Aeolian Dust Inputs in the Mediterranean and Black Sea Marine System

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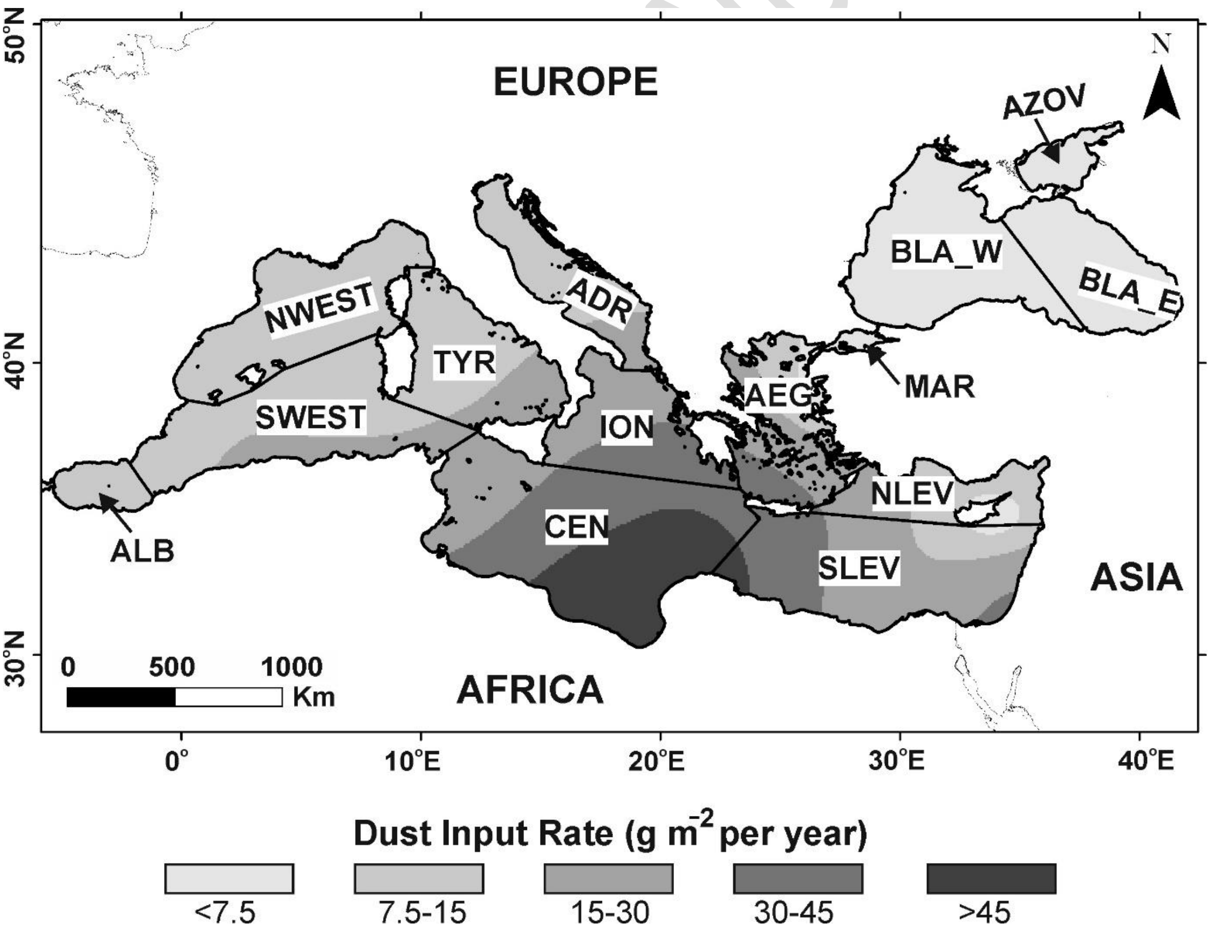
GRAPHICAL ABSTRACT



ABSTRACT

The aim of this paper is to estimate the amount of aeolian dust, deposited by dry and wet processes, that is deposited to the eleven marine regions of the Mediterranean-Black Sea

Marine System (MBMS) and to compare it to the riverine influxes (i.e. suspended and dissolved sediment loads). This research is based on information for aeolian dust deposition at several coastal stations, around the MBMS, following an extended research of the available literature. For data elaboration, processing, and visualization a G.I.S. environment was utilized. The total annual amount of dust input for the whole system has been estimated to 59.9 × 10^6 tonnes, of which 57.2 × 10^6 tonnes are deposited in the Mediterranean Sea and only 2.7 ×10^6 tonnes in the Black Sea. The contribution of dust input (load), corresponding to 6.2% and 0.8% of the total amount of suspended and dissolved load, for the Mediterranean and Black Sea respectively, reveals the significant role of the aeolian dust inputs to the MBMS marine environment, in particular, at its southern Mediterranean domain.

Keywords: Marine Regions, Sahara dust, Dust Load, Sediments

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1 Introduction

According to the "Glossary of Atmospheric Chemistry Terms" (IUPAC, 1990) dust is defined as "Small, dry, solid particles projected into the air by natural forces, such as wind, volcanic eruption, and by mechanical or man-made processes such as crushing, grinding, milling, drilling, demolition, shoveling, conveying, screening, bagging, and sweeping. Dust particles are usually in the size range from about 1 to 100 μm in diameter, and they settle slowly under the influence of gravity." Atmospheric dust particles are removed from the atmosphere through three processes: (a) dry deposition, where the particles are deposited directly to the earth's surface (mainly through aerodynamic transport and or Brownian transport); (b) wet deposition, where the material is transferred by precipitation to the ground; and (c) cloud deposition, which is less important, than the other two processes and involves the movement of material that is trapped in non-precipitating droplets of clouds or fog (Lovett, 1994).

The presence of dust in the atmosphere can affect the temperature of the atmosphere and ocean through the process of absorption and scattering of solar radiation by dust particles (e.g. Alpert et al., 1998; Miller & Tegen, 1998; Yue et al., 2010). Dust may also affect marine biological processes by providing valuable nutrients (Jickells et al., 1998). Although the fertilizing potential of atmospheric deposition on ocean production in the Mediterranean is a matter of debate, the coupling between dust deposition and the annual chlorophyll-a cycle can, on average, account for 11.5% of the total of nutrients (Gallisai et al., 2012). Similarly, Kalinskaya & Varenik (2019) have reported cases of dust transport over the Black Sea associated with high concentrations of inorganic phosphorus and silicon. Moreover, Rahav et al. (2020) have shown that cyanobacteria (i.e. Prochlorococcus) biomass, may be attributed, at least to some extent, to the impact of bio-aerosol deposition related to dust emissions in the case of oligotrophic "Low-Nutrients-Low-Chlorophyll-a" regions such as that of the Mediterranean basin.

The scope of this work is to estimate the amount of aeolian dust being transferred by the atmosphere to the various marine regions of the Mediterranean-Black Sea Marine System (MBMS), through wet and dry processes, and to compare dust inputs to the suspended and dissolved sediment fluxes.

2. Mediterranean and Black Sea marine system

The Mediterranean Sea and the Black Sea comprise a semi-enclosed intercontinental marine system (i.e., MBMS: Mediterranean and Black Marine System), bordered by the Eurasian and African continents, having a total surface of circa $3x10^6$ km^2. The MBMS includes the three Mediterranean basins (Carter et al., 1972) i.e. Western, Centre, Eastern Mediterranean

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(WMED, CMED, EMED) and the Black Sea (BLS), which are subsequently divided into 11 marine regions (Cruzado, 1985; Ludwig et al., 2010; UNEP, 2012; Poulos & Kotinas 2020), as characteristically shown in Figure 1.

The basins of the Mediterranean and Black Sea receive a non-negligible amount of aeolian inputs compared to the riverine sediment fluxes. For example, the annual rate of aeolian sediment supply (mostly Saharan dust) for the Aegean Sea is of the order of 10-40 g m^{-2} (Nihlén & Olsson, 1995) that corresponds to a total dust deposition of 1.5-6.5 x 10^6 t $year^{-1}$ (Poulos, 2009) when the total of suspended and dissolve load equals to 48 x 10^6 t $year^{-1}$ (Poulos, 2019). The principal natural source of aeolian dust in the case of MBMS is the Sahara Desert (covering an area of about 9.2×10^6 km^2) while a secondary source is the Arabian desert (spanning over an area of circa 1.85×10^6 km). In the case of the Black Sea and in particular at its eastern part additional sources of aeolian dust are the Central Asia deserts: the Kyzyl-Kum (0.30×10^6 km^2); Karakum (0.35×10^6 km^2); and the Aralkum (0.04×10^6 km^2).

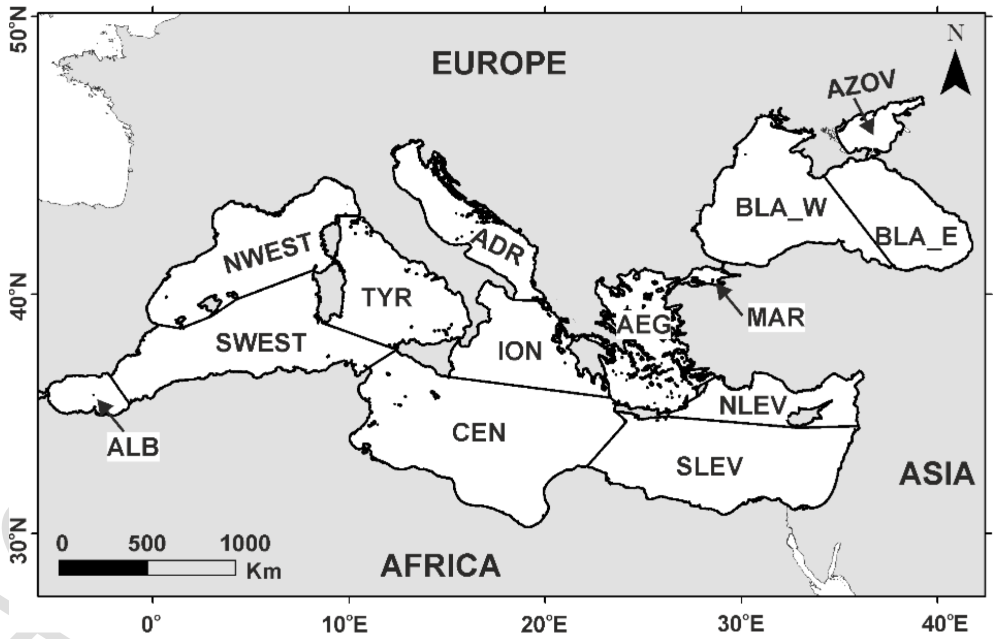

Figure 1. The Mediterranean and Black Sea marine system (ALB: Alboran, WEST: West MED (North & South marine basins), TYR: Tyrrhenian, ADR: Adriatic, ION: Ionian, CEN: Centric MED, LEV: Levantine (North & South marine basins), AEG: Aegean , MAR: Marmara, BLA: Black Sea (West & East marine basins) and finally AZOV: Azov Sea.

Most of the northward dust transportation across the MBMS (mainly affecting the Mediterranean but reaching also the Black Sea) is related to the southerly winds (Scirocco, Ghibili, Khamsin), which are associated with seasonal displacement of cyclones over the Mediterranean (e.g. Rodriguez et al., 2001). Maximum dust transport is observed during spring over the central and eastern parts of the Mediterranean (Luck & Ben Othman, 2002; O'Hara et al., 2006). During summer, when anticyclonic conditions are prevalent, and drought characterizes the Mediterranean area (e.g. Roberts et al., 2008; Israelevich et al., 2012; Bout-Roumazeilles et al., 2013), significant amounts of dust can be transported from the Sahara desert by the aforementioned southerly winds. Moreover, the transportation of dust to the eastern part of the Black Sea is associated with easterly /southeasterly winds related to the low- and mid-tropospheric flows from the Caspian – Central Asia regions in the east and warm advection from the Middle East in the south (Davitashvili, 2019). In general, the dust transport occurs in the form of "pulses", and the annual dust flux can be controlled by a few episodes, with several researchers (e.g. Barnaba & Gobbi, 2004; Pey et al., 2003) reporting that a single Sahara outbreak can account for 40–80% of the total annual flux.

The relative contribution of dry or wet deposition to dust inputs is determined by the rainfall regimes, which are highly variable in this region. For instance, in the eastern Mediterranean, the relative contribution of dry deposition can reach 93% of the total dust input during summer (Kubilay et al. 2000), whereas in the north-west of the Mediterranean wet deposition is prevalent (Vincent et al., 2015).

3. Materials and methods

The observed rates of dust deposition (wet and dry) in several stations of the study area (obtained from several researchers; see Table 1) were imported into a geodatabase. In Table 1 the mean observed rates of dust deposition at coastal stations of the MBMS system are listed. Most of these stations cover periods that are longer than 2 years of continuous fields measurement but in the case of the Black Sea, where measurements are limited, stations with shorter durations of measurements were available.

The values presented in Table 1, are within the same order of magnitude with the values reported by other researchers; for example, Guerzoni & Molinaroli (2005) have given annual values of 2-25 g m^{-2} and 6-46 g m^{-2} for the WMED and EMED, respectively. On the other hand, the values of Table 1 are one to two orders of magnitude higher than those simulated for MED by Gallisai et al. (2012), using the BSC-DREAM8b model for the period January 2000 - December 2007: 0.18-0.36 g m^{-2} $year^{-1}$ (southern part) and 0.007-0.01 g m^{-2} $year^{-1}$ (northern part). These differences can be attributed to the fluctuations of frequency and intensity of the

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recorded dust events for different time periods and to the data (average monthly values) utilised in mathematical simulations.

Table 1. Dust deposition rate (wet and dry) around the MBMS.

Location	**Dust ($g\ m^{-2}\ yr^{-1}$)**	**Period**	**Reference**
Lanjaron (S Spain)	11.1	2001–2002	Morales-Baquero et al. (2006)
Montseny (NE Spain)	5.2	1983-1994	Avila et al. (1997)
Palma de Baleares (E Spain)	~14	1982-2003	Fiol et al. (2005)
Cap Ferrat (SE France)	11.4	2003-2007	Ternon et al. (2010)
Capo Carbonara (SE Sardenia) Sardinia (2 sites)	12.8 9.8	1990-1992 1990/91/93	Guerzoni et al., 1999 Le Bolloch et al. (1996)
Capo Cavallo (NW Corsica)	12.5 9.7	1985-1986 1986-1987	Bergametti et al. (1989) Remoudaki (1990)
Lemnos Island (N Aegean Sea)	11.2		Nihlén & Olsson (1995)
Mytilene (NE Aegean)	5.4	2001-2002	Guieu et al. (2010)
Crete (S. Aegean)	36.4	1989-1990	Nihlén et al. (1995)
Erdemili (SE Turkey)	13	1991-1992	Kubilay et al. (2000)
Cavo Greco (Cyprus)	4.2	2001-2002	Guieu et al. (2010)
Varna (E Bulgaria)	4.9	2009	Theodosi et al. (2013)
Azov Sea (Russia)	36	2009-2013	Sorokina & Soier (2016)
Sinop (N. Turkey)	1.9	2009	Theodosi et al. (2013)
Haifa, Israel	~36	1992-1995	Herut & Krom (1996)
Alexandria (N Egypt)	20.3	2001-2002	Guieu et al. (2010)
North Libya (14 sites)	58	2000-2001	O'Hara et al. (2006)
Mahdia (E Tunisia)	23.3	2001-2002	Guieu et al. (2010)
Cap Spartel (NW Morocco)	7.2	2001-2002	Guieu et al. (2010)

For the estimation of the dust inputs for each marine region of the MBMS the point data of Table 1 were imported in G.I.S., wherein Thiessen polygons were created, and a natural neighbour interpolation (Sibson, 1981) was used to calculate the spatial distribution of dust in the MBMS (grid size 1x1 km), followed by the calculation of total dust load for each of the marine regions. The algorithm behind the interpolation method (also known as "Sibson" or "area-stealing" interpolation) finds the closest subset of input samples (Okabe et al., 2000) to a query point and after applying weights, based on proportionate areas, it interpolates a value. It uses only a subset of samples that surround a point of interest, and interpolated values are within the range of the samples used for the interpolation. The calculated surface is smooth and

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free of discontinuities and trends (e.g. peaks, pits). Also, this method doesn't require to make statistical assumptions, can be applied to very small datasets as it is not statistically based (Etherington, 2020) and, finally, it is parameter free (no input parameters need to be specified). As a result of these properties this interpolation technique is well suited for the interpolation of continuous variables for which only a limited set of data points with highly irregular spatial distribution are available (Hofstra et al., 2008), like in our case.

It has also to be noted that there is an uncertainty caused by either the inaccuracy of the measured mean annual value (mainly attributed to the small duration of the measurements), and/or the inherent error of the interpolation technique. Assuming that mean dust input for each site is accurately representative, in order to estimate the inaccuracy introduced by the interpolation method a cross validation method was applied: through an iterative procedure we excluded all sites, through rotation (one sample at a time), followed by the calculation of a new interpolated surface for the new data set (Ghosh et al., 2012; Joseph et al., 2013). The estimated dust input value of the omitted point, for each rotation, was then compared with the observed value and a series of measurements of accuracy where calculated : (a) mean absolute error (MAE) and (b) root mean squared error (RMSE).

4. Results and Discussion

The dust load (DUL), expressed in tonnes per year, for each of the marine regions of the MBMS (as shown in Figure 1) was calculated and is presented against the riverine sediment fluxes (SSL & DL) that are derived from the literature (SSL: suspended sediment load, DL: dissolved sediment load (Table 2).

Dust deposition in the Mediterranean ranges between < 0.1 $\times 10^6$ t year^{-1} (Sea of Marmara, to 26 $\times 10^6$ t year^{-1}). The dust inputs for the Black Sea are generally <1 $\times 10^6$ t year^{-1}, with the exception of the Azov marine region (approx. 1.5 $\times 10^6$ t year^{-1}); this increased value is most probably related to the dust inputs of its surrounding flat area, and its proximity to the central and eastern Asian deserts.

On an annual basis, the Mediterranean basin receives 57.17 $\times 10^6$ tonnes of dust and the Black Sea 2.71 $\times 10^6$ tonnes, which corresponds to 6.2% and 0.8% to their riverine inputs (suspended and dissolved load), respectively (Table 2). It has to be mentioned that in the case of the Centric Mediterranean marine basin dust contribution is 1.5 times higher than the contribution of riverine inputs (SSL+DL); this is explained by the absence of significant riverine inputs and

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the proximity of this marine region to the Libyan coast, where the highest concentrations in aeolian dust form Sahara have been monitored

Table 2. Catchment area (CA in km^2) and annual estimates of suspended sediment load (SSL), dissolved sediment load (DL), Dust load (DUL) and the ratio between DUL and the sediment load (SSL+DL) for the marine regions of the Mediterranean and Black Seas Marine System (see also Figure 1).

Marine Basin	**Area[1]**	**Dust rate**	**DUL**	**SSL[2]**	**DL[2]**	**SSL+DL**	**DUL/ (SSL+DL)**
	km^2	($g\ m^{-2}\ yr^{-1}$)	$\times10^6$ tonne				(%)
ALB	54,173	10.09	0.55	21.1	11.7	32.8	1.67
WEST	573,340	12.87	7.38	150.1	61.7	211.8	3.48
NWEST	261,240	12.52	3.27	85.7	37.6	123.3	2.65
SWEST	312,100	13.17	4.11	64.4	24.1	88.5	4.64
TYR	217,497	11.03	2.40	62.5	25.7	88.2	2.72
WMED	**845,010**	**11.57**	**9.78**	**233.7**	**99.1**	**332.8**	**2.94**
ADR	140,320	10.01	1.40	196	52.09	248.09	0.57
ION	173,493	23.38	4.06	80.6	21.4	102	3.98
CEN	616,527	42.17	26.00	10.6	6.1	16.7	155.68
CMED	**930,340**	**33.82**	**31.46**	**287.2**	**79.59**	**366.79**	**8.58**
LEV	552,100	21.71	11.98	151.6	15.18	166.78	7.19
NLEV	138,126	13.48	1.86	25.9	8.8	34.7	5.37
SLEV	413,974	24.45	10.12	125.7	6.38	132.08	7.66
AEG	192,026	20.21	3.88	28.6	19.3	47.9	8.10
MAR	11,887	5.23	0.06	2.1	2.1	4.2	1.48
EMED	**756,013**	**21.07**	**15.93**	**182.3**	**36.58**	**218.88**	**7.28**
MED	**2,531,363**	**22.58**	**57.17**	**703.2**	**215.27**	**918.47**	**6.22**
BLA_W	261,013	3.65	0.95	138.2	129	267.2	0.36
BLA_ E	161,221	1.69	0.27	28.4	15.6	44	0.62
BLA	**422,235**	**2.90**	**1.23**	**166.6**	**144.6**	**311.2**	**0.98**
AZOV	41,274	36	1.49	18.8	16	34.8	4.27
BLS	**463,509**	**5.85**	**2.71**	**185.4**	**160.6**	**346**	**0.78**
MBMS	**2,994,872**	**19.99**	**59.88**	**888.6**	**375.87**	**1264.47**	**4.74**

[1]From Poulos and Kotinas (2020); [2]Poulos (2019)

The overall spatial distribution (Fig. 2) of dust inputs presents a W-E zonal distribution with values decreasing northwards. Therefore, aeolian dust inputs are expected to play a crucial role in bio-geo-chemical cycles at the southern parts of the central and eastern oligotrophic

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Mediterranean Sea (Kress et al., 2003; UNEP/MAP, 2010; Poulos 2020), where the highest dust inputs occur and this work can help other researchers in marine or environmental studies. We have calculated the following accuracy measurements for our applied interpolation method: (a) MAE = 2.68, (b) RMSE = 1.5 which are relatively low compared to the range of the values that were used for the interpolation (Table 1), and in all cases the absolute error was less than 25%.

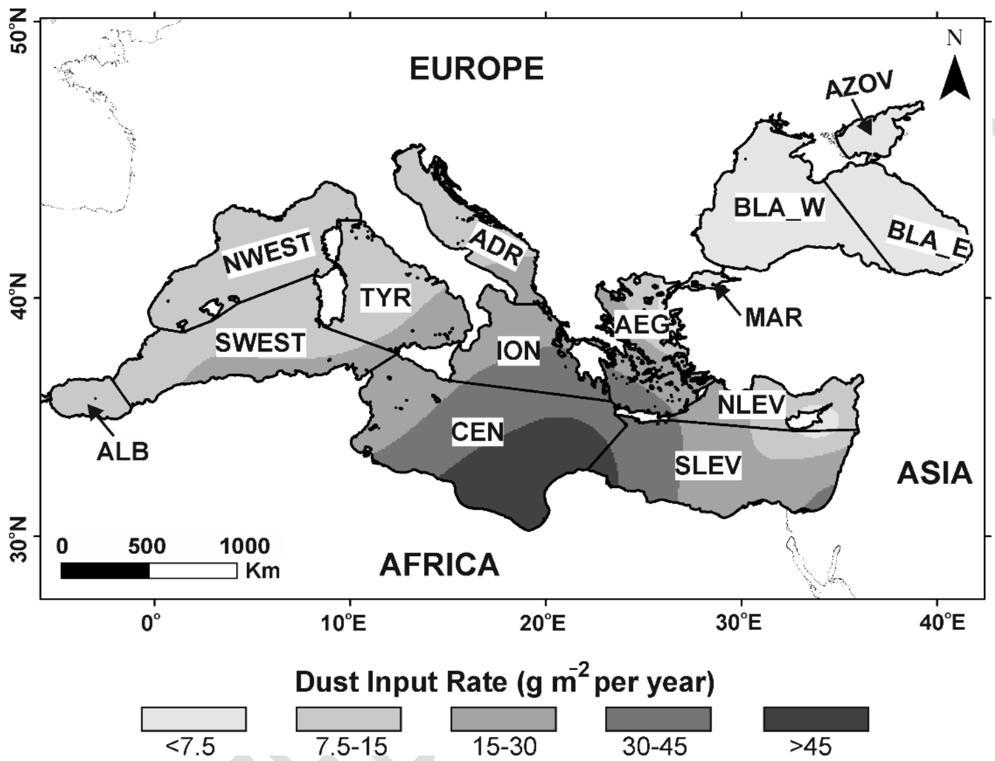

Figure 2. Indicative Spatial distribution of the rate of dust inputs in the Mediterranean and Black Sea marine system (MBMS).

5. Conclusions

The MBMS is estimated to receive 59.9 x 10^6 tonnes of aeolian dust per year, from which 57.2 x 10^6 tonnes are settled in the Mediterranean Sea (MED) marine region and 2.7 x 10^6 tonnes in the Black Sea (BLS) marine region. The central part of the Mediterranean (CMED) receives about 55% of the total dust load of the whole MED due to its proximity with the Sahara Desert, while the Black Sea (BLS) receives very small amounts of aeolian dust.

Dust inputs (dry and wet), mostly of Saharan origin, cannot be ignored in environmental studies (i.e. biological productivity, sedimentation), regarding the Mediterranean Sea (primarily) and the Black Sea (secondarily), as they represent a significant percentage (almost 5%) to their total terrestrial influxes.

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