Investigation of sediment pollution in the Gulf of Elefsina using environmental indicators

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Abstract: - In this paper, the sediment pollution in the Gulf of Elefsina, over the period 1986-2010, has been measured and presented. The pollution had been measured regarding heavy metals, like cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni) and zinc (Zn). Initially, the measured area is presented, along with the sources of pollution in the historical background and the wider region. Three pollutant indicators had been calculated for the investigation of Sediment Pollution: The Pollution Load Index (PLI), the Enrichment Factor (EF) and the Geo-accumulation index (I_{geo}). The results of the Pollution Control and Environmental Quality Office measurements had been used for the calculation of these indicators, taken at six locations of the coast and three locations in the center of the Gulf of Elefsina. The study of these indicators reveals that there is heavy metal pollution at all sampling locations, while the most heavily affected areas of the Gulf are these near Skaramangas Shipyards and Elefsis Shipyards. More intense pollution is recorded for Cd, Cu, Fe, Pb, Zn. More specifically, high values of Cd had been measured at all sampling points, while for Cu, Fe, Pb and Zn high values had been measured in areas that are active in shipbuilding-repair and dismantling units. In contrast, there is no pollution for Mn.

Key-Words: - Gulf of Elefsina, sediment pollution, heavy metals, pollution indicators.

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1 Introduction

Thriasio Field is located 20km from the center of Athens (Greece) and consists of the Municipalities of Elefsina, Mandra-Idyllia, Aspropyrgos and the Community of Magoula. The lowland area is approximately 100,000 acres, crossed by two rivers (Sarantapotamos, Aghios Georgios) and in it the above settlements have been developed, along with agricultural crops, craft and industrial units and a military airport. The sea area that wets its shores is called the Gulf of Elefsina (alias Elefsis), after the name of the largest and oldest city in the area [1].

The Gulf of Elefsina is part of the Saronic Gulf, which has an area of 2,600 km2 (Fig. 1). The Saronic Gulf (alias Saronikos) is bounded to the north and east by the coasts of Attica, to the west by the coasts of Corinth and to the southwest by the coasts of Argolis. The boundary of the Saronic Gulf with the Aegean Sea can be considered the imaginary line of Poros – Sounio (about 45 km). Saronic extends from 38° 03΄N to 37° 27΄N latitude and from 23° 00΄E to 24° 02΄E longitude [2].

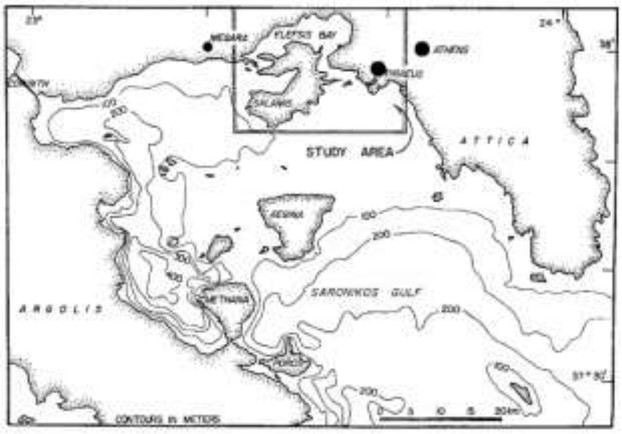

Figure 1. Saronikos Gulf – Gulf of Elefsis [3].

The Saronic Gulf can be considered to consist of four sub-regions: The South Saronic, which is in direct communication with the S. Aegean Sea, with a maximum depth of 200 m; the Western Saronic, with the maximum depth of about 450 m; the Eastern Saronic, where the islet of Psytallia is located, where the Athens wastewater treatment center of the same name (KELP) operates; and the Gulf of Elefsina, which is located in the northern part of the Saronic Gulf [4].

The Gulf of Elefsina has a surface area of 67 Km^2 and a total water volume of approximately $1.3 \cdot 10^6$ m^3, with a maximum depth of 33 m, while its average depth is 18 m. The volume of water is distributed by 77% up to a depth of 18 m and by 23% at a depth between 18 and 33 m. In other words, it is a shallow basin (Fig. 1), which communicates with the rest of the Saronic Gulf through two narrow channels, formed between the coasts of Attica and Salamis Island, i.e., the Megara Channel in the west with a depth of 8 m, a surface width of 600 m and a bottom width of 170 m, and the Keratsini Channel with a depth of 12 m, a surface width of 1200 m and a bottom width of 250 m, which is located east of Salamis [1].

The morphology of the closed shallow basin directly affects the water circulation and its renewal time. Specifically, it has been established that the circulation of water is thermohalo, controlled by low temperatures in winter and high salinities in summer, compared to the rest of the Saronic. The waters are fully mixed in winter and stratified in summer, the thermocline is clear and placed at about 15 m. The direction of traffic changes seasonally and is significantly affected by prevailing winds. The net flow in winter is 240 m3/s from W to E, while in summer it reverses and is 450 m3/s. The average water renewal time is estimated at 2 – 3 months, a fact that favors the concentration of pollutants mainly in the bottom sediments [1].

2 Pollution Sources

The rapid residential and industrial development of Athens, Piraeus and, in general, Attica led to the discharge of a very significant polluting load into the Saronic Gulf, with the result that it is the first marine area in the Greek territory to show severe environmental problems. It is worth noting that about 40% of the Greek population has gathered around the Saronic coast, as well as a large number of industrial and port activities. Most and the largest industries of Attica are concentrated on the Saronic coast, including oil refineries, shipyards, foundries, cement industries, chemical industries, small tanneries, spinning mills, food and beverage processing plants, such as dairy plants, soft drink bottling plants, distilleries, etc. There are also located the most important port, naval and shipbuilding facilities of Greece. Piraeus is one of the most important ports in the Mediterranean, with approximately 24,000 ships a year anchoring there (www.olp.gr). In addition, both on the coasts of Attica and on the coasts of the Peloponnese (see Fig. 1: Corinth and Argolis), tourist activities have been particularly developed, which also contribute to the pollution of the Saronic. To the above sources of pollution, we must add the coastal boulevards with heavy car traffic, as well as the airports of Attica [4] [5].

The Saronic Gulf and especially the Gulf of Elefsina is one of the few regions in Greece where seawater quality has been systematically monitored since 1985, within the framework of national and regional programmes. From 1985 to 2004 with the "National Monitoring Program for the Assessment and Control of Marine Pollution in the Mediterranean" (MED-POL) MAP / UNEP and from 2004 to the present day with the program "Monitoring of the Saronic Ecosystem under the influence of the Psyttalia Sewage Outflow Pipeline". At the same time, from 2011 Saronic joined the National Water Quality and Quantity Monitoring Network (Government Gazette 2017/2011), in the framework of the implementation of the WFD (Water Framework Directive), while systematic sampling began in 2012 [2] [4] [5]. Because of the importance of the Gulf of Elefsina and Thriasio Field as the first historically and still major industrial area of Greece, the environmental interest and monitoring is continuous, until nowadays [6] [7].

2.1 Industrial waste pollution

In the Gulf of Elefsina the sources of pollution are due to various anthropogenic activities, mainly due to the existence of the industrial zone in the area. The legislated area of the industrial zone of Thriasio Field adjacent to the sea is 2500 acres. Of the 15 kilometers of coastline, 12 kilometers have been occupied by port activities of craft industries [8]. Indicatively, 1623 industrial units have been developed here and there. In the wider area of Triasio Field, many smaller industries of oil, plastics, chemicals, paper industry, quarries, mineral oil regeneration units, etc. operate. The environmental burdens related to the above activities are summarized as follows [4] [5] [9]:

- Industrial waste, originating either from land leakages or from atmospheric deposition, such as atmospheric suspended particles and photochemical pollution (nitrogen oxides, ozone and total hydrocarbons).
- Handling, repair and construction of ships, decommissioned anchored ships, shipwrecks, ship breakers, oil spills from accidents and decontamination of these through submersion using special detergents.
- Landfill operations with metallurgical rusts and inert materials from various industries (approx. 1000 acres of sea).
- Focal points (such as the stream of Aghios Georgios, which carried the liquid waste of the tanneries, the paper industry, the bituminous industries, as well as the drainage from the Ano Liosia Waste Burial Ground).
- Washing away by the rains of the agricultural fertilizers, used in the agricultural crops of the region.

2.2 Heavy metals sources

The natural sources of metals in the sea are soil erosion and volcanic activity. Anthropogenic sources are mining, industrial activity, fuel use, combustion processes at high temperatures. Also, deforestation, the construction of deep harbors and artificial lakes increase the transport of metals with particles [2] [10]. Thus, the investigated heavy metals in the present study were the following: Copper (Cu), Cadmium (Cd), Iron (Fe), Chromium (Cr), Manganese (Mn), Lead (Pb), Zinc (Zn) and Nickel (Ni).

2.3 Sampling Points

The measurements for pollution control in the marine area of the Gulf of Elefsina were carried out at three (3) locations in the center of the bay and at six (6) locations along the coasts [8]. More specifically, the three locations at the center of the bay where:

- 800m away from Skaramangas Shipyards (K1),
- 1500m away from the local steel industry (K3),
- 1500m away from Eftaxias area (K5).

The six locations along the coast where at:

- Skaramangas' Shipyards (A1),
- Aspropyrgos' Refineries (A2),
- Elefsina's Refineries (A4),
- Aghios Georgios stream (estuary) (A5),
- Bakopoulos dismantling unit (A8),

- Elefsina's Shipyards (A11).

Therefore, the coastal sampling sites were chosen to be at points where a variety of industrial and craft units are active. The measurements had been conducted on sediment samples, a practice still followed until recently [11].

3 Heavy Metals Pollution Indicators

The estimation of the pollution levels in the sediment of the bottom of the Gulf of Elefsina was based on the calculation of three pollution indices, i.e., the Pollution Load Index (PLI), the Enrichment Factor (EF) and the Geo-accumulation index (I_{geo}). Different environmental tracers have been also used in other studies, for different purposes (e.g., see [12]).

3.1 Pollution Load Index (PLI)

PLI was proposed by Tomlinson et al. [13] and is derived as the concentration in the sample of each metal from the heavy metals, in relation to the background concentration value of the metal in an average uncontaminated sediment, according to the mathematical relationship:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_1 \times \ldots \times CF_n} \qquad (1)$$

where CF_i is the enrichment index for each metal, as the quotient of the concentration of the metal in the sample C_i to the concentration of each metal in an average uncontaminated sediment ($C_{background}$), and n is the total number of heavy metals analyzed in each sample [14].

PLI was proposed in order to estimate the levels of metal pollution in the samples to be studied. It is a simple and quick tool to estimate the level of heavy metal pollution, in order to compare the pollution situation in different areas. According to Tomlinson et al. [13], a value of zero indicates perfection for the area, a value of one indicates a baseline level of pollutants, while values above one indicate progressive degradation of environmental quality. Zhao et al. [15] further categorized the scale of PLI as presented in Table 1.

Table 1. PLI sediment classification index [15].

Class	PLI	Sediment Quality
1	$0 < PLI \leq 1$	Zero-burden
2	$1 < PLI \leq 2$	Zero-burden to moderate pollution
3	$2 < PLI \leq 3$	Moderate pollution
4	$3 < PLI \leq 4$	Moderate to high pollution
5	$4 < PLI \leq 5$	High pollution
6	$PLI > 5$	Very high pollution

PLI cannot provide information about the effects of pollutant combination for the area under consideration. It is also possible to calculate low index values if only one pollutant is at high levels, while the others have values close to background concentrations.

3.2 Enrichment Factor (EF)

The enrichment factor EF is the quotient of the ratio of the concentration of the metal of interest (X_n) to the concentration of a reference element (C_n) in the sample in mg/Kg, to the same ratio for a reference material [14] [16]. We usually use as a reference metal a metal whose concentration is not due to anthropogenic influence. Such metals are iron and aluminum. In this paper, iron is considered as the reference metal. The classification of sediments based on EF is presented in Table 2.

Table 2. Sediment classification index EF [14].

Class	EF	Sediment Quality
1	$EF < 1$	Zero-burden
2	$1 \leq EF < 3$	Low pollution
3	$3 \leq EF < 5$	Moderate pollution
4	$5 \leq EF < 10$	Moderate to high pollution
5	$10 \leq EF < 25$	High pollution
6	$25 \leq EF < 50$	Very high pollution
7	$EF > 50$	Extremely high pollution

3.3 Geo-accumulation index (I_{geo})

I_{geo} was proposed by Müller (in [17]). It is a common approach to estimate the increase in metal concentrations in an area, above baseline concentrations. The method assesses the degree of heavy metal pollution and categorizes areas into seven pollution classes, based on increasing numerical values of the index. The I_{geo} index is calculated as follows:

$$I_{geo} = \log_2 \frac{C_n}{1{,}5 \cdot B_n} \qquad (2)$$

where C_n is the measured concentration of the examined metal n in the sediment, B_n is the reference geochemical concentration in pre-industrial sediment for that element. The factor of 1.5 is introduced to minimize the effect of possible changes in background values, attributable to lithological changes in the sediments [16]. The classification of sediments based on I_{geo} (according to Müller) is presented in Table 3.

Table 3. I_{geo} Sediment classification index [14].

Class	I_{geo}	Sediment Quality
1	$I_{geo} < 0$	Zero pollution
2	$0 \leq I_{geo} < 1$	From zero pollution to moderate pollution
3	$1 \leq I_{geo} < 2$	Moderate pollution
4	$2 \leq I_{geo} < 3$	Moderate to high pollution
5	$3 \leq I_{geo} < 4$	High pollution
6	$4 \leq I_{geo} < 5$	From high to extremely high pollution
7	$I_{geo} > 5$	Extremely high pollution

4 Calculation of Pollution Indices per Metal

The aggregated PLI, EF and I_{geo} indices per metal were calculated and studied for the various sampling points and for five five-year periods (1986-1990, 1991-1995, 1996-2000, 2001-2005, 2006-2010), until the official recording was stopped (2010). All sampling points have PLI values >1 and according to Tomlinson et al. [13], we are led to the conclusion that there is pollution. Therefore, a more careful study of the sediments in the area of the Gulf of Elefsina is required. It is also observed that there is a tendency to decrease the values for PLI and in fact a stronger decrease is observed in the points of the two most burdened areas of the coast. More specifically, two areas are characterized by very high pollution, despite the very strong drop in PLI values, according to the scale presented by Zhao et al. [15], with mean values ranging from 16.8 for the 1986–1990 five-year period to 7.1 for the 2006–2010 five-year period. According to the same scale, two more areas in parts of the coast are characterized as moderately to highly polluted, with the exception of the five years 1996–2000, in which they show maximum values of 4.5 and 4.4 respectively and are classified as highly polluted areas. In one area of the coast, very high pollution appeared for the period 1986–2000, with values of 5.5-5.7, while in the period 2001-2010 that area is characterized by high pollution, since PLI decreased to the value of 4.4. In another area, there is an increase in pollution from moderate pollution with a value of 3.2 in the five-year period 1986–1990 to very high pollution with a value of 5.2 in the five-year period 1996–2000. Afterwards, the PLI index decreases to a value of 4.4 (2005–2010), but this area is classified among the highly polluted areas. The central point area with a PLI value of 3.0 in the five years 1986–1990 has values consistently above 4.0, with a slight drop for the five years 2005–2010, therefore it is characterized as a highly polluted area. Finally, in the other two central areas, the PLI values are 2.6 and 2.8 respectively (low pollution) in the five years 1986–1990, while afterwards an increase in PLI values is observed to 3.2 and 3.7 (moderate to high pollution).

4.1 Copper (Cu)

According to EF, the most polluted area of the Gulf in terms of copper is the area where the Elefsina Shipyards are located (Fig. 2, A11). The values of this index start from 2.9, i.e., at the upper limit of the low pollution classification in the five years 1986-1990, and end at the value of 10.3 at the lower limit of the high pollution area. For the last period of five years, the areas where the Skaramangas Shipyards and the Elefsina Refineries are located are characterized by low pollution, with index values of 1.9 and 1.4 respectively. The areas in the remaining sampling points for EF are areas of zero-burden.

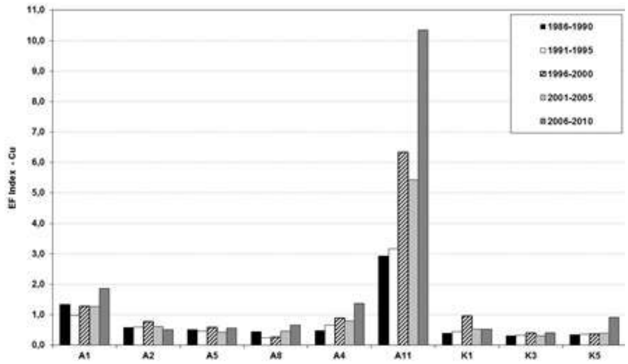

Figure 2. EF Index for Cu [17].

According to I_{geo}, the most polluted area in copper is Elefsina Shipyards (Fig. 3, A11), with index values around 5.5, i.e., stable in the area from high to extremely high pollution in the first twenty years, while in the last five years period the index value is 6.7, i.e., in the area of extremely high pollution.

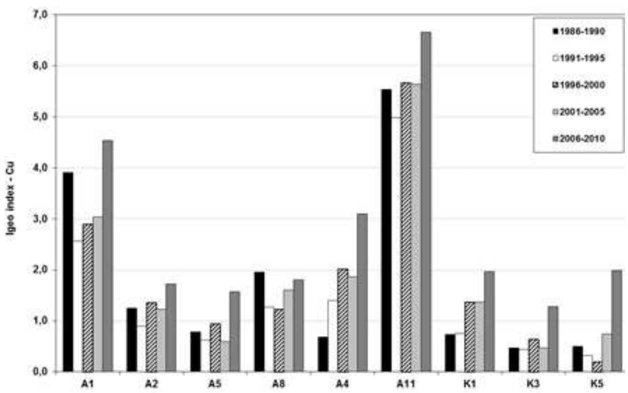

Figure 3. I_{geo} Index for Cu [17].

At Skaramangas Shipyards, in the five-year period 1986-90, the value of the index is 3.9 at the upper limit of high pollution. Then, while initially there is a sharp drop to a value of 2.6 (moderate to high pollution) in the five years 1991–1995, the values then increase with a final value of 4.5 in the high to extremely high pollution range. At Elefsina Refineries, we observe a continuous increase in the index values for copper, with a final value of 3.1 (high pollution). In the rest of the regions, I_{geo}'s values for copper show an increase, with the final values in the area of moderate pollution.

4.2 Cadmium (Cd)

The values of EF for cadmium do not show large deviations in the different sampling points, remaining in the area of low pollution (Fig. 4).

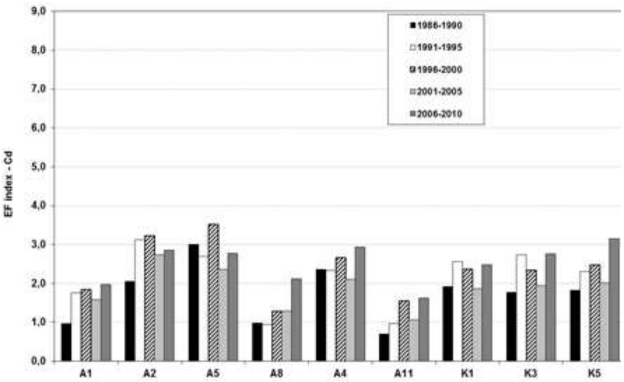

Figure 4. EF Index for Cd [17].

However, comparing the values of the index in the first five years 1986–1990 and the last five years 2006–2010 for the same point, we notice that there is an increasing trend in almost all regions. The most intense increase is observed at the central point of the Gulf, located at a depth of 33 m, where the EF value in the five years 1986–1990 was 1.8, while in the five years 2006–2010 the value of the index reached 3.2. The only point where a small drop is observed is that of the coast in the stream of Aghios Georgios, from 3.0 to 2.8.

The values of I_{geo} for the sediments of the Gulf of Elefsina show even greater stability than their EF counterparts (Fig. 5). But almost all I_{geo} values are in the high pollution area. The upward trend in values over time is also observed in I_{geo}'s values, although it seems to be less pronounced. The strongest increase in the values of this index over time is observed at a central point, from 2.9 to 3.8.

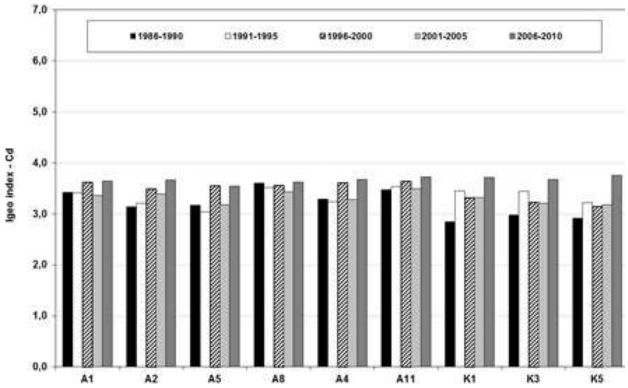

Figure 5. I_{geo} Index for Cd [17].

4.3 Chromium (Cr)

The EF values for almost all sample points are less than one (Fig. 6). Only at the point of the Aghios Georgios stream and for the five-year period 1986-1990, a value at the upper limit of low pollution (2.8) is calculated (A5), which, however, decreases rapidly in the following five years period, to reach a value of 0.5 in the five-year period 2006-2010.

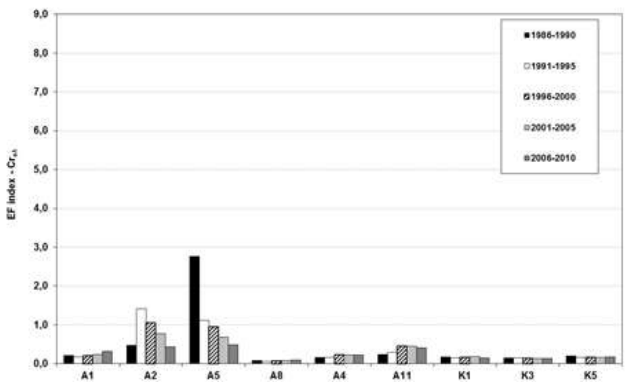

Figure 6. EF Index for Cr [17].

The three sampling points located in the center of the Gulf of Elefsina are zero-burden points for chromium, according to I_{geo} values (Fig. 7).

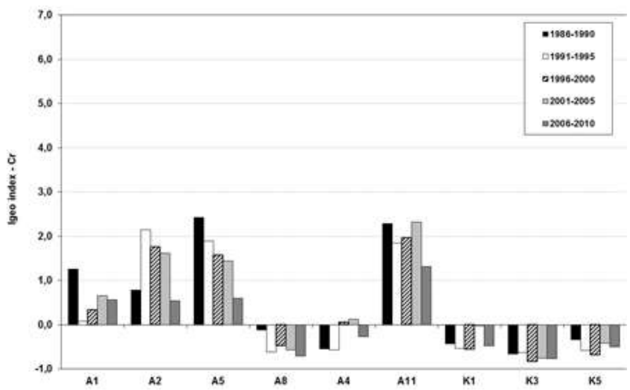

Figure 7. I_{geo} Index for Cr [17].

We come to the same conclusion for the locations of the ship breakers and the Elefsina Refineries. For the rest of the coastal points, a moderate pollution is initially calculated, which however decreases over time. The only area in which a moderate burden is calculated in the five years 2006–2010 is the area of the Elefsina Shipyards (A11).

4.4 Manganese (Mn)

According to the EF values, the sediments in the Gulf of Elefsina are characterized as an area of zero-burden, throughout the time period of the measurements.

The sediments in the Gulf of Elefsina are also characterized as a zero-burden area by the values of I_{geo}. Only in the areas near the two shipyards (A1, A11) and for the five years 1986 – 1990, moderate pollution is calculated which, however, subsequently decreases to the levels of zero-burden.

4.5 Lead (Pb)

The EF values for lead at the sampling site of the Skaramangas Shipyards show a decline from a value of 4.1 (moderate pollution) in the five-year period 1986–1990 to a value of 2.3 (low pollution) in the five-year period 2006-2010 (Fig. 8). At the shipbreaking site (A8), the index values are stable over time near the lower limit of low burden. In the rest of the points, an increase in values is recorded in the first three five-year periods, while in the next two there is a decrease, but remaining in the area of low pollution. The only point where values of 3.7 and 3.5 (moderate pollution) are calculated in the five years 1991–1995 and 1996–2000 is the point where the Elefsina Shipyards are located (A11). The worst five-year period for the Gulf is the five-year period 1996–2000, since the highest values are recorded in most sampling points.

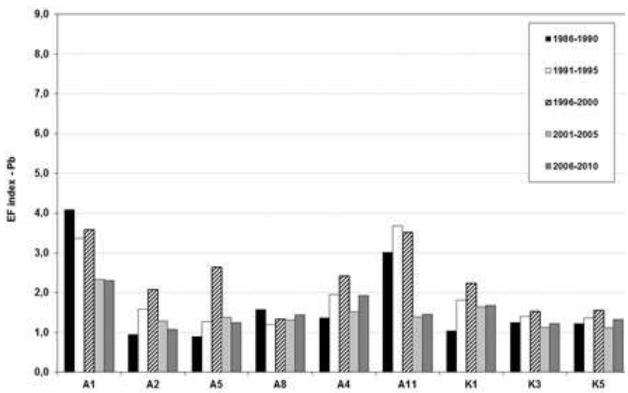

Figure 8. EF Index for Pb [17].

The I_{geo}'s values for lead are decreasing over time at the sampling points of the Skaramangas Shipyards, the ship breaking site and the Elefsina Shipyards (Fig. 9).

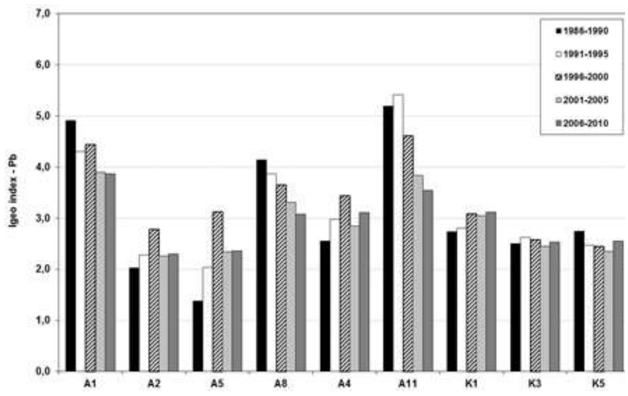

Figure 9. I_{geo} Index for Pb [17].

More specifically, in the first point, in the five-year period 1986-1990, the value of this index was calculated at 4.9, very close to the upper limit of the designation high to extremely high pollution, while in the five-year period 2006-2010, the value was 3.9, very close to the limit of the designation high pollution. For the second point, the values in the corresponding time periods are 4.1 (near the lower limit of high to extremely high pollution) and 3.1 (near the lower limit of high pollution). For the third point, in the time period 1991–1995, the value is 5.4 (extremely high pollution), which is also the maximum I_{geo} value for lead over time, while in the five years 2006–2010 the value is reduced to 3.5 (high pollution). At the point of the Aspropyrgos Refineries (A2), this index values show an increase from a value of 2.0 (the limit of moderate pollution) in the five years 1986-1990 to 2.8 (moderate to high pollution) in the five years 1996 -2000, and then a drop to a value of 2.3 (moderate to high pollution). We have a similar behavior of this index at the point of the Aghios Georgios stream (A5) and the Elefsina Refineries (A4). For the areas of the center of the Gulf, an increase is observed from a value of 2.6 (moderate to high pollution) in the five years 1986–1990 to a value of 3.1 (high pollution) in the five years 2006–2010, while in two places, a stability of values is also observed.

4.6 Zinc (Zn)

The values of the EF index at five points of the coast correspond to a zero-burden area (Fig. 10). At one point, the value of the index in the five years 1986–1990 is 4.2 (moderate pollution). In the five years 1991–1995, the value increases sharply to 8.1 (moderate to high pollution) and then decreases to the value 2.0 (low pollution) in the five years 2001–2005, to end up with the value 2.9 (low pollution) in the five years 2006–2010. At the other points of the coast, the value of EF increases from 0.8 (zero-burden) in the five-year period 1986–1990 to 3.0 (the limit of low-moderate pollution) and then decreases to 0.5 (zero-burden). We have a similar fluctuation in values elsewhere.

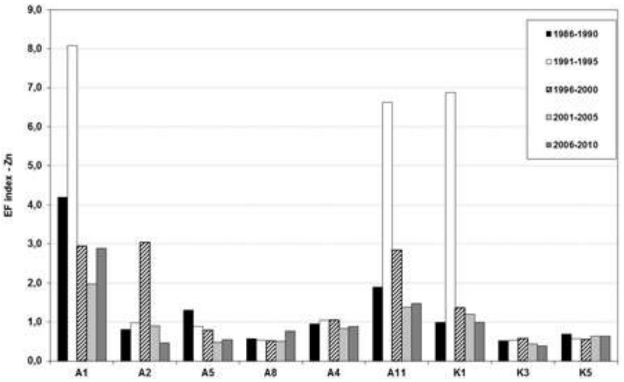

Figure 10. EF Index for Zn [17].

The I_{geo} values for a point on the coast are high, but show a downward trend from 5.6 (extremely high pollution) in the five-year period 1986–1990 to 4.1 (high to extremely high pollution) in the five-year period 2006–2010 (Fig. 11). We also observe a downward trend in I_{geo} values in other places, with values of 2.2 (moderate to high pollution) in the five-year period 1986–1990 to 1.0 (the lower limit of moderate pollution) for the time period 2006–2010. For two points we have values from 2.8 (moderate to high pollution) for the five years 1986-1990 to 1.9 (moderate pollution) for the period 2006–2010, and from 1.2 (moderate pollution) to 0.8 (zero-burden) in the corresponding periods. In the rest of the points, I_{geo}'s values initially increase and then decrease.

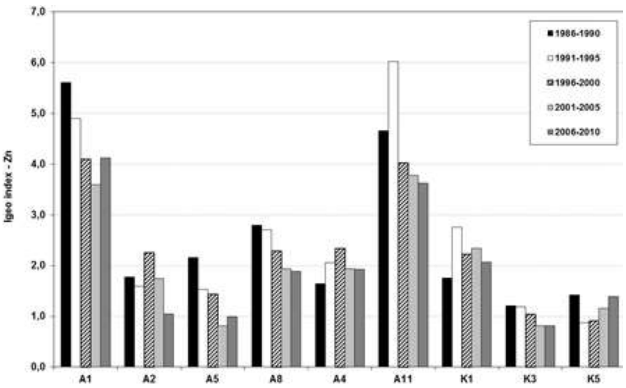

Figure 11. I_{geo} Index for Zn [17].

4.7 Nickel (Ni)

We observe that the values of the EF index for all sampling points and in each time period of the study are less than unity. Based on these values, we conclude that the area of the Gulf of Elefsina is a zero-burden area.

We observe that the values of I_{geo} for all sampling points, except one (A11), and in every time period of the study are less than unity. Based on these values, the areas of the Gulf of Elefsina, except for the area at the Elefsina Shipyards (A11), are characterized as of zero to moderate pollution. The area in Elefsina Shipyards with index values from 1.4 to 1.8 is characterized by moderate pollution.

4.8 Iron (Fe)

For iron, only I_{geo} is calculated, since it is considered a reference metal for the EF index (Fig. 12). The lowest value of I_{geo} starts from 3.4 (high pollution) in the 1986-1990 five-year period, then decreases to 1.7 in the 1991-1995 five-year period, then increases to 2.2 (moderate to high pollution) in the 1996-2000 five-year period, followed by increasing trends until the 2006-2010 five-year period.

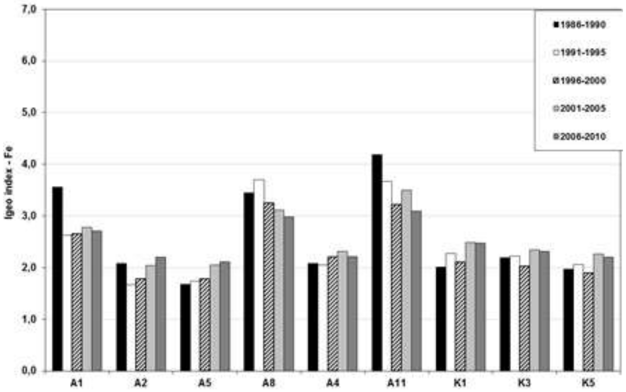

Figure 12. I_{geo} Index for Fe [17].

5 Summary

The above study was carried out in order to assess the level of pollution of the sediments of the Gulf of Elefsina by the heavy metals Cu, Cd, Cr, Pb, Zn, Mn, Fe and Ni. For this purpose, the values of the PLI index were initially calculated at nine sampling points, six on the coasts and three in the center of the Gulf of Elefsina. PLI estimates pollution as a whole, taking into account the concentrations for each of the above metals equally. If its value is greater than unity, we conclude the existence of pollution and therefore the necessity of further study.

At all sampling points, PLI values greater than unity, and in some cases much greater, were calculated. We are therefore led to the conclusion that pollution occurs at all sampling points. The highest values of this index were recorded at the points of the Elefsina Shipyards and the Skaramangas Shipyards. However, it should be noted the tendency to decrease the values of PLI, which concerns all the points, but is more intense in the points of the most burdened areas of the coast. In order to specify the PLI results, the EF and I_{geo} indices were calculated for each of the studied metals.

The I_{geo} values show more intense pollution than the EF values in the corresponding areas. This is probably due to the choice of iron as the reference metal for calculating EF. I_{geo} for iron, however, shows that the sediments contain iron at concentrations greater than the background concentration. Therefore, I_{geo} is judged to be the most reliable index for the assessment of sediment pollution for each metal.

For copper, both indicators show pollution in the area of Elefsina Shipyards. I_{geo} shows intense pollution both at Skaramangas Shipyards and at Elefsina Refineries, which are very close to Elefsina Shipyards. It is also observed that the values of the indices for copper are increasing at all points over time.

For cadmium, the EF values are in the low pollution area, while for I_{geo} in the high pollution area, throughout the Gulf. Both indicators show increasing trends in most sampling points.

For chromium, the EF index only in the stream of Aghios Georgios, which is the recipient of wastewater from many industrial units, and for the five years 1986–1990, has a value at the upper limit of low pollution, which, however, decreases rapidly in the following five years. I_{geo} shows moderate pollution in addition to the stream of Aghios Georgios and at the Aspropyrgos Refineries, which are located next to the mouth of the stream, but also at Elefsina Shipyards; but these values are also decreasing over time.

For lead, the highest index values are calculated at the two Shipyards. But over time the values decrease. For the rest of the points, I_{geo} has high values that generally show stability.

For zinc, the highest index values are calculated at the two Shipyards. The very high values of EF in the five years 1991–1995, both in the areas of the two Shipyards and in the central area of the Gulf, are noteworthy. For zinc, as well, the index values generally decrease over time except for one central point.

For manganese, the values of both indicators show no pollution.

For nickel, the EF values show no pollution, while the I_{geo} values show moderate pollution only for the area of Elefsina Shipyards.

For iron, I_{geo} values are elevated at all sampling points. The highest values are calculated for the two Shipyards and for the ship breakers. This is to be expected due to the activities that take place in the specific units (construction, maintenance, dismantling of ships).

If we want to summarize the above conclusions from the study of the EF and I_{geo} indices, we can conclude that the most serious problems of heavy metal pollution in the sediments of the Gulf of Elefsina are located in the areas of the two Shipyards, which are located at its two ends. The sediments in these areas appear enriched in copper, cadmium, iron, lead and zinc. Moreover, in Elefsina Shipyards pollution appears, in addition to the above metals, in chromium and nickel, as well.

In the areas of the two Refineries, more intense pollution is recorded for cadmium. Additionally, in the area of Aspropyrgos Refinery we have higher values for chromium, while in the area of Elefsina Refinery we have higher values for lead and copper.

For the area of the mouth of the Aghios Georgios stream, we notice that we have more pollution in the sediments for cadmium. At the same time, there is a strong downward trend in values for chromium and zinc.

In the area of the ship breakers, there is intense pollution for cadmium, iron, lead and zinc. For the first two metals we have approximately the same pollution over time, while for the next two there is a strong downward trend.

Finally, for the points in the center of the Gulf, the most intense pollution is recorded for cadmium. Milder pollution for all three of these points is observed for lead and iron. Especially at one central point, we also have high index values for zinc, which are likely due to the short distance of this point from Skaramangas Shipyards.

6 Conclusion

Concluding this study and regarding the heavy metal pollution indices, and especially for the EF index, aluminum, which is provided in the literature, or manganese for which, according to I_{geo}, the pollution levels are almost negligible, could be used as a reference metal in future studies. We could also say that it is a blow to a region, such as the region of Elefsina and Western Attica in general, the degradation of the Office of Pollution Control and Environmental Quality, which led to the interruption of measurements in the Gulf of Elefsina in 2010.

In general, all the necessary actions must be taken in order to carry out measurements for the pollution of the marine environment, in every area of high industrial activity. Practical applications of this direction are the mapping of high industrial activity areas, the installation of pollution measurement devices at crucial points there and the setting of monitoring agencies for processing the data collected by these devices. In this respect and to facilitate the collection of environmental data, a robotic system is being developed at the Department of Industrial Design and Production Engineering of the University of West Attica, in the form of an Unmanned Sea Vessel (USV). This robotic USV is being designed to take measurements with results in situ, following instructions given in natural language that are processed by semantic modelling software [18] [19].

In conclusion, the present work shows that significant heavy metal pollution is observed in the sediments of the Gulf of Elefsina, at least for the time period of the study. It is therefore necessary to carry out measurements over time and to take the necessary measures in order to improve the quality of the area's environment.

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