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Mapping the Pollution Gradient of the Saronikos Gulf Benthos Prior to the Operation of the Athens Sewage Treatment Plant, Greece

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The effects of sewage effluent on the soft bottom benthos of Saronikos Gulf have been mapped near the main sewage outfall of Athens, Greece. Previous benthic studies in the area were carried out by traditional benthic surveys (Zarkanellas and Bogdanos, 1977; Zarkanellas, 1979; Friligos and Zenetos, 1988; Zenetos *et al.*, 1990; Nicolaidou *et al.*, 1989; Simboura *et al.*, 1995). In the present study the sediment profile imagery (SPI) method (Rhoads and Germano, 1982, 1986; O'Connor *et al.*, 1989) was used. At the time of the investigation in February 1992, the sewage of the city of Athens (with an estimated flow rate averaging 600 000 m^3 day^{-1}) was discharged untreated into the shallow waters of Saronikos Gulf. Since 1994, the effluent has been treated and then discharged through a 1870 m triple outfall at 63 m water depth. The results presented here describe the conditions in the affected area of the Saronikos Gulf prior to the commencement of the sewage treatment and may serve as a baseline for future comparisons.

The SPI camera (SPI I 3731 Marine Technology, Ireland) supplied by Aquafact International Services, Ireland, was deployed at 17 stations at various distances from the sewer outfall (Fig. 1). Three replicate images were taken at each station. Sediment grain size, camera prism penetration depth, surface boundary roughness, apparent redox potential discontinuity depth (RPD) and infaunal successional stage were measured from each negative. The infaunal successional stage ranges from I (pioneering species) to III (equilibrium species) and is interpreted against a well documented successional paradigm for soft marine sediments (Pearson and Rosenberg, 1978). A multi-parameter SPI Organism-Sediment Index (OSI) was calculated in order to characterise habitat quality. According to Germano and Rhoads (1984), the lowest value of −10 is given to those bottoms which have low or no dissolved oxygen in the overlying bottom water, no apparent macrofaunal life and methane gas present in the sediment. At the other end of the scale, an aerobic bottom with a deeply depressed RPD, evidence of a mature macrofaunal assemblage, and no apparent methane gas bubbles is given an index of 11. The three replicate images for each station used in the present study were analysed separately and the mean values of the parameters measured were used in the statistical analyses. The mapping of SPI variables was carried out using WINSURF and Principal Component Analysis (PCA) by the STATGRAFICS package.

The physical and biological parameters measured by SPI are mapped in Fig. 2(a)–(f). Finer sediments were found near the sewage outfall and these also extended to some of the deeper stations (Fig. 2(a)). A similar trend was followed by the prism penetration depth (Fig. 2(b)). The depth of the Redox Potential Discontinuity (Fig. 2(c)) showed a regular increase from zero near the outfall, where methane-filled voids were present, to values of 4 cm at approximately 4 km distance from the outfall. In the centre of the investigation area values as high as 6–7 cm were observed, while in the south-eastern region the RPD depth decreased again. Surface boundary roughness (Fig. 2(d)) giving an indication of the effects of currents on the sediment surface, was higher in the western part of the study area. Fig. 2(e) shows the distribution of successional zones (according to Rhoads and Germano, 1982) in the area. The zone nearest to the outfall represented a community at successional stage I, encountered at a high intensity of disturbance. This was followed by a transition zone where the community was between successional stages I and II. No stage III (corresponding to equilibrium assemblages) was reached, although there was a tendency towards it (stage II–III) at the outer stations. Near the outfall, the transition from one zone to the next occurred over shorter distances. On the west, there was an intrusion of higher stages closer to the source of pollution. The overall habitat quality of the area represented by OSI is shown in Fig. 2(f). The values ranged from −10 (close to the outfall) to 10 (at Stations 8, 17 and 18). Taking into account (Germano and Rhoads, 1984) that values of 10 and 11 represent an undisturbed environment while values below 6–7 correspond to pollution affected areas, only a small part of the study area can be considered to be undisturbed. The pollution gradient from the outfall to the outer region is clearly evident.

In the plot of PCA based on the SPI data (Fig. 3), axis I represents the pollution load, which is related to the

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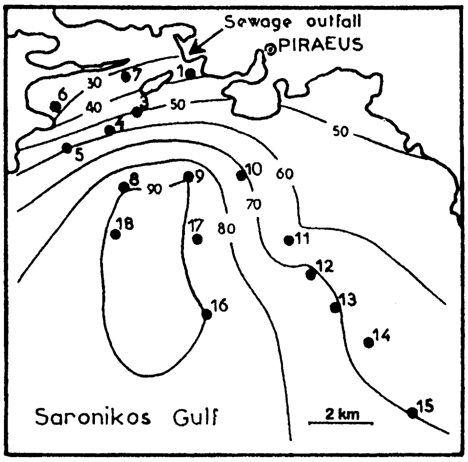

Fig. 1 Sampling stations and depth contours (m) of the study area in Saronikos Gulf.

distance from the main source of pollution, i.e., the sewer outfall. Station 1, nearest to the outfall exhibited the highest score on Axis I, followed by the nearby Stations 7, 3 and 6. Stations 12, 17 and 18 had the lowest scores on the same axis. The second axis is related to sediment characteristics (penetration, particle size). Stations 8 and 18 with finer sediments, where penetration is high, exhibited higher scores on Axis II, while the stations with coarser sediments occupied the lower parts of the graph.

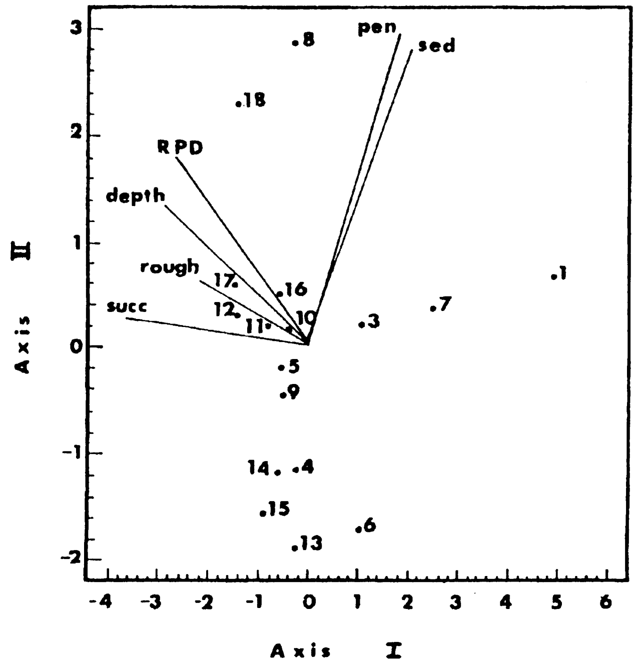

Fig. 3 Results of PCA based on SPI data. Depth: station depth, pen: prism penetration depth, rough: surface boundary roughness, RPD: Redox Potential Discontinuity depth, sed: sediment grain size, succ: infaunal successional stage.

The application of SPI in the present study produced a useful representation of the bottom characteristics related to pollution. The OSI, which includes the RPD

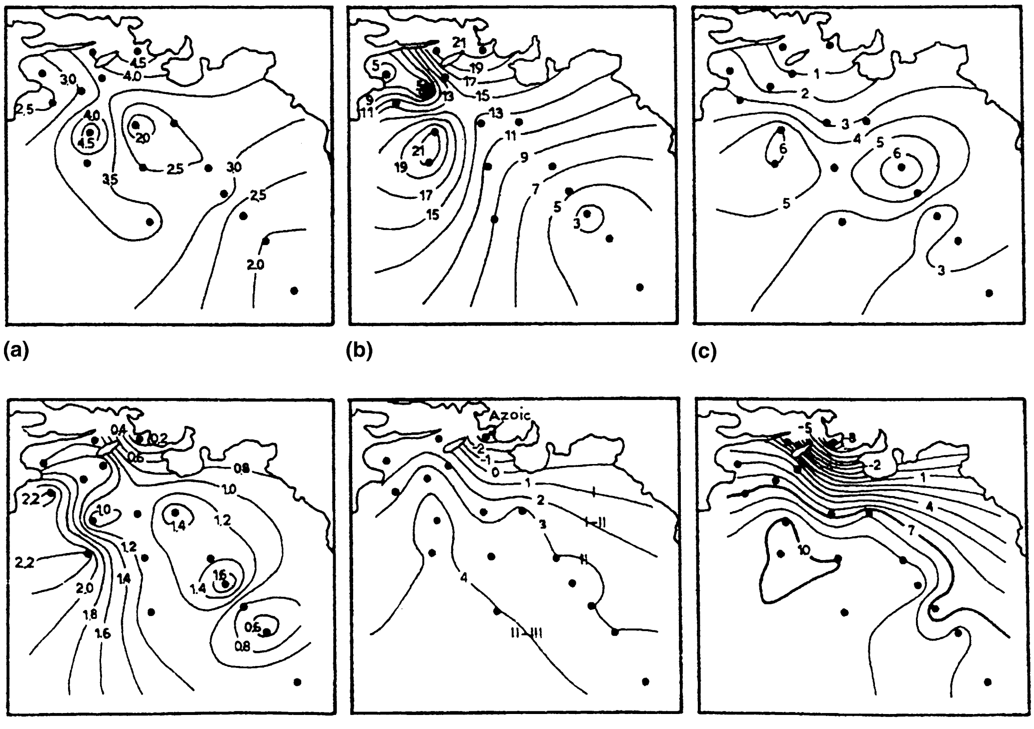

Fig. 2 Mapping of physical and biological parameters measured by SPI: (a) sediment grain size (ϕ); (b) prism penetration depth (cm); (c) RPD (cm); (d) surface boundary roughness (cm); (e) infaunal successional stage; (f) OSI.

depth, the successional stage of the benthic community and the apparent reducing conditions, is considered an excellent parameter for mapping disturbance gradients in an area (Rhoads and Germano, 1982). In the Saronikos Gulf the pattern of OSI values demonstrated a steep pollution gradient from the sewage outfall to the outer Gulf. Thus, in 1992, the heavily polluted area extended approximately 1 km from the outfall. This was followed by a polluted but less heavily impacted zone extending up to 2.5 km to the south of the pollution source. This zone expanded to the southeast along the coastline, indicating secondary pollution sources from urban sites on the shore. A similar divergence of low OSI values near the coast was observed by O'Connor *et al*. (1989). The undisturbed area (with an OSI > 10) was restricted to three stations surrounded by an extensive transitional area.

Early zoobenthic studies (Zarkanellas and Bogdanos, 1977; Zarkanellas, 1979) revealed the presence of an azoic zone close to the outfall, which had expanded after a period of eight years (Friligos and Zenetos, 1988). In 1987 (Zenetos *et al*., 1990) the azoic zone did not extend further than 1km from the sewage outfall, while a polluted zone extended up to 3 km further. Two years later, in 1989, the application of multivariate (cluster) and univariate (ecological indices, ABC curves) techniques to the benthic communities revealed three zones of decreasing pollution impact (Simboura *et al*., 1995) which is broadly in agreement with the gradient observed in the present study. However, there are occasions when SPI data do not agree well with traditional benthic surveys, especially when other disturbances alter the vertical structure of sediment, as in the case described by Rumhor and Karakassis (1999). Nevertheless, when a steep pollution gradient exists as in Saronikos Gulf, the use of SPI is an effective method. The mapping of the pollution gradient before the commencement of the operation of the sewage treatment plant provides useful information against which future comparisons can be made.

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