.Aouda	Algeria	1978	235	8.0	29	GRanD
86	Sarno	Algeria	1953	22	0.2	110	GRanD
87	Sejnane	Tunisia	1990	130	5.8	22	GRanD
88	Sekkak	Algeria	2004	30	2.0	15	ANBT
89	Sidi abdelli	Algeria	1988	110	0.8	138	GRanD
90	Sidi el barek	Tunisia	2002	275	9.2	30	GRanD
91	Sidi saad	Tunisia	1981	209	9.8	21	GRanD
92	Sidi salem	Tunisia	1981	555	40.1	14	GRanD
93	Sidi Yakoub	Algeria	1983	286	6.4	45	GRanD
94	Siliana	Tunisia	1987	70	4.7	15	GRanD
95	SMB taiba	Algeria	2005	75	2.9	25	ANBT
96	Souani	Algeria	1988	14	2.0	7	GRanD
97	Teksebt	Algeria	2001	180	4.6	39	ANBT
98	Tichy haff	Algeria	2009	80	4.6	18	ANBT
99	Tilsedit	Algeria	2009	83	9.7	9	ANBT
100	Zardezaz	Algeria	1973	31	1.3	24	ANBT
101	Zit Emba	Algeria	2002	117	7.7	15	ANBT

Note: NB: number of dams; CAP: reservoir storage capacity; S: reservoir surface; H: height of dike; ABHL: Loukkos Hydraulic Basin Agency, Morocco; ANBT: National Agency for Dams and Transfers, Algeria; DGBGTH: General Directorate for Dams and Major Hydraulic Works, Tunisia; GRanD: Global Reservoir and Dam database.

In a second step, we enlarged our database through manual digitization of additional reservoirs from Google satellite maps. In this approach, we mainly focused on the inclusion of small and hillside reservoirs, but also a few large reservoirs previously not identified could be added that way. To facilitate our work, we first imported our river network map and the previously collected dams (GRanD and Maghreb agencies) in order to avoid the re-digitization of existing reservoirs. The maps were imported in kml-format at a resolution of 5 arc-minutes and consisted of polygons, vectors and points.

We then created our own layer on which we digitized the rest of the reservoirs by zooming in on the Google maps to their maximum resolution and following the river network from upstream to downstream in each river basin. Reservoirs were identified initially by the blue color of the waters and the presence of a dike downstream. Two layers were created, the first one to digitize the surface of the reservoirs with polygons and the second one to locate the dams by fixing a geographical reference point downstream the reservoir (near the dike), which represents the outlet of the dam. It was sometimes difficult to distinguish between small dams, hillside reservoirs, and natural lakes. Besides checking the legend of reservoir names provided by Google maps, we used the shape of the water surfaces as a distinguishing criterion. Reservoirs are generally characterized by their longitudinal shapes and the existence of a dike downstream the flow direction, whereas natural lakes are usually characterized by a round shape and the absence of the dike. Hillside reservoirs are not implemented on major river courses and typically found in agricultural fields.

For the manually-digitized reservoirs we had no information on the storage capacity. In order to produce an estimate for this parameter too, we calculated a linear regression between the storage capacity (CAP) and the surface (S) of the reservoir. In fact, two regression models were established, one for the GRanD database reservoirs (Figure 2A)

$$\text{CAP} = 34.79 S \quad (1)$$

$$n = 323, r^2 = 0.82, p < 0.001$$

And one for the hillside reservoirs (Figure 2B)

$$\text{CAP} = 9.29 S \quad (2)$$

$$n = 25, r^2 = 0.89, p < 0.001$$

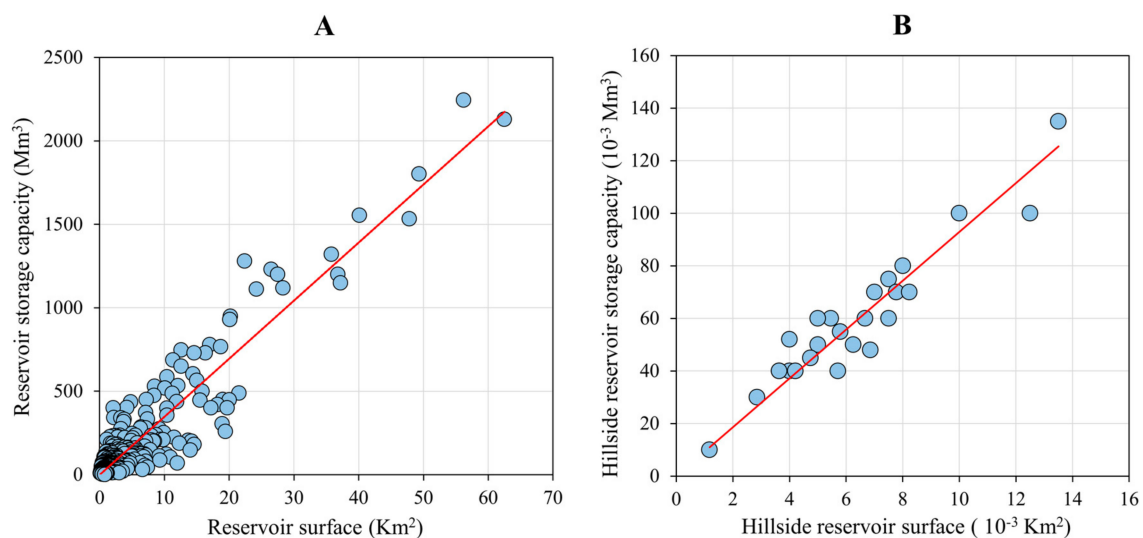


Figure 2. Linear relationships between storage capacity and reservoir surface (A) using the Mediterranean reservoirs of the GRanD database [8] and (B) using the hillside reservoir database of [39].

Both regressions were forced to pass through the origin (i.e.; no intercept). Equation (1) is based on information for all Mediterranean reservoirs in the GRanD database, and Equation (2) on the compilation of hillside reservoirs in the Tizi-Ouzou region (Algeria) produced by [39], which is the only available study in the area (Table 2).

Table 2. Characteristics of the hillside reservoirs of the Tizi-Ouzou region (Algeria) described by the authors of [39] and considered in this study.

NB	Name of Hillside Reservoir	S (10^3 m^2)	H (m)	CAP (10^{-3} Mm^3)	Year of Construction
1	Bouzeguene N° 2	4.0	13	52	1999
2	Bouzeguene N° 3	7.5	10	75	1999
3	Iloula oumalou N° 1	3.6	11	40	2000
4	Iloula oumalou N° 399	8.0	10	80	2000
5	Timizart N° 201	6.7	9	60	1989
6	Timizart N° 360	5.0	10	50	1988
7	Timizart N° 363	7.8	9	70	1986
8	Timizart N° 366	13.5	10	135	1985
9	Timizart N° 388	7.5	8	60	1985
10	Freha N° 389	6.3	8	50	2000

Table 2. Cont.

NB	Name of Hillside Reservoir	S (10 ³ m ²)	H (m)	CAP (10 ⁻³ Mm ³)	Year of Construction
11	Freha N° 395	5.8	9.5	55	1985
12	Freha N° 396	12.5	8	100	1987
13	Freha N° 397	4.7	9.5	45	1986
14	Freha N° 398	10.0	10	100	1989
15	Mekla N° 367	1.2	8.5	10	1985
16	Mekla N° 368	8.2	8.5	70	1986
17	Mekla N° 391	4.0	10	40	1989
18	Mekla N° 393	6.9	7	48	1985
19	Mekla N° 394	5.7	7	40	1986
20	Souomaâ N° 1	5.5	11	60	1999
21	Azzefoun N° 10	4.2	9.5	40	1986
22	Azzefoun N° 11	5.0	12	60	1997
23	Azzefoun N° 12	7.0	10	70	1988
24	Azzefoun N° 14	3.6	11	40	1994
25	Azzefoun N° 15	2.9	10.5	30	1995

Note: S: hillside reservoir surface; H: Dike height; CAP: reservoir storage capacity.

It should be noted that the database produced by [39] was only used to determine Equation (2). Since the database does not include the geographic coordinates of the reservoirs, it is difficult to differentiate them from other newly digitalized hillside reservoirs. To avoid confusion and duplications, we kept this database only to determine Equation (2).

The storage capacity of the reservoirs can be strongly influenced by their morphology, and notably by the slope of the reservoir surface. The slope of hillside reservoirs is generally very low compared to that of the dams, in particular large dams. Two reservoirs that have the same surface but a different slope can have a very different storage capacity; this is the reason why we kept two different regression models (Figure 2A,B).

Overall, we were able to digitize the surface of 569 additional reservoirs, mostly consisting of small dams and hillside reservoirs. This expanded our database to 670 reservoirs with areas larger than one hectare. On the basis of Equations (1) and (2), we then calculated the storage capacity of these additional reservoirs (i.e., when the newly digitized reservoirs were identified as hillside reservoirs, we applied Equation (2); elsewhere, we used Equation (1)). All the reservoirs were then classified according to their storage capacities into seven classes: C₁ (CAP > 200 Mm³), C₂ (100 < CAP < 200 Mm³), C₃ (50 < CAP < 100 Mm³), C₄ (20 < CAP < 50 Mm³), C₅ (5 < CAP < 20 Mm³), C₆ (1 < CAP < 5 Mm³), and C₇ (CAP < 1 Mm³). It should be noted that hillside reservoirs never exceeded a storage capacity of 1 Mm³, and almost 90% of them had a storage capacity lower than 0.8 Mm³. For small dams, we considered that the maximum capacity limit was 20 Mm³ (see Section 3.2) and found that only 21% of these dams had a storage capacity lower than 1 Mm³. Although there is some overlap with the maximum size of hillside reservoirs, we considered this value to be a reasonable lower limit for small dams.

The integration of all these reservoirs in our modeling framework suffered however from the limited spatial resolution of this framework. In many cases several reservoirs fell within one single 5 arc-minutes grid cell. For the calculation of sediment retention, in addition to the storage capacity we need the amount of water entering and leaving the reservoirs annually. This parameter can only be calculated at the grid point level from our empirical modeling of mean annual water discharge (see Section 2.2). We therefore decided to retain for our modeling of sediment retention only the largest reservoir in a given grid point cell, to which we attributed the corresponding average annual water discharge following the assumption that this reservoir has been constructed along the principal grid point drainage direction. This reduced the total number of reservoirs which could be properly used for modeling to 450.

3. Results and Discussion

3.1. Natural Water and Sediment Fluxes

Average water fluxes in the MMB are rather low (Figure 3A). Drainage intensity (water discharge divided by the basin area) for the entire region is only 59 mm per year (Table 3), with little differences between the three countries (52, 62 and 62 mm year⁻¹ for Morocco, Algeria and Tunisia, respectively). More humid conditions are restricted to mountainous areas in the vicinity of the coast and exist in the NW part of Morocco (e.g., the Martil and Laou rivers with Q values of 332 mm year⁻¹ and 252 mm year⁻¹, respectively) and along the central and NE coast of Algeria (e.g., the Sebaou and Bou-Namoussa rivers with Q values of 387 mm year⁻¹ and 290 mm year⁻¹, respectively). The driest conditions are found in the Saharan part of Tunisia and the drainage basins and basin parts which stretch far to the South. All MMB rivers together discharge about 16.2×10^3 Mm³ year⁻¹ of water to the Mediterranean Sea, which corresponds to less than 4% of the total freshwater flux exported by the Mediterranean drainage basin [7]. About 48% of the MMB water flux stems from the rivers in Algeria. The mean annual water discharge for individual rivers ranges from 1 Mm³ for the Tunisian Saharan rivers to 1720 Mm³ for the Moulouya in Morocco, the largest river in the MMB (55,713 km²). Only about 7% of all rivers have an average water discharge greater than 1000 Mm³ year⁻¹, but they provide more than 32% of the total water flux. On the other hand, 50% of the rivers have a water flux which does not exceed 100 Mm³ year⁻¹ and represent only 7% of the total water flux.

Table 3. Summary of average water and sediment fluxes in the Mediterranean Maghreb Basin (MMB) before and after dam construction, and total number of reservoirs considered in this study.

Parameters	Morocco	Algeria	Tunisia	Maghreb
A (10 ³ km ²)	69	126	78	274
A-drained by dams (10 ³ km ²)	59	110	40	209
Q (mm year ⁻¹)	52	62	62	59
FSPMs pre-damming (t km ⁻² year ⁻¹)	506	328	250	351
FSPMs post-damming (t km ⁻² year ⁻¹)	229	120	69	133
NB LD tot	12	62	25	99
NB SD tot	18	126	80	224
NB Hil tot	26	190	131	347
NB Dams tot	56	378	236	670
NB LD mod	12	62	25	99
NB SD mod	18	126	80	224
NB Hil mod	8	87	32	127
NB Dams mod	38	275	137	450

Note: A: Basin area; Q: Drainage intensity; FSPMs pre-damming: specific natural suspended particulate matter flux; FSPMs post-damming: specific anthropogenic suspended particulate matter flux; NB LD tot: Total number of large dams; NB SD tot: Total number of small dams; NB Hil tot: Total number of hillside dams; NB Dams tot: Total number of dams; NB LD mod: number of large dams used for modeling; NB SD mod: number of small dams used for modeling; NB Hil mod: number of hillside dams used for modeling; NB Dams mod: number of dams used for modeling.

Mountainous regions have also a dominant role for the average sediment fluxes (Figure 3B). High sediment yields (specific suspended particulate matter fluxes, FSPMs) are associated with high Q values, although peak values can also stretch further to the South to lower discharge regions in combination with higher elevations (e.g., in the larger basins such as the Moulouya and Medjerda basins). On average, sediment yields (Table 3) are greatest in Morocco (506 t km⁻² year⁻¹), followed by Algeria (328 t km⁻² year⁻¹) and by Tunisia (250 t km⁻² year⁻¹). Peak values are obtained for the Agrioum River in Algeria (4001 t km⁻² year⁻¹) and the Nekor River in Morocco (2956 t km⁻² year⁻¹), whereas the lowest values are found for the Bou-Namoussa River in Algeria (15 t km⁻² year⁻¹), which is located east of the Seybouse River, and for the Ighzar n-Thyaouth River in Morocco (21 t km⁻² year⁻¹), which lies between the Moulouya and Kert rivers. Notice that for the former

two rivers, which are probably the most erosive rivers in Africa, our empirical modeling resulted in somewhat lower values than those found in the literature (see Section 2.1). This is due to the fact that we excluded from our regressions a few rivers (notably the Agrioum and Nekor rivers) that had average SPM concentrations greater than 15 g L^{-1} . We considered that such extreme values might indicate possible errors in the literature citations or refer to highly peculiar erosion processes that cannot be reproduced by general regression models (for a more detailed discussion, see [7]).

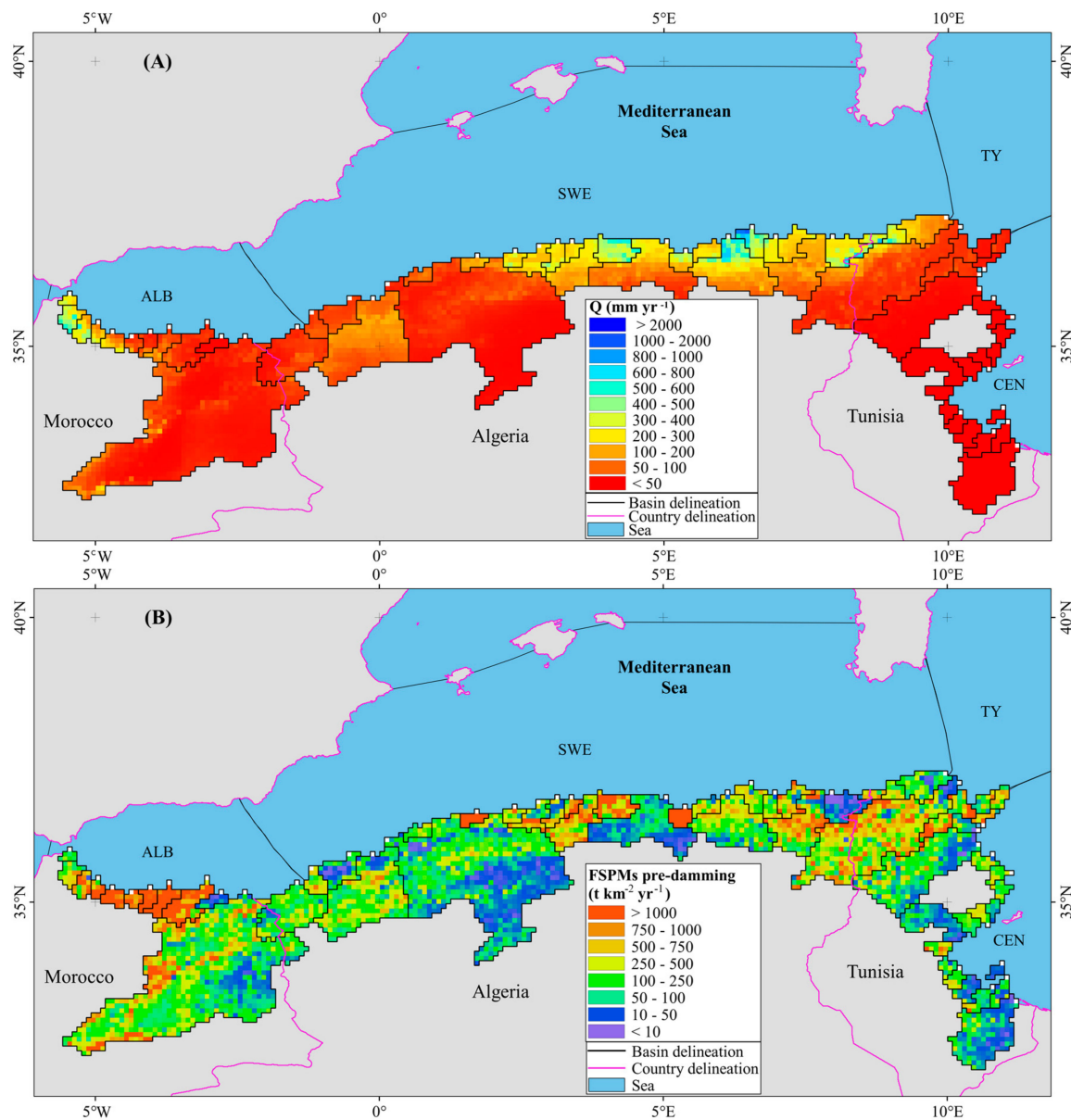


Figure 3. Spatial distribution of (A) specific riverine water discharge ($Q\text{-mod}$) and (B) specific suspended particulate matter fluxes (FSPMs pre-damming) in the Mediterranean Maghreb Basin according to the study of [7].

We estimate that the specific natural suspended particulate matter flux (FSPMs pre-damming) for the entire MMB is $351 \text{ t km}^{-2} \text{ year}^{-1}$ and corresponds to an overall sediment delivery to the Mediterranean Sea of 96 Mt year^{-1} . This value is very close to the estimate of 100 Mt year^{-1} presented by [15] for the same study area. About 60% of this value is exported by only seven rivers (Moulouya, Medjerda, Agrioum, Kert, Nekor, Chelif and Seybousse), and Algerian rivers alone account for about 43% of it. Compared to the world average FSPMs of $150 \text{ t km}^{-2} \text{ year}^{-1}$ [40], it becomes evident that the

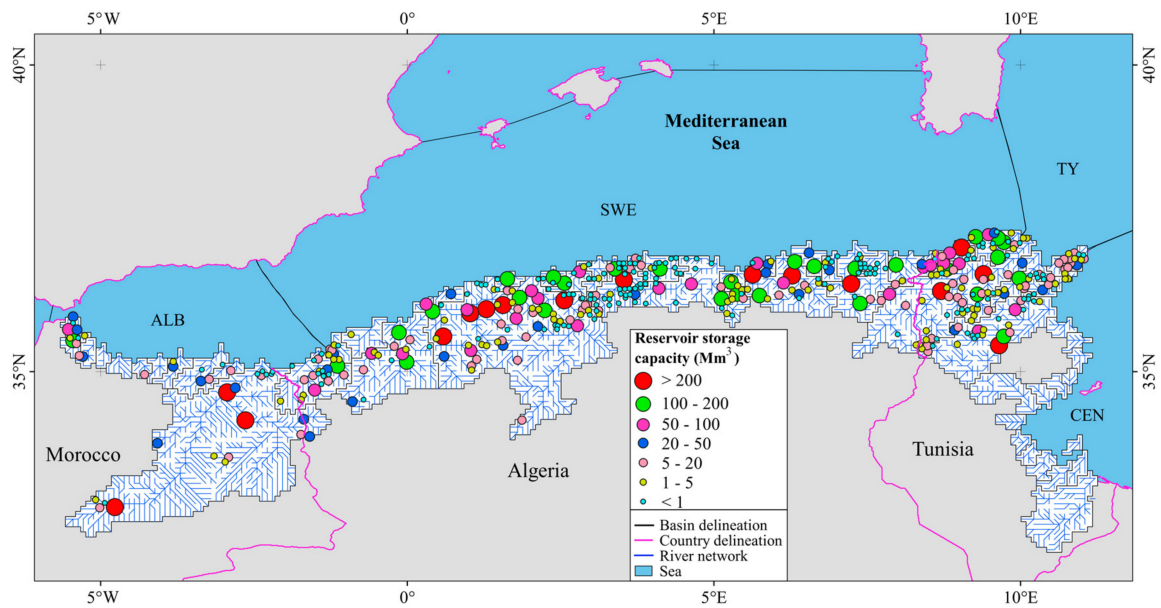
Mediterranean Maghreb basin average erosion rates are higher than those in other regions of the world. This is also apparent when compared to other key environments in the Mediterranean Sea. Taking the Gulf of Lions (GoL) drainage basin as an example (which includes the Rhone River, nowadays the largest Mediterranean river in terms of its average water discharge and also characterized by remarkable sediment yields—[34]), we calculate that, despite the fact that the GoL rivers discharge into the Mediterranean a water flux that is four times greater than the water flux of the MMB rivers, their SPM flux represents only 40% of the SPM flux from the MMB rivers.

3.2. Sediment Retention by Dams

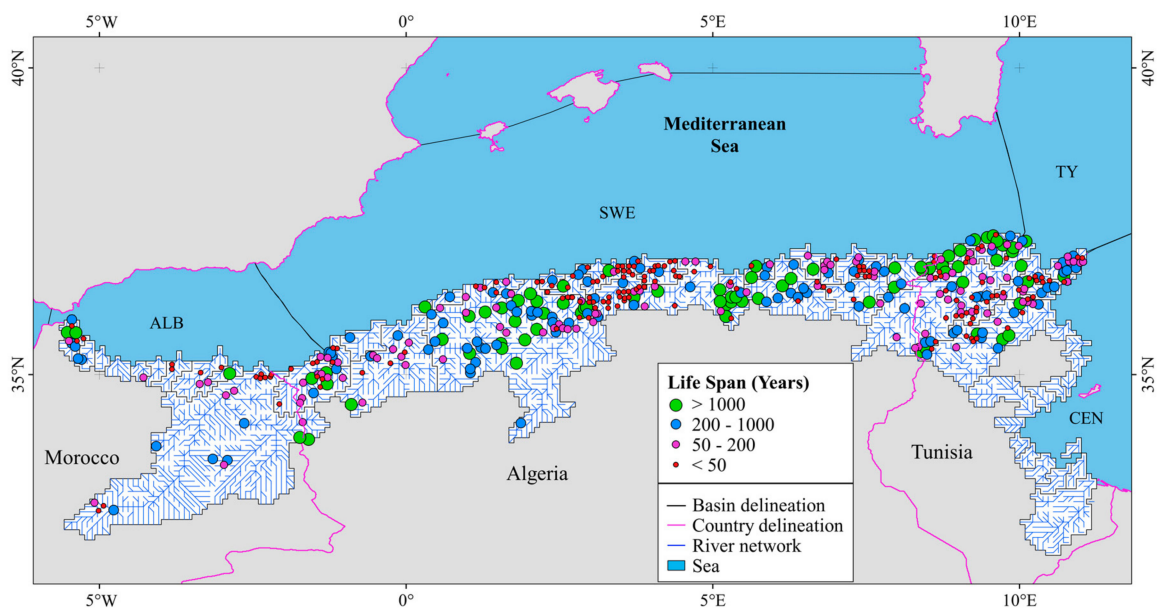
The values cited above represent average long-term means that do not take into account sediment retention by recent damming of the MMB rivers. In order to quantify the latter at the scale of our study region, we combined our inventory of dams (Figure 4A and Table 3) with our modeling of water and SPM fluxes according to the method described by [7]. Dams of various sizes stretch over the entire study region (Figure 4A), except in the Saharan part of Tunisia, where conditions are too dry for the sustainable exploitation of surface water resources. Consequently, about 76% of the MMB area is drained into dams (87% for Algeria, 86% for Morocco and 51% for Tunisia). The average density of all types of dams is about 2.5 dams per 10^3 km^2 , with increasing densities as the size of the dams decreases (0.4, 0.8 and 1.3 dams per 10^3 km^2 for large dams, small dams and hillside reservoirs, respectively). When relating the densities to the areas which are drained into the dams (hence omitting to some extent the Saharan part of Tunisia), it is clear that the average dam densities increase from Morocco to Tunisia (1.0 dams per 10^3 km^2 for Morocco, 3.4 for Algeria and 5.9 for Tunisia), which is opposite to the average sediment yields in these countries (see Section 3.1). Construction of dams is obviously constrained by the availability of existing water resources and the natural erodibilities of the corresponding land surfaces. Notice also from Table 3 that while all large and small dams in our inventory could be included in the modeling approach, we could only include 37% of the hillside reservoirs (46%, 31% and 24% for Algeria, Morocco and Tunisia, respectively) due to the model limited resolution (see Section 2.3). Sediment retention by hillside reservoirs may therefore be somewhat underestimated in our study.

Including dams in the routing of suspended sediments to the sea reduces the average SPM flux from the MMB to the sea to 36 Mt year^{-1} , which corresponds to a post-damming FSPMs value of $133 \text{ t km}^{-2} \text{ year}^{-1}$. In other words, 62% of the natural SPM flux (Section 3.1) is retained behind dams. Retention rates are highest in the Tunisian basin part (72%), followed by the Algerian (63%) and the Moroccan basin parts (55%). This is in agreement with the density of dams, which is highest in Tunisia and decreases westward toward Morocco. In terms of the absolute SPM fluxes, the greatest retention is observed for Algeria (26 Mt year^{-1}), followed by Morocco (19 Mt year^{-1}) and Tunisia (14 Mt year^{-1}). Interestingly, when only considering the dams included in the GRanD database (as was the case in the study by [7]), sediment retention behind the dams accounts for only 36% of the natural SPM flux to the Mediterranean Sea. The present results therefore demonstrate that small reservoirs are quantitatively crucial for the interception of sediments in river basins compared to large reservoirs. The majority of the MMB reservoirs (~85%) in the GRanD database have a storage capacity greater than or equal to 20 Mm^3 . If we consider this value as an appropriate threshold between small and large reservoirs, we can make the following observations: small reservoirs have very limited capacities (cumulative capacity of 1.1 versus 12.8 km^3 for large dams), intercept annually less water discharge (cumulative interception of 8.4 versus $20.1 \text{ km}^3 \text{ year}^{-1}$ for large dams), drain smaller areas (mean area of 151 versus 1525 km^2 for large dams), and have shorter water residence time in the reservoir (mean of 0.13 versus 0.63 years for large dams). They nevertheless assign a significant anthropogenic signature to the global sediment flux in the MMB (Figure 5) and enhance mean retention by 13% (from 49 to 62%) as compared to large reservoirs. It can also be seen from Figure 5 that the different size classes we created increase about linearly the average sediment retention in the MMB from large to small basins (except for very

large reservoirs which are underrepresented in the MMB), whereas the total number of these reservoirs increase more or less exponentially.



(A) Average reservoir storage capacity (Mm³)



(B) Average life span (LS, years).

Figure 4. Geographical distribution of the 450 dams and hillsides implemented in the modeling part of this study.

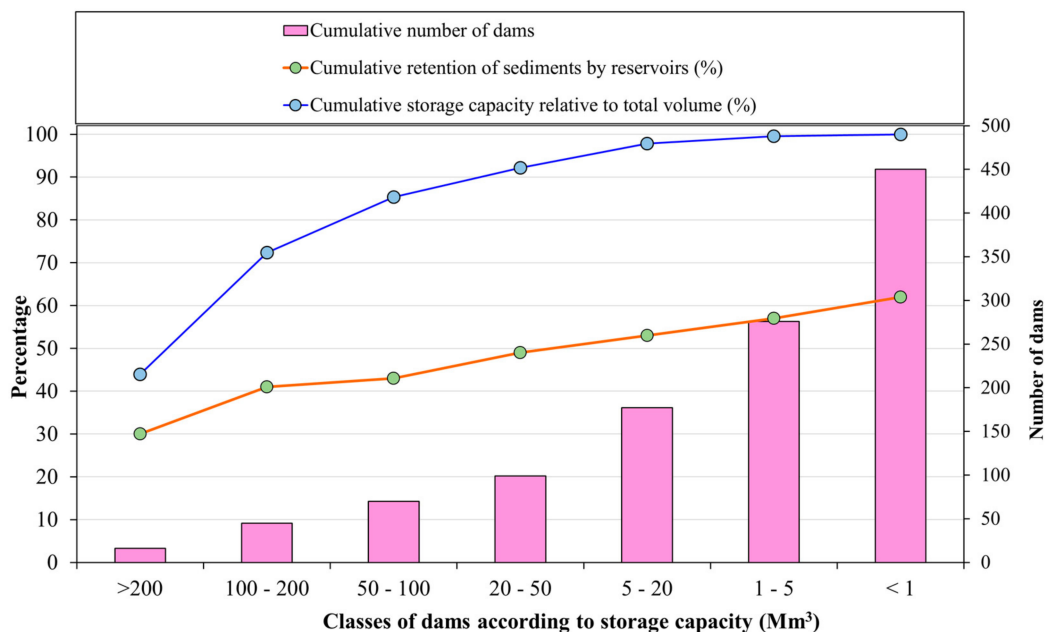


Figure 5. Cumulative reservoir storage capacity (blue line) and sediment retention (orange line) according to various classes of reservoir storage capacities. The cumulative number of dams in each class is shown as well (purple bars). For further explanations, see text.

3.3. Economic and Environmental Implications

Our combination of a spatially explicit mapping of natural sediment yields with an inventory of reservoirs in the MMB also allows evaluating the loss of storage capacity and the life spans of the reservoirs. On the one hand, this can be compared with observed accumulation rates behind dams for validation purposes. On the other hand, it may also help to assess the loss of performance and economic value of existing dams and to evaluate the feasibility of future damming projects.

For this purpose, we followed the approach of [7] and converted the calculated mass accumulation of sediments into volumetric values by assuming an average density of 0.96 t m^{-3} , as proposed by [41]. The reservoirs of the MMB consequently retain a volume of 54 Mm^3 of sediment each year, which corresponds to an annual loss of storage capacity of about 0.39%. This volume can be further split into 22 Mm^3 for the Algerian part (annual loss of 0.27%), 14 Mm^3 for the Tunisian part (annual loss of 0.39%) and 18 Mm^3 for the Moroccan part (annual loss of 0.89%). These values match well with other estimates from the literature. Remini estimated the sediment retention in reservoirs behind Algerian dams to be 20 Mm^3 [42], which accounts for a reduction of their capacity (6.2 Mm^3 according to [43]) of 0.3% each year. This value is identical to our estimate. Mammou and Louati proposed a capacity loss for Tunisian dams between 0.5 and 1% each year [28], compared to the 0.4% we found. Due to its greater relief and higher natural sediment yields, the values proposed for the Moroccan part of the MMB generally exceed 0.7% [20,22]. We estimate an annual capacity loss of about 0.9%. At larger scales, Remini, W. and Remini, B. evaluated the annual capacity loss of the 230 dams in North Africa to be 0.54% per year [25], which is only slightly higher than our results for the MMB. But many of the reservoirs in their study are located outside our study region, especially for Morocco. Notice that only the three Moroccan dams Eddahabi, El Massira and Ben El Ouidane in the Atlantic drainage basin of the Maghreb retain annually 18.3 Mm^3 of sediment, which is equivalent to one third of the overall sediment retention in the entire MMB.

The life span of reservoirs (LS, year) can consequently be estimated via the ratio between the reservoir capacity and the annual volume of sediments that is retained behind the reservoir dams. Figure 4B shows the average LS for the 450 reservoirs considered in our modeling approach. It varies from less than 10 years to 143×10^3 years, with a median of 150 years and lower and upper quartiles

of 50 and 550 years. About 35% of these reservoirs have a LS of less than 50 years in relation to reduced storage capacities (90% have a storage capacity of less than 2.5 Mm³). The majority is in the Algerian basin part (62%), followed by the Tunisian (28%) and the Moroccan basin parts (10%). On the other side, 25% of all reservoirs have LS between 50 and 200 years, and 23% between 200 and 1000 years. Only for 17% of the reservoirs LS exceeds 1000 years.

For the 101 dams in our database which were collected from the GRanD database and the national agencies of the Maghreb countries (see Section 2.3), the precise construction dates were known (Table 1) and therefore we could predict their filling. In 2016, the total sediment volume accumulated in these dams was 1.5 km³, equivalent to a fill of 12% of the total storage capacity (11.7 km³). The average silting is thus 37 Mm³ year⁻¹, and if nothing changes, about 30% of their initial capacity would be lost by 2060. Interestingly, with our modeling tools we can also calculate that, if these were the only dams in the MMB and no smaller and hillside dams existed to catch part of the sediment fluxes further upstream, the average silting would increase to 42 Mm³ year⁻¹ and the 30% capacity loss would arrive by the year 2050. These results confirm the findings of [24], who suggested that the delay of siltation of large dams is possible by installing smaller structures further upstream.

Table 4 lists the siltation rates for the 11 dams in the MMB that are the most affected by rapid filling. Two examples are worth being cited more in detail. One is the Mohamed Ben Abd Lekrim El Khattabi dam in the Nekor basin of Morocco, with a storage capacity of 43 Mm³. Our study shows that average annual silting is here 3.1 Mm³, which corresponds to a storage capacity loss of 7.2%. These figures are well confirmed by the study of [26], who estimated an average silting rate of 2.7 Mm³ year⁻¹ and an annual storage capacity loss of 6.3%. The accelerated siltation of this dam is closely linked to the extremely high erosion rates in the Nekor basin, one of the highest in the world (see Section 2.1). Without measures to prevent siltation, this dam would have been completely filled only 15 years after its construction in 1981.

Table 4. Calculated volume of sediments retained in some Mediterranean reservoirs that are threatened by rapid silting in comparison with other literature estimates.

Dams	Count	Source	Year-Cons	CAP (Mm ³)	Vsed (Mm ³ year ⁻¹)	Vsed (% year ⁻¹)	Vsed 2016 (Mm ³)	Vsed 2016 (%)	LS (Years)	Vsed-lit (%)	Source-lit
Bakhada	ALG	GRanD	1935	56	0.1	0.1	4	8	1033	20	2
Beni Amrane	ALG	ANBT	1988	12	0.3	2.3	8	64	44	80	2
Beni Bahdel	ALG	GRanD	1946	63	0.1	0.2	9	15	469	17	2
Bou Hanifa	ALG	GRanD	1948	73	0.5	0.7	36	50	137	57	2
Boughzoul	ALG	GRanD	1934	55	0.5	1.0	43	78	105	56	2
Fergoug	ALG	GRanD	1970	18	0.3	1.7	14	77	60	100	2
Ighil Emda	ALG	ANBT	1953	156	1.0	0.7	66	42	149	54	2
M.B.A.L.khattabi	MAR	GRanD	1981	43	3.1	7.2	108	251	15	59	3
MohammedV	MAR	GRanD	1967	730	8.2	1.1	403	55	89	56	1
Mellegue	TUN	GRanD	1954	300	3.3	1.1	203	68	92	85	1
Sidi Salem	TUN	GRanD	1981	555	2.9	0.5	100	18	194	21	1

Note: Count: Country; Year-Cons: Year of Construction; CAP: reservoir storage capacity; Vsed: volume of sediment trapped by dams; Vsed 2016: volume of sediment trapped by dams until 2016; LS: life span of the dams; Vsed-lit: volume of sediment trapped by dams from the literature; Source-lit: source according to the literature. Source-lit: 1: [25] (silting until 2002); 2: [24] (silting until 2006); 3: [26] (silting until 1990). For the Source abbreviations, see Table 1.

The second example is the Ighil Emda dam in Algeria, located in a drainage basin with the same name. We calculated here an average sediment filling of $1.1 \text{ Mm}^3 \text{ year}^{-1}$ and an average capacity loss of $0.67\% \text{ year}^{-1}$. Since its commissioning in 1953, the Ighil Emda dam has accumulated nearly 66 Mm^3 of sediments and lost 42% of its capacity. These results are very close to those presented in the study by [44], who estimated the cumulative silting during the period 1953–1993 from bathymetric surveys to be 52 Mm^3 . During this 40-year period, the dam has lost nearly 35% of its initial capacity. This corresponds to an average capacity loss of $0.87\% \text{ year}^{-1}$. The main reason for this rapid silting is the nature of its drainage basin, formed by soft rocks, in combination with a thin plant cover and a predominance of the agricultural domain [44].

It is finally also interesting to look at the theoretical sediment starvation in the coastal areas, which can be estimated from the difference between the pre-damming river fluxes of SPM and the present-day SPM fluxes normalized to the coastline length. The latter is about 422 km, 1210 km, and 1225 km for Morocco, Algeria and Tunisia, respectively. Although this information does not take into account the integration of sediment starvation over time (which depends on the precise construction date of dams), neither the existence of littoral drifts which redistribute the sediments into the coastal domain, it is nevertheless indicative for the potential risk of coastal erosion in relation to decreasing river sediment supply. Maximum values of $45 \times 10^3 \text{ t km}^{-1} \text{ year}^{-1}$ are obtained for the coast of Morocco, which should consequently be the most threatened by beach erosion and sea level rise. Note that this value per kilometer of coastline corresponds to about the average SPM flux produced annually within the whole basin of a typical coastal river in the Gulf of Lions—like the Tet River, with a basin area of 1400 km^2 [34,45]. In other words, the sediments produced elsewhere in a hinterland area of 1400 km^2 are equivalent to the amount of sediments missing every km along the Moroccan coast. The corresponding values for Algeria and Tunisia are also rather high: $21 \times 10^3 \text{ t km}^{-1} \text{ year}^{-1}$ and $12 \times 10^3 \text{ t km}^{-1} \text{ year}^{-1}$, respectively.

4. Conclusions

For the first time a spatially explicit assessment of the impact of river damming on the natural sediment fluxes to the sea could be produced for the Mediterranean Maghreb basin (MMB), a region which is characterized by a critical state of the available surface water resources and by strong mechanical erosion rates. Our data are based on modeling, which often represents simplifications with respect to reality and which is always constraint by the validity of the basic assumptions leading to the model formulations. Modeling on a grid point scale is limited by the quality of the input data and the adequacy of the regression models used to predict the riverine sediment fluxes. It is furthermore difficult to assess the quality of the literature estimates we used to adjust our regressions and which define the natural (pre-damming) state of the river systems, because anthropogenic perturbations can have a long history in the Mediterranean area. Nevertheless, the values we produced fit very well with other literature estimates, both in terms of the general sediment budgets and with regard to the measured reservoir silting rates, which makes us confident on their reliability.

Our results clearly demonstrate that, because of damming, nowadays only slightly more than one third of the natural river sediment fluxes reach the coastal Mediterranean waters of the Maghreb. Contrary to other hot spot areas of river damming, such as the East, Southern and Southeast Asian region where most of the sediment retention is related to the existence of mega dams [46], a considerable part of the sediment retention is here related to the existence of small dams and hillside reservoirs. Consequently, when only considering the large dams as those documented in the GRanD database, sediment retention is strongly underestimated. Using the latter database alone results in an overall sediment retention of about 36%, while the supplementary dams and hillside reservoirs we collected increase this value to 62%.

Large and small reservoirs in regulated basins trap 30% and 23% of the global riverine sediment fluxes according to [9]. Our retention estimates are therefore substantially higher than those given at the global scale, but the differences are not as striking as one may expect. In the [9] estimate, large

reservoirs correspond to $CAP > 500 \text{ Mm}^3$, which are rare in the MMB, and the 62% retention we calculated should rather be compared to the 23% retention that [9] found for small dams. The major difference is that small dams have shorter life spans than large dams, and the economic exploitation of these structures is limited in time. Notice that according to our assessment, 35% of the MMB reservoirs have life spans of less than 50 years in relation to reduced storage capacities, which requires frequent renewal and replacement of these structures for further development. It should be also mentioned that sediment retention rates alone are not necessarily an appropriate measure of the potential impact of damming on natural systems. Our data reveal some negative correlation between sediment retention and natural erosion rates in the three Maghreb countries (see Section 3.2), which could be explained by the greater difficulties to build dams in terrains with steep slopes and high natural sediment yields. Although sediment retention rates are “only” 55% in the Moroccan part of MMB, it is probably here where riverine sediment starvation may have the greatest impacts on the coastline dynamics.

Author Contributions: M.S. conducted the data analysis and wrote the draft of the manuscript. M.S. and W.L. worked on subsequent drafts of the manuscript. M.S., W.L., F.B., Y.L. and E.R. contributed to the final version of the manuscript.

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