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Research Article

Infaunal Community Responses to the Gradient of Heavy-metals in Langstone Harbour, UK

Langstone Limanı (Birleşik Krallık) İçfaunal Komünitesinin Ağır Metal Değişimlerine Tepkileri

Elif Kılıç*
Ministry of Agriculture and Forestry, General Directorate of Water Management, 06560, Yenimahalle - ANKARA
elif.kilic@tarimorman.gov.tr (https://orcid.org/0000-0002-0508-4368)
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Abstract

The complex nature of the marine environments including a broad array of factors seems inconvenient to have specific indicator organisms alerting the changes in ecological quality based on pollutant inputs to water bodies. Benthic infauna, however, may respond to the pollution-induced spatial quality changes in a tidal inlet as they are incapable to avoid from the pollution sources and hence, from low quality of sediment and water. This research suggested that the interaction of sediment metal stressors and the possible associated factors finer grain fractions, estuary position and depth is likely to encounter with a specific distributional pattern of infauna. The communities of macroinfauna in Langstone Harbour were studied spatially from 36 samples collected across four subtidal stations, two each to the upper northern and the southern of the platform. The distinct variations in communities between and within stations and the most contributed species to variations were determined using multivariate analysis techniques. The structured model showed that the measured environmental factors explained 29.4% of infaunal community structure in the harbour with the highest contribution of chromium (6.6%). Environmental patterns suggested the increasing metal deposition in the finer-grained muddy sediments towards the innermost basin with stagnant and shallower waters.
Keywords: *Macroinfaunal distribution, infaunal community, subtidal sediment, heavy metals, Langstone Harbour*

Öz

Denizel ortamların çok çeşitli faktörler içeren karmaşık doğası, kirlilik kaynaklı ekolojik kalite değişimlerinde uyarı veren spesifik indikatör organizmalar barındırabilme açısından elverişsizdir. Kumun içerisinde hareketsiz veya sınırlı hareketle yaşamını sürdüren bir canlı grubu olan bentik içfauna ise; kirlilik kaynaklarından ve dolayısıyla da sediman ve suyun düşük kalitesinden uzaklaşamaz. Bu nedenle, kıyı-geçiş sularında kirlilik ile tetiklenen konumsal kalite farklılıklarına cevap verebilecek bir grup olarak görülmektedir. Bu çalışma, sediman stres etkenlerinden ağır metaller ve ilişkili faktörler olan sediman tanecik fraksiyonu, haliç pozisyonu ve derinlik interaksiyonunun; bentik içfaunada spesifik dağılımsal bir örüntü ile karşılaşabileceğini önerir. Langstone Limanı makroiçfaunal komünite, ağır metal dağılımı ve sediman granülometrisi, platformun kuzeyi ve güneyinde ikişerli konumlanan

** Corresponding author*

4 farklı gelgit altı istasyon boyunca 36 noktada gerçekleştirilen örneklemeler ile çalışılmıştır. Komünitelerin istasyon içi ve istasyonlar arası ayırt edilen varyasyonları ve bu varyasyonlara en çok katkıda bulunan türler çok değişkenli analiz yöntemleri kullanılarak belirlenmiştir. Yapılandırılan modellere göre, ölçülen çevresel faktörler ve interaksiyonlarının, halicin bentik içfaunal yapısını %29.4 oranda açıkladığı, ve krom metalinin %6.6'lık oran ile bu açıklamaya en büyük katkı yapan faktör olduğu belirlenmiştir. Analizler sonucu çevresel patern; çok ince kum ve silt-kil partiküllerinin havzanın durgun sulara sahip sığlaşan iç alanlarına doğru artışıyla birlikte yükselen ağır metal birikimini ortaya koymaktadır.

Anahtar kelimeler: *Makroiçfaunal dağılım, içfaunal komünite, gelgit altı sediman, ağır metaller, Langstone Limanı*

Introduction

The analysis of benthic infaunal communities has been a widely used environmental monitoring tool for the transitional and coastal marine environments over the years (Bilyard, 1987; De Jong & Tanner, 2004; Salas et al., 2006). The relative longevity and stable living conditions of infauna as compared with other monitorable biological groups such as plankton increase the reliability and strength of their responses to altered environmental conditions (Pearson & Rosenberg, 1978; Bilyard, 1987; Ritz et al., 1989; Persaud et al., 1993; Weisberg et al., 1997; Salas et al., 2006). The environmental disturbance is a considerable mortality source for these organisms and therefore is a critical component of community structuring (Woodin, 1978). The expected responses from macroinfaunal communities exposed to contaminated sediments in estuaries are shifts in community structures followed by the dominance of few resistant species (Gray & Mirza, 1979; Gray, 1989; Dauer, 1993).

Increasing human activities in coastal areas have been resulting in elevated concentrations of heavy metals and higher pressure on the biological equilibrium of marine ecosystems (Förstner, 1981; Jiao et al., 2018). The main sources of metal input produced by human activities in transitional coastal marine areas are the loads from industrial, domestic and agricultural runoffs, ship-related anti-foulant paints and waste dumping, shipbreaking and mining activities (Weichart, 1973; Davutluoglu et al., 2011). A large amount of discharged heavy metals initially forms part of suspended matter and hence, accumulate in sediments (Groot et al., 1982; Usero et al., 1998) which is the living space and feeding ground of benthic infauna. Grain size, the size of sediment particles, is the primary environmental factor determining the distribution of heavy metals by affecting their binding to the sediments (Singovzka et al., 2016). The feeding modes of infauna, deposit and suspension-feeding, enable the organisms to contact inescapably with the sediment and hence, cause to the greatest exposures to these contaminants present in the sediments and the pore water (Dean, 2008). Thus, these organisms could be affected directly by heavy metal concentrations because of their interactions with the substratum throughout their lifespan (Persaud et al., 1993; Geffard et al., 2005; Jiao et al., 2018).

Heavy metals have toxic, environmentally persistent, undegradable and unremovable nature alongside their ability to being included in the food chain of marine systems (Wood, 1974; Förstner, 1981; Demirbas et al., 2005; Sharifuzzaman et al., 2016; Gheorghe et al., 2017). These chemicals mainly affect the process of growth, metabolism, and the reproduction system of an organism by inducing toxic effects (Stankovic et al., 2014). The metal-related stress on the marine environments and organisms could be strong and long-acting since the recovery of these contaminants is extremely hard and tend to remain inconclusive (Gall, 2010; Jiao et al., 2018). Hence, sediment monitoring relative to heavy metals could greatly contribute to biological monitoring studies to evaluate the impact of human-related disturbance. The studies examining the biological responses against the potential toxicity of heavy metals in tidal estuaries in the UK and France demonstrate that copper, zinc, cadmium and lead are of the major concerns for these aquatic systems (Wright & Mason, 1999; Statham, 2000; Geffard et al., 2005; Callier et al., 2009). The pressure by these synthetic chemicals is likely to occur particularly in the estuaries that function as harbours and recreational waters with concentrated human uses and the related vessel density such in Langstone Harbour.

Langstone Harbour is a tidal basin of the English Channel locating in the centre of three extensive adjacent connected harbours on the south coast of the UK. The inlet locates within the East Hampshire catchment with its intense urbanization and agriculture activities (Environment Agency, 2016). There are several reported outfalls with unidentified sources across the harbour (Thomas et al., 2016). A wastewater treatment plant (WWTP), Budds Farm WWTP, where situates at the northern end of the harbour have had difficulties resulting in stormwater discharges directly into the water from various points during the periods of heavy rainfall (Southern Water, 2011) which is likely to cause contaminant inputs into the water system. The last performed intertidal survey in Langstone Harbour under the authority of Natural England (Thomas et al., 2016) reported the benthic infauna as relatively diverse however with spatial distributional differences. These spatial dissimilarities may illustrate their responses to gradients in stressor and certain environmental parameters that are addressed for subtidal sediments in the present project.

The objectives of the present study are: (1) To observe the pattern of macroinfaunal species concerning potential spatial variations in heavy metal loads in surface sediments of the harbour; (2) To evaluate the probable impacts of station position and sediments grain sizes on the gradient in heavy metal concentrations in the harbour and hence, on distributions of macroinfaunal communities. In line with these objectives, the project was underpinned by two hypothetical scenarios for better understanding of transitional estuarine ecosystems and factors which affect the distribution of sensitive benthic organisms residing in sediments: (1) The sediments with different metal contamination levels among the stations could be characterised by certain species of infauna based on their physiological or functional tolerance and hence could result in different compositions in specified stations. (2) The environmental variables of site positions and sediment very fine grain size proportion may contribute to the variation in macroinfaunal benthic communities between stations by affecting their community structure directly and also indirectly through having impacts on the distribution of sediment metals in the estuarine environment.

Materials and Methods

Sampling Design of the Project

The study was carried out along the channels of the inlet in 4 determined subtidal stations (Table 1) named as Budds, Hayling, Milton and Salterns at 3 randomly chosen sites in each station (Figure 1). Samples for infauna and surficial sediment were collected in triplicate at each site.

Figure 1. A map of Langstone Harbour (50.8167° N, 1.0000° W) indicating the field sampling stations in the studied areas (The abbreviations of Bu, Sa, Mi and Ha represents the Budds, Salterns, Milton and Hayling stations, respectively; and A, B, C within the codes indicates the three different sites for each station)

Table 1

GPS Coordinates for the Stations Shown in Figure 1

Station	Longitude (X)	Latitude (Y)
Budds	N 50˚ 49.704′	W 0˚ 59.849′
Hayling	N 50˚ 48.079′	W 1˚ 01.483′
Milton	N 50˚ 48.138′	W 1˚ 01.867′
Salterns	N 50˚ 49.142′	W 1˚ 02.133′

The sampling process was performed over a period of two months, November and December 2018. Time, water depth, the height of tide and GPS coordinate were recorded during each sampling interval. The charted depths are the approximate values as they were calculated without reference to wind and atmospheric pressure.

Collection and Process of Benthic Macroinfauna Samples

Infaunal samples were collected by applying Van Veen grab sampler with 0.1 m^2 diameter for each station. Each collected grab sediment sample was sieved on a 0.5 mm mesh screen onboard, using gentle hose pressure to extract the macroinfauna. The organisms retained in the mesh were placed into labelled plastic bags along with some seawater covering the samples. Transported animal samples to the laboratory were fixed in 25% formaldehyde and then transferred to polyethylene bottles with 70% ethanol to preserve for later sorting. Identification was performed to the possible lowest taxonomy, mainly to species level, using the literature and keys (Campbell, 2005; Sterry & Cleave, 2012; Plass, 2013) under a stereo microscope.

Collection and Process of Sediment Samples for the Analyses of Heavy Metals and Grain Size

The sediment core samples were extracted by taking subsamples from the upmost centimetres (~5 cm) of Van Veen grab sediments (used for macroinfauna collection) using a polyethylene 50 ml syringe applied onto the inspection doors of grab. The samples were placed into polystyrene cooler boxes on board to stop the possible biological activity and prevent any chemical transformation within. Samples were frozen (–20 Cº) until analysed to prevent microbial degradation.

Before starting the treatment of sediments for the analysis of heavy metal concentrations, the samples were placed into the beakers and dried in oven cabinet at 60 °C through 48 hours following defrosting at room temperature. Dried samples were digested in Aqua Regia solution (2 ml HCl + 9 ml HNO_3 + 1 ml 30% hydrogen peroxide for each dried sample placed into vessels) using microwave accelerated reaction system (model-CEM, The MARS 6™) based on US EPA Method 3051 (Environmental Protection Agency, 1994). Acid digested samples were filtered using glass microfibers filter papers with 0.45 mm thickness (Fisher Scientific, MF 300) to remove the undissolved sediment residuals within the samples and diluted up to 50 ml in polypropylene tubes (Fisher Scientific, 50 ml). Digests produced by the method were analysed by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) analytical technique for the detection of total concentrations of Cr, Cu, Ni, Pb and Zn (ppm = mg L- wet weight) in sediment samples.

The rapid partial analysis of the sediment samples from each site was conducted following the dry sieving technique by Bale and Kenny (2005) to determine the quantitative distribution of particle sizes to characterize the physical type of the sediments.

All fractions of ten sizes along with the particle size classifications and the sediment types corresponding to them were defined following the Wentworth (1922). As to corresponding sediment types, the criteria were: gravel (>2 mm), sand (63 µm-2 mm), silt and clay (<63 µm).

Data Analyses

Associated environmental data set to the community structure included water depth (m), the grain sizes (***µ***m) and sediment concentrations (mg L^{-1} wet weight) of five high metals (Ni, Cu, Cr, Zn and Pb). The particle sizes of very fine sand (125-63 µm) and silt clay (<63 µm) were matched to the data set for the multivariate analyses to examine the effects of very fine particulates on metal distribution in the harbour.

The abundance data on macroinfaunal invertebrate species and the environmental data set were subjected to multivariate analyses using the software packages PRIMER (Plymouth Routines in Multivariate Ecological Research, version 6) (Clark & Gorley, 2006). An add-on package for PRIMER, PERMANOVA+ (Anderson et al., 2008), was also used due to the suitability to the complex design of the presented study involving multi factors.

Multivariate analyses of environmental variables.

The environmental dataset was examined through the draftsman plot and a log-transformation was applied to the sediment particle size values. Because of the different ranges of measurements, all environmental data were normalised prior to multivariate analyses. Euclidean distance matrix, the accepted default resemblance measure for environmental data (Clark & Gorley, 2006), was applied to environmental normalised values to see the pattern of similarity/dissimilarity and also as an underlying construction for other multivariate analyses. The data subjected to an ordination using a correlation based principal component analysis (PCA). The significant differences between stations and sites were tested by applying the Permutational Analysis of Variance (PERMANOVA) routine.

Univariate measures of infaunal community structures.

Diversity (Shannon-Wiener index, H') and species richness (Margalef's diversity, d) were calculated for each associated station for the further spatial information about the structure of assemblages. Because the number of different species (S) is greatly affected by sampling effort and size (Melo et al., 2003), Margalef's richness was rather applied to data. One-way analysis of variance (ANOVA) and Tukey's tests were conducted to examine the significance of differences between stations and compare these differences between the station pairs.

All the infaunal assemblages were classified according to their feeding characteristics to interpret the possible spatial changes in community structure based on their different intake mechanisms of contaminants as well as grain size preferences to living in comply with their feeding mode.

The data relative to some community characteristics from related soft bottom benthic invertebrates -opportunistic and/or invasive species- were used to compare the species composition by stations.

Multivariate analyses of ınfaunal species composition with associated environmental variables.

For the biological data, the triangular matrix of similarities between every pair of samples from four stations was constructed by using data transformations and Bray-Curtis (dis)similarity coefficient (Bray & Curtis, 1957) for further analyses. The abundance data of species were pre-treated before the analyses with fourth root transformation to reduce the influence of very abundant species. The resemblance of infaunal communities between every pair of samples (Clark & Warwick, 2001) were analysed using non-parametric multi-dimensional scaling (nMDS) ordination (Kruskal, 1964) and canonical analyses of principal coordinates (CAP) to visualise any pattern of similarities in species composition. PERMANOVA was used for formal significance tests. To find the individual species having the highest contribution to significant dissimilarities among the stations were visualised using the CAP analysis which includes the rank correlation (Spearman) vector overlays of the species data.

A distance-based linear modelling (DISTLM) routine-a regression type analysis- based on dbRDA (distance-based redundancy analysis) was used to model the infaunal community structure using the associated environmental variables (Anderson et al., 2008).

Results

Environmental Variables

The northern inner stations Budds and Salterns had remarkably higher sediment contamination with metals whereas heavy metal content of sediments decreased in southern stations Milton and reached their lowest mean values in Hayling, towards the mouth of the harbour (Table 2). Budds station, near the WWTP, had the most metal contaminated sediments with by far higher mean concentrations at all metals with approximately the difference of changing between tenfold and twentyfold compared with the mean concentration of Hayling, the least contaminated area of the study (Table 2). It is worth noting that the B site of Budds, which is the nearest site to WWTP, had the highest mean concentrations of all metals in the station (Cr: 26.5 ± 1.0, Cu: 8.9 ± 2.0, Ni: 23.3 ± 5.1, Pb: 41.5 ± 1.5, Zn: 122.1 ± 6.8 mg L^{-1} ww). The same trend was observed in Salterns station which had the greatest metal concentrations in its innermost site, site B (Cr: 22.4 ± 1.4, Cu: 29.3 ± 1.1, Ni: 19.6 ± 1.2, Pb: 41.5 ± 2.9, Zn: 147.5 ± 26.7 mg L^{-1} ww).

The concentrations of all five metals were found below the Effects Range-Low (ERL) which is a derived value to estimate for the potential biological adverse effects of metals in sediments by Long et al. (1995) through the data from excessive numbers of lab-based, field and modelling studies. For Budds station, however, the mean concentration of nickel (20.3 ± 4.0 mg L^{-1} ww) was found at almost low-effect threshold level (20.9 mg kg^{-}).

Table 2

Means and Standard Deviations (SD) of Charted Water Depths (m), % Sediment Types (Gravel, Sand, Silt/Mud), % Very Fine Sand + Silt/Clay Particle and Heavy Metal Concentrations (mg L^{-1} wet weight) in Sediment Core Samples

Stations	% gravel (<2 mm)	% sand (63 µm-2 mm)	% silt and mud (<63 µm)	% very fine sand + silt/clay	Cr	Cu	Ni	Pb	Zn	Water depth
Budds										
Mean	16.5	78.5	5.0	36.1	25.0	28.7	20.3	39.7	119.1	1.9
SD	18.4	16.8	5.9	18.4	3.9	3.2	4.0	3.3	11.8	0.8
Hayling										
Mean	0.0	100.0	0.0	4.9	2.0	0.3	1.2	3.5	18.2	4.3
SD	0.0	$1.00E^{-14}$	0.0	1.9	0.4	0.6	0.2	1.0	2.0	1.7
Milton										
Mean	1.2	98.5	0.2	19.1	6.8	4.1	5.2	11.1	35.5	3.5
SD	2.2	2.1	0.5	15.2	2.5	2.3	2.6	3.7	8.0	0.8
Salterns										
Mean	0.2	96.6	3.2	38	13.6	15.8	11.9	25.6	86.2	2.2
SD	0.5	2.9	2.9	26.9	7.3	10.8	6.5	13.2	50.2	1.2

Note. *Sediment core samples from four stations in Langstone Harbour, November and December 2018, Cr=Chromium, Cu=Copper, Ni=Nickel , Pb=Lead, Zn=Zinc*

The sediment of Budds, Salterns and Milton had a heterogeneous character which was comprised of mud and coarse-mixed materials, whereas sediments from Hayling comprised only sand classes indicating comparatively a homogeneous sediment structure in this station (Table 2). Particularly Budds was found gravellier in nature despite the general-sand characteristic of the harbour. There was a clear occurrence of blackened sludge layer intensely on the seabed of the sites within the station Budds (the highest silt and mud of 5% among the stations) and Salterns where locate in the inner part of the harbour.

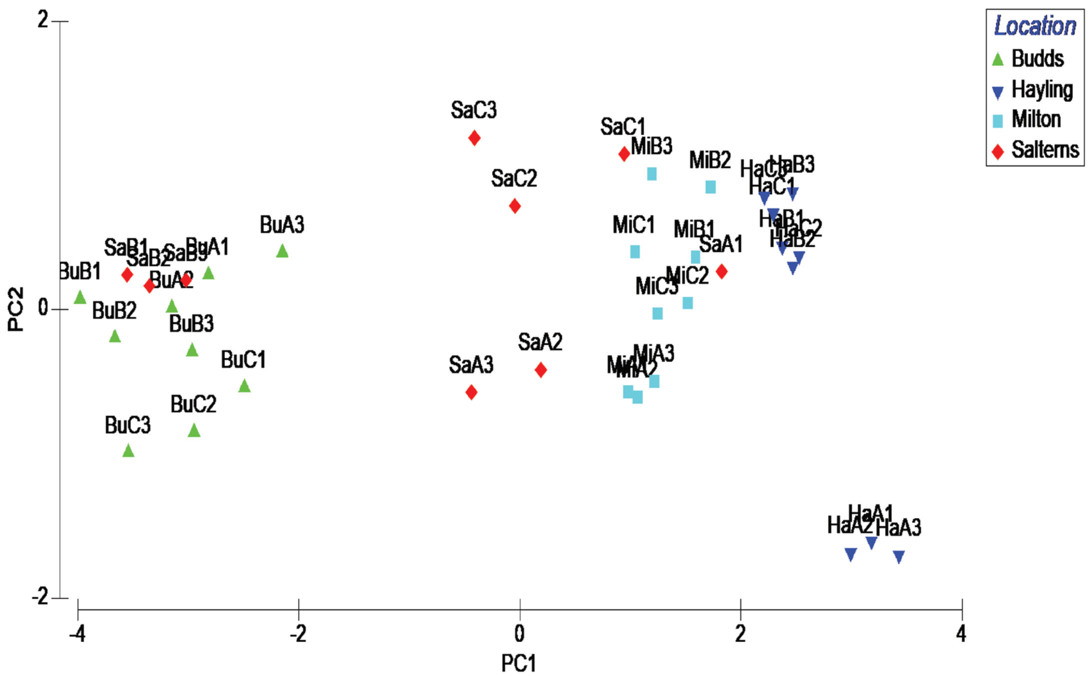


Figure 2. Two-dimensional principal component analysis (PCA) representing the ordination of normalised metals, grain size and depth data for Langstone Harbour, from each of the sediment samples of four stations, Budds (Bu), Hayling (Ha), Milton (Mi) and Salterns (Sa). (A, B, C represents the three sites for each station; 1, 2, 3 represents the replicates for each site). PC1 (x-axis) and PC2 (y-axis) jointly account for 92.1% of the total sample variability. PC1 accounts for the greater part of the variation (84.2%).

PERMANOVA test strongly suggested that there was a significant effect of the station groupings on variability in environmental factors including metals, very fine grain size and depth in Langstone Harbour (pseudo-F = 8.7575, P = 0.0012, calculated with 4255 unique permutational combination). The ordination of environmental data by PCA (Figure 2) showed the clear separation of Budds along with B site of Salterns from other stations due to changing contaminant loads and very fine sand and silt-clay fraction of sediments towards inner parts (Budds and Salterns) of the harbour. This clear separation was also confirmed by PERMANOVA pairwise tests (Table 5) strongly. The environmental grouping in Budds differed from the inner stations Hayling and Milton (p = 0.0004 for both pair) whereas not from Salterns station which may result from the consistent environmental values of Salterns-B site with Budds. Moreover, Salterns B significantly varied from site A (p = 0.0066) and site C (p = 0.0014) within the station. Budds and Salterns station had a fairly scattered pattern with its inconsistent values of environmental variables. The distant cluster of Hayling site A indicated the large change in environmental composition by contributing the within-station variability that was also confirmed statistically (A-B sites p = 0.001; A-C sites p = 0.0012). The explained variability of 92.1% by two-dimensional PCA plot demonstrated a satisfactory description of structure of environmental variables among the stations.

The further PCA analyses (Figure 3) showed that Hayling, Milton and some sites within Salterns had relatively unpolluted sediment by heavy metals comparing with Budds. The distinct grouping of Budds and C site of Salterns mainly resulted from the pattern of increasing concentrations of all the heavy metals (Zn, Ni, Cu, Cr and Pb) in company with higher percentages of very fine sand and mud towards shallow waters.

The metals contributed more to the variation of in the ordination (Figure 3). The southern stations Hayling and Milton had a close grouping indicating their relative resemblance in terms of having less contaminated larger sediment particles in deeper waters whereas the Salterns demonstrated a great variation in all environmental parameters of this study. The increasing water depth was the main reason contributing the by far separation of site A from the other sites in Hayling station.

Univariate Measures of Macroinfaunal Community Structures

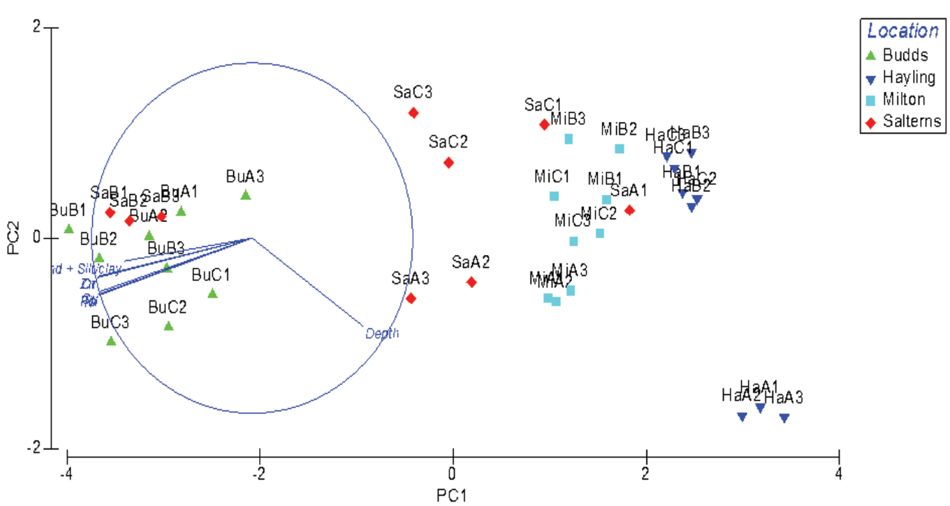


Figure 3. Two-dimensional abiotic PCA ordination on the basis of Euclidean distance measure of normalised metals, grain sizes and depth data for Langstone Harbour. The vector overlays show the variables accounting for the environmental grouping in the stations Budds, Hayling, Milton and Salterns.

The observed species of macroinfauna per sample were sparse along the harbour, with a mean number of species and individuals being 1.3 and 19.7, respectively. The dominant group of the harbour was Annelida which was completely composed of Polychaete worms and made up 57.1% of all observed species and followed by Crustaceans and fully bivalves Molluscs with 20.4% and 14.3%, respectively, constituting the 91.8% of infauna overall.

Table 3

Pairwise Comparisons of Stations from Tukey's Test for Significant Differences in Margalef's Richness (d) and Shannon-Wiener Diversity

Station pairs	Margalef's richness (d) p-values	Shannon-Wiener diversity (H') p-values
Budds-Hayling	0.9994	0.9957
Budds-Milton	**0.0460**	**0.0307**
Budds-Salterns	**0.0006**	**0.0019**
Hayling-Milton	**0.0349**	0.0520
Hayling-Salterns	**0.0004**	**0.0035**
Milton-Salterns	0.3547	0.7023

Note. Bold values indicate the significant differences where, $p < 0.05$.

Species richness (Margalef's) and diversity (Shannon Wiener) for macroinfaunal data varied significantly ($p < 0.05$) among the stations of the harbour (richness: $p = 0.0001$, $F = 9.78$; diversity: $p = 0.0004$, $F = 7.879$). The pairwise comparisons of stations (Table 3) disclosed that the richness and diversity of the infaunal communities in station pairs Budds-Hayling and Milton-Salterns varied not significantly despite the occurring substantial variation in environmental parameters in these pairs. Infaunal community structure of Budds had the lowest diversity (mean $H' = 0.34$) among the stations and fairly low species richness (mean $d = 0.4$) following the Hayling (mean $H' = 0.40$, mean $d = 0.35$), however, had the highest total assemblage in number ($n = 260$). The outer stations Hayling and Milton showed no statistically significant macroinfaunal diversity ($p = 0.052$) in comply with the statistically non-significant difference in metal concentrations, grain sizes and depth between this pair ($p = 0.1046$).

Regarding the feeding modes of infaunal organisms observed along all harbour, interface feeders, which could switch between suspension and deposit feeding, were predominant group by accounting for 52.8% and the succeeding feeding type was suspension feeding, by constituting 28.1% of all feeding modes. The analysis of feeding types based on stations (Table 4) indicated that the organisms with two feeding strategies seemed to be adapted the environmental conditions of relatively more contaminated stations Budds and Salterns whereas Hayling inversely dominated predator and deposit feeder infauna. Milton station varied from other stations with the dominant filter feeding type of the community with the ratio up to 75.9%.

Table 4

The Percentages (%) of Infaunal Species Assemblages from the Specified Stations in Langstone Harbour Based on Their Feeding Modes

Stations	Deposit feeder	Suspension feeder	Predator	Interface feeder	Omnivore	Scavenger	Parasitic
Budds	0.8	1.2	11.9	87.1	0	0	0.8
Hayling	42.9	4.8	52.4	0	0	0	0
Milton	9.4	75.9	1.3	9.9	0	1.9	1.4
Salterns	4.7	14.5	10.3	61.7	2.1	0	0.5

The observed invasive benthos from the samples across the harbour were non-native species the common slipper shell *Crepidula fornicata* (Linnaeus, 1758), the orange-tipped sea squirt *Corella eumyota* (Traustedt, 1882) and native European green crab *Carcinus maenas* (Linnaeus, 1758). *C. fornicata* was particularly aggregated in Milton station and then in Salterns and Budds with the mean individual numbers per site of 120, 47 and 33, respectively. Their presence substantially decreased in Hayling station to mean number of 4 individual. Besides, the absence of *Corella eumyota* and *Carcinus maenas* in Hayling was also worth mentioning.

Multivariate Analyses of Infaunal Species Composition with Associated Environmental Variables

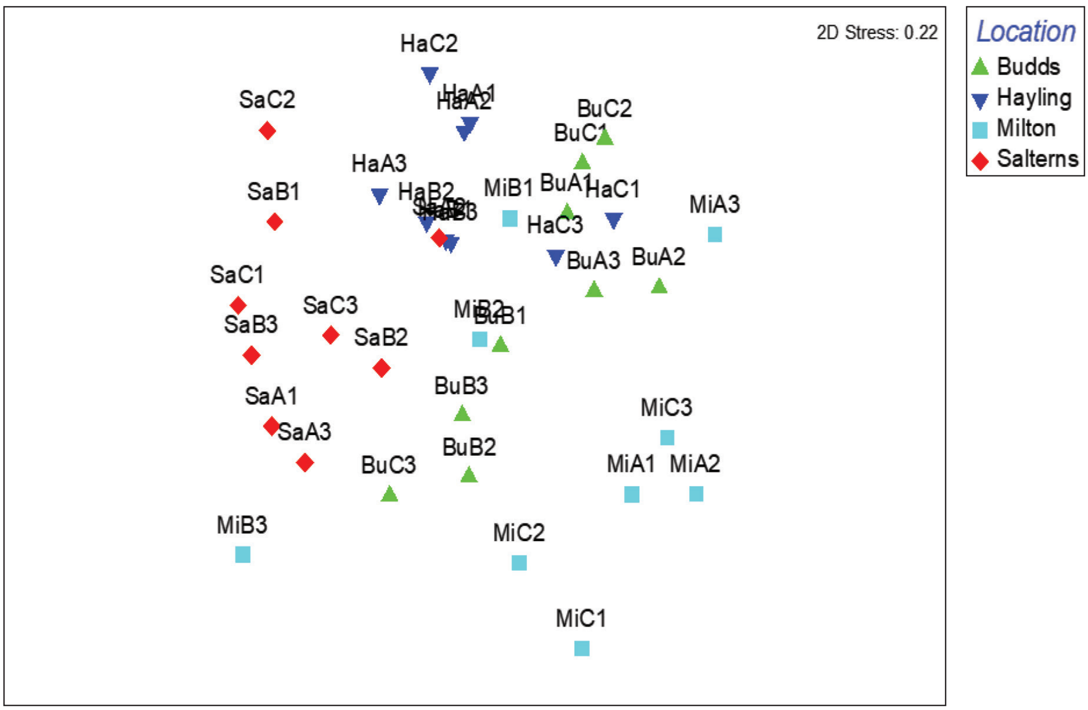


Figure 4. 2-d non-metric multidimensional scaling (nMDS) ordination (rank-based order of the similarities) for fourth root transformed species abundance data-subtidal soft-sediment infauna-from Langstone Harbour at each of the samples of four stations.

MDS ordination (Figure 4) of all samples demonstrated a relative gradation in infaunal structure. Hayling had relatively consistent species composition throughout the station despite the present two separate groups of A and B site within. One of the Northern stations, Salterns had also a separate grouping of composition however with a great variety of distributions within the station. Regarding the Budds, which had the clear separate grouping in terms of sediment contaminants, finer particle content along with water depth (Figure 3), it showed similarities in species structure with some sites from Hayling as well as from rather scattered Milton. However, Hayling and Milton stations fairly differed from Budds ($p = 0.0004$ for both comparisons) in terms of contamination level in combination with certain environmental variables. The ordination of metal contamination (Figure 3) began with the least contaminated station Hayling and was followed by Milton, A and C site of Salterns and culminated in by far higher metal concentrations of B site of Salterns and Budds station. The gradation of infaunal compositions in stations (Figure 4), therefore, showed no pattern as their ordination could not be supported with spatial trends obtained from environmental variables. Besides, the plot had no clear separation between the assemblages from inner north (Bu and Sa) and southern stations (Ha and Mi).

Table 5

Pairwise Comparisons from PERMANOVA for Significant Differences in the Composition of Environmental Factors and Species between Stations

Stations	Environmental p-values	Biota p-values
Budds, Hayling	**0.0004**	0.0872
Budds, Milton	**0.0004**	0.1988
Budds, Salterns	0.1316	**0.021**
Hayling, Milton	0.1046	**0.0384**
Hayling, Salterns	**0.0268**	**0.0216**
Milton, Salterns	**0.0366**	**0.0288**

Note. Bold values indicate the significant differences, = $p < 0.05$.

According to the results from PERMANOVA, the groupings of stations in MDS (Figure 4) significantly represented the changes in subtidal macroinfaunal communities (pseudo-F = 2.57, p = 0.0006, calculated with 4227 unique permutation). The pairwise tests of biota data from stations (Table 5) confirmed that Budds (i.e. the nearest station to the WWTP) differed from only Salterns station. Besides, Budds and Salterns had no significant difference (p = 0.1316) in their distributions of environmental variables although the outermost site of Budds, C site, varied significantly in infaunal distribution within the station (A-C: p = 0.0192; B-C: p = 0.014). This similarity was also supported by the statistical difference (p = 0.0166) between C and innermost A site in environmental variables. Salterns station, with a marked change in contamination and particle sizes compared to Hayling and Milton, had unsurprisingly significantly different species compositions from these stations suggesting evidence against the null hypothetical scenarios of no difference in species compositions among the stations.

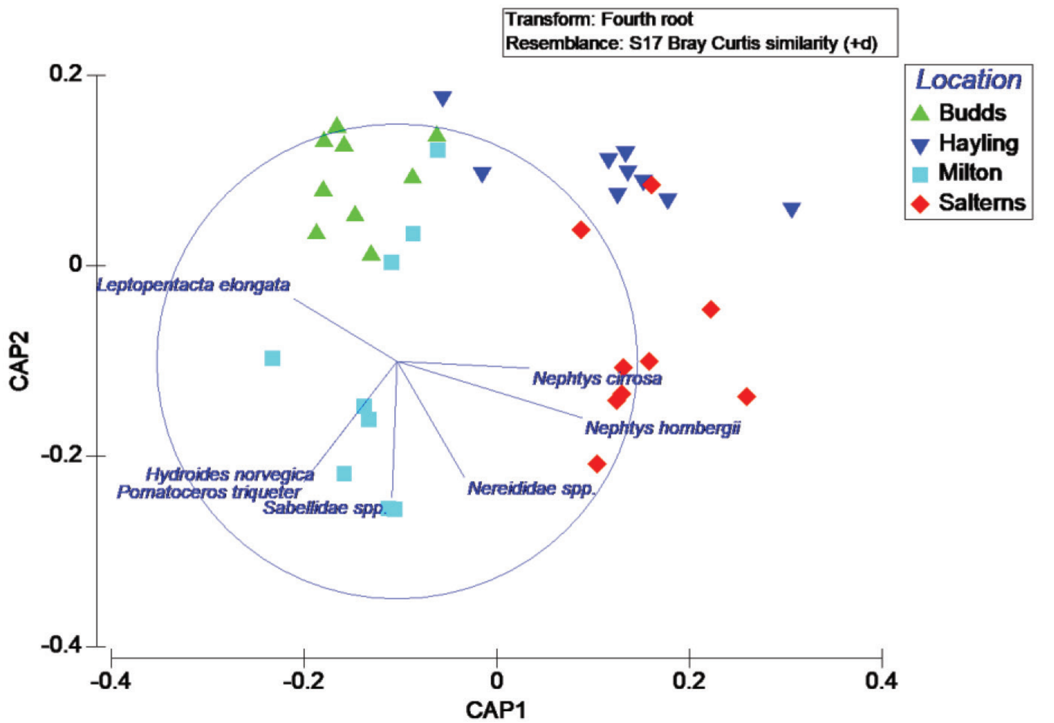


Figure 5. 2-d CAP (canonical analysis of principal coordinates) ordination (distance-based order of similarities) for fourth root transformed species abundance data from each of the samples of four stations in Langstone Harbour. The plot includes the vector overlay showing the most contributing species to dissimilarities among the stations (The adjusted Pearson's correlation for the analyses, $r > 0.5$).

Further CAP analysis including the vector overlay of species that characterise each macroinfaunal community structure of stations (Figure 5) clearly showed the contribution of an echinoderm species *Leptopentacta elongata* (Düben & Koren, 1846) to the significant separation of the community structure of Budds from the Salterns ($p = 0.021$). Two infaunal species and a ragworm family of Polychaetas, *Nephtys hombergii* (Savigny in Lamarck, 1818), *Nephtys cirrosa* (Ehlers, 1868), and Nereididae, were the typified (representing) taxa of the significantly differentiated community structure of Salterns from all the stations in the harbour. The particular presence of tube-building Polychaetas *Hydroides norvegica* (Gunnerus, 1768), *Pomatoceros triqueter* (Linnaeus, 1758) and Sabellidae family were the main contributor organisms to the dissimilarity of Milton station from Hayling and Salterns.

Table 6

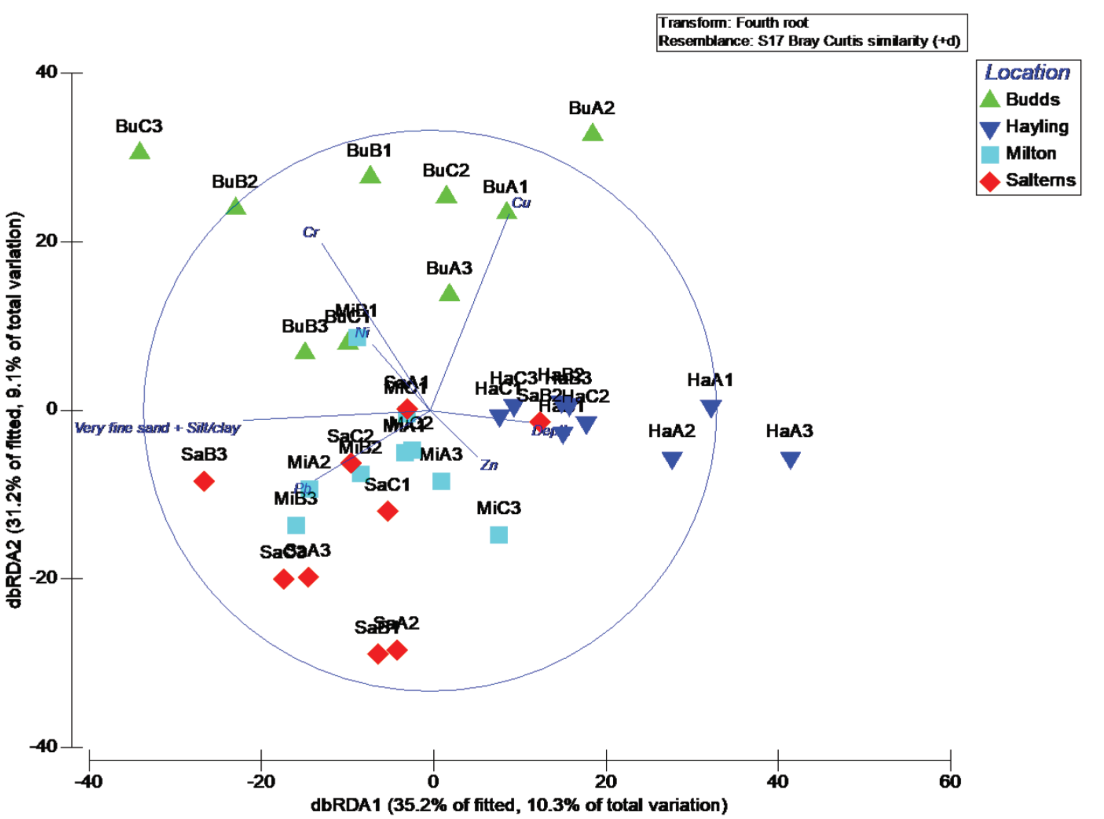
Results of Marginal Test from the Distance Based Linear Modelling (DISTLM) Indicating the Significance of Correlations between the Infaunal Structure and Each of the Environmental Data in Langstone Harbour

Environmental variables	Pseudo-F values	p-values
Depth	1.813	**0.046**
very fine sand + silt/clay	2.346	**0.007**
Cr	2.396	**0.007**
Cu	1.956	**0.033**
Ni	2.038	**0.025**
Pb	2.06	**0.021**
Zn	1.676	0.075

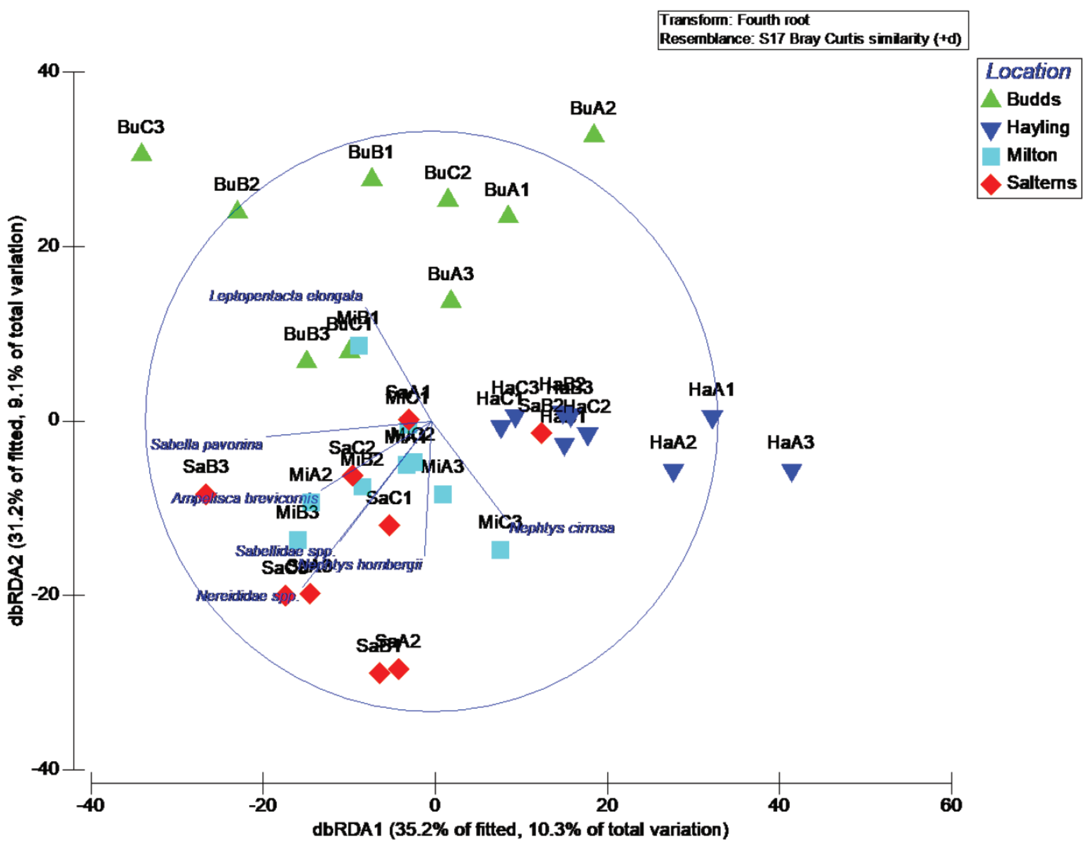
Note. Bold values indicate the significant differences, = p < 0.05, Cr=Chromium, Cu=Copper, Ni=Nickel, Pb=Lead, Zn=Zinc.

The individual impacts of fine sediment particles ($p = 0.007$) and Cr metal ($p = 0.007$) on the infaunal structure had stronger evidences comparing to other metals and depth. Considering the sequential tests, the best model of environmental variables explained the 29.4% of the spatial variation ($R^2 = 0.294$) in infaunal community of the harbour. The dbRDA plot (Figure 6a) with environmental vectors showed the particular contribution of Cr and Cu metals and depth on this model. The contamination of Budds sediment by Cr and Cu metals may affect the changes in infaunal assemblages of this station, however, with a great within-variation of community. The model also clearly showed the possible impact of depth on the infaunal separation of A site of Hayling station whereas the increase in the proportion of very fine sediment particles along with a decreasing water depth played a role in infaunal differentiation towards Budds and Salterns.

The model presented by dbRDA ordination plot (Figure 6b) showed the prominent presence of certain species in infaunal variations explained by abiotic factors. This model was greatly supported by the pattern in CAP ordination plot (Figure 5) which showed the main contributor species to dissimilarities among stations. In this model (Figure 6b), an echinoderm species, *Leptopentacta elongata* appeared in Budds station which had the highest sediment contamination by heavy metals and also the sediments with a higher proportion of very fine sand and mud in decreasing water depth. *Nephtys cirrosa* and *Nephtys hombergii*, polychaeta worms, occurred in sediments with the lowest heavy metals in deeper waters of Hayling and in moderate contaminated muddy sediments of Salterns. Polychaeta tube worms from Sabellidae family, particularly observed in Saltern and Budds stations having infaunal variations best explained by very fine particle proportion and higher metal enrichment. The model also indicated the particular occurring of ragworms from Nereididae, another polychaeta family, in muddy and relatively contaminated sediments of Salterns. All these observed prominent species of infaunal variations in the model might disclose the relative toleration of observed polychaeta worms and echinoderms for more contaminated sediments having more muddy characteristics within the harbour.



(a)



(b)

Figure 6. The dbRDA (distance-based redundancy analysis) ordination plots illustrating the correlation among the environmental variables which best explain the variation (Axis 1 = 10.3%, Axis 2 = 9.1%) in infaunal assemblages between the sites from the stations in Langstone Harbour. The first plot (a) includes the vector overlays showing the predictor variables that explain the variation. The vector overlays of second plot (b) visualize the prominent species occurring in the infaunal assemblage model under the influence of environmental variables (The adjusted Pearson's correlations for the analyses, r > 0.3 and r > 0.4, respectively).

Through the further DISTLM analysis (step-wise procedure), the model suggested that the prominent impact on the infaunal pattern of this tidal basin- among from other abiotic factors of the study- is Cr contamination (P = 0.042) of the sediments. Cr metal provided this impact with the contribution of 6.6% (Figure 7) to total variation among infaunal samples in this estuarine system. The model explaining the 29.4 % of infaunal variation between the stations based on the effects of abiotic factors, however, also particularly related to the depth (p = 0.046) and then to the proportion of very fine particles (p = 0.007) in sediments which explained the spatial infaunal variation of 5.1% and 4.2%, respectively. The metals except for Zn also had a significant impact on variation according to marginal test results (Table 6). The reason for this was that the contribution of Cr (6.6%) to the total of variation was not a value which could explain greatly the variation in community structure by surpassing the impacts of other predictor variables substantially.

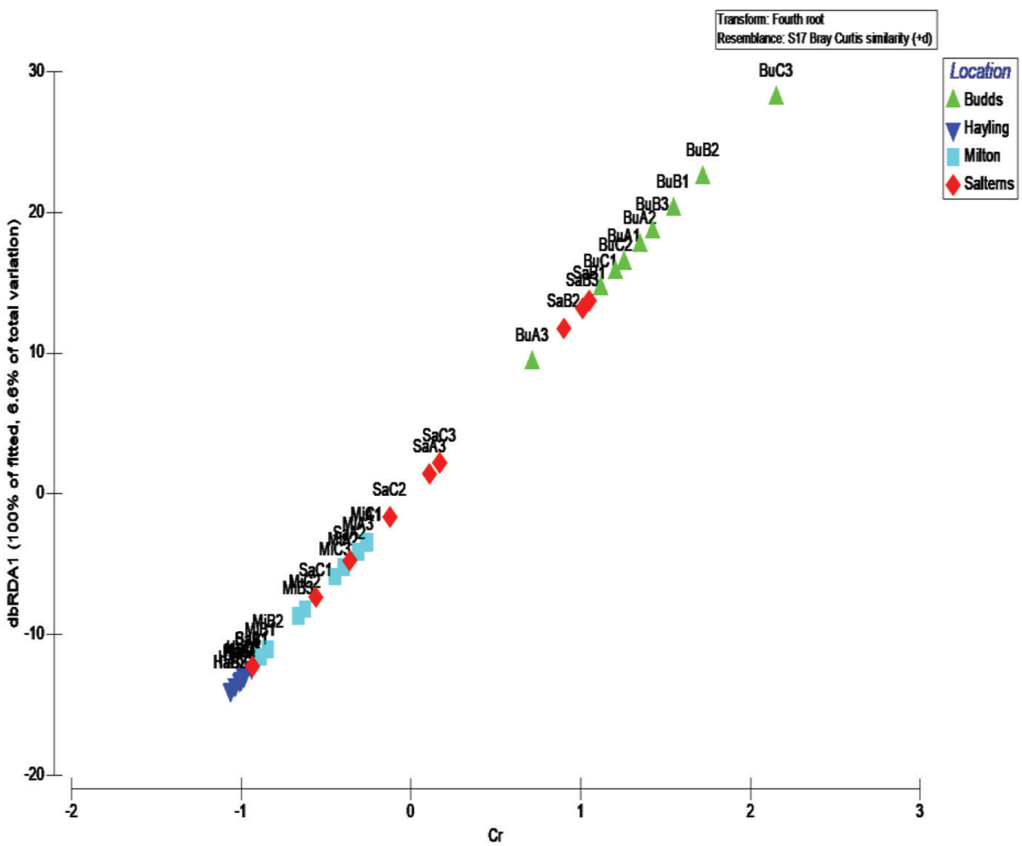


Figure 7. The dbRDA ordination plot of illustrating the contribution of the single variable Cr to the infaunal variations of 6.6% among the assemblage samples from Budds, Hayling, Milton and Salterns stations in Langstone Harbour.

Cr contamination seems taking its impact mostly on the infaunal assemblages of Budds and B site of Salterns within the harbour (Figure 7) which complies with their relative high concentrations which may due to the proximity to the wastewater discharge point. According to this model, echinoderm *Leptopentacta elongata* was the main species causing an infaunal variation in this area which explained mostly by Cr metal.

Discussion and Conclusion

In general, the composition of infaunal communities tends to remain steady by preserving their structure in undisturbed and stabilized sediment conditions (Chen & Orlob, 1972; Ritz et al., 1989). The communities of infauna may have small changes resulting from the acceptable natural variability of abiotic factors under natural conditions (Woodin, 1978; ANZECC & ARMCANZ, 2000). The present study has evidence of clear spatial differences in infaunal community structure between different stations (Table 6), which may be due to differences in metal contamination in the subtidal sediments of the harbour. As explained by Pearson and Rosenberg (1978), the reason of variation in benthic communities within a marine area is the abnormal variability of abiotic factors based on pollution loading in different sites. The present study found important variation in sediment concentrations of metals from the samples across the harbour.

The relatively by far higher concentrations of all metals analysed in the present study at near the inner eastern shore of the harbour could be arising due to Budd's Farm WWTP. The near location to this treatment plant which experiences unavoidable stormwater discharges in severe rainfalls (Southern Water, 2011) likely to cause heavy metal input to the estuary system by causing overloaded and hence overflowing local sewage works (Wittmann, 1981). The groundwater input of Bedhampton and Havant Springs with excessive chemical contaminants and the enter of rivers Hermitage and Lavant to the north east of the harbour (EA, 2016) could be attributed to comparatively higher metal load measured in north-eastern part of the harbour. Besides, lower hydrodynamics of water in inner parts of the tidal basin based on less tidal flushing is also known as a primary reason of increasing contamination of sediments (Förstner & Salomons, 1980; Knott et al., 2009).

Multivariate analyses showed an important differentiation of inner and outer basin in abiotic factors of the study (Table 5) which may also reveal the impact of station positions on the distribution of metal contaminants and grain sizes in the sediments of estuarine systems. The distinct within-station variation of site B in Salterns (Figure 2), the innermost site with greater metal content, seem supporting the estuary position effect on concentrations of pollution. The observed tendency for inner regions of estuaries to accumulate higher contaminations of heavy metals has been observed previously by Nguyen et al. (2019). Furthermore, the results of analyses in the present study demonstrated the higher potential of very fine particles to accumulate the heavy metals (Figure 3) which is parallel with the suggested results by Förstner and Salomons (1980), Groot et al. (1982) and Labianca et al. (2018). For the inner sampling locations, towards to the Budds, to the vicinity of the WWTP, metal and mud content of the sediment increase, and the within-group variability of environmental factors decrease (Figure 3). In several observational ecological surveys conducted to determine the environmental impact on biota, the models clearly indicate the more impacted areas explains a greater variation in represented biological assemblages (Warwick & Clarke, 1993). The generated model of this study coincides with this by demonstrating greater variations in inner stations Budds and Salterns which are the more impacted areas of the harbour (Figure 6a).

Although the distinct grouping of environmental factors in the eastern inner side of the harbour due to fairly higher metal load induced by increased very fine granulation of sediments, multivariate analyses showed a non-significant variation in infaunal community structure in this area. This result is contrary to expectations based upon the statement by Pearson and Rosenberg (1978) which indicate the importance of spatial variability of pollution loads on the benthic community variation within a marine environment. Besides, the absence of a clear separation between the species assemblages of northern and southern stations may disproof the position effect on the distribution of infaunal species. The inconsistency between the infaunal and environmental pattern in Langstone Harbour suggests that the metal contamination present in the harbour are not an underlying explanatory factor for the observed spatial variations in infaunal communities. Contrary to Budds, other stations with different pollution load -changing between moderate and low- and granulation in sediments differ significantly from each other with their benthic infaunal communities (Table 5). But still, the generated model which determine whether any impacts of these abiotic factors on the biotic pattern does not provide a convincing explanation for these spatial dissimilarities. Further multivariate analyses show the important individual impacts of all each abiotic factor except for Zn on infaunal pattern (Table 6). However, when all biota and abiotic factors are presumed as an interdependent whole to consider also their interrelationships which comply with the aim of the present study, the indicated best individual explanatory factor for spatial infaunal variations by the model is chromium metal (Figure 7) with its contribution of 6.6%. According to the model (Figure 6a), all abiotic factors within the research even together explain 29% of the variation in infaunal distribution and there is not any particular striking contribution by a single abiotic factor within this total explainable variation. These results may signify the presence of a different stressor or stressors in the harbour which accounts for the changes in infaunal community structures of Salterns, Milton and Hayling stations.

The absence of distributional responses of infauna to heavy metal contents of sediments across the harbour likely to be related with the concentrations which are detected below the Effect-Range Low (ERL). This specified effect (Long et al., 1995) corresponds to rarely observed biological disturbance to sediment-dwelling organisms which possibly have no necessity to be tolerated by the species with high tolerance to heavy metal pollution. Thus, the existing concentrations of heavy metals (Table 2) in this tidal basin seem to have negligible effects on the spatial differences of infaunal community structure, despite the presence of some concentrations of Cu, Ni and Zn exceeding the low effect threshold level (ERL) in samples from innermost sites in the estuary.

The extremely low and approximate diversity and richness of infaunal species in Budds and Hayling, which is the most dissimilar station pair in terms of contamination levels and other abiotic factors of the study, may also support the assumption about the presence of a different key stressor or stressors. The vicinity to WWTP may partly explain the low species diversity and richness for the surrounding marine area involving Budds station due to storm discharge-related possible pressures on the natural condition of the area. During the sampling from the present coarser substrates in Budds station sometimes resulted in the sample losses and collection of inconsistent sediment volumes due to large gravel particles that cause a half-open bucket of grab. This loss likely to affect the accuracy of the sampling process of benthic infaunal organisms, and hence the analysis results by possibly leading to collect less organisms that represent their site. For Hayling, however, it might be hard to explain based on the position of the station towards the mouth of the harbour which has good flushing conditions. The advantageous estuary position with its higher hydrodynamic in this area likely to prevent the deposition of substances causing contamination in compliance the results of this study regarding metals which considers the sediments of Hayling as the comparatively healthiest across the harbour. The heterogeneous sediments with the mixture of particles often host more species comparing with homogeneous due to having more ecological niches (Gray, 1974). Therefore, homogeneous sediment structure of Hayling consisting of only sand classes of particles could be a physical stressor for the diversity and richness of infauna for this area.

The toxicants in marine systems could directly affect the abundances of organisms by increasing the mortality or supressing the fecundity of sensitive species (Fleeger et al., 2003). Most sensitive conservative infaunal species are the first organisms fail to resist the pressure of contaminated marine sites (Ritz et al., 1989; Persaud et al., 1993). Their disappearance results in community decline and consequently the least sensitive organisms which utilize these conditions get a chance to predominate (Pearson & Rosenberg, 1978; Woodin, 1978; Warwick, 1988; Weisberg et al. 1997). Using the groupings proposed by Borja et al. (2000), there is no observation across the stations regarding a dominance of an infaunal organism known as characteristic opportunistic species of estuary systems in disturbed conditions. This could indicate the relative balanced condition in this tidal basin, thus, observed significant dissimilarities between the stations more likely to result from the natural, physical or biological stressors rather than a pollution-induced stress.

The presence or absence of infaunal species in an area depends on various natural, biological, physical and chemical environmental processes such as their competition, habitat type and dissolved oxygen level rather than just the contamination level of the sediment or water system (Persaud et al., 1993). For instance, the water depth and sediment granulometry greatly affect the benthic community structure spatially based on species (Warwick, 1988). Besides, depth also affects the distribution of grain size in sediments (Gogina et al., 2010). Environmental pattern of this study shows the homogeneous sandy sediment presence towards the mouth of the basin whereas the shallower inner stations comprised of heterogeneous very finer sediments with gravels. However, the explained spatial variability in infaunal community structure (Figure 6a) by depth is only 5.1% which is likely due to relatively small variation of depth in the study area (0.8 - 6.6 m). The model indicates that the contribution of depth more likely to affect the *Nephtys cirrosa* occurrence in homogeneous clearer sediments of Hayling.

According to structured model (Figure 6b), the predominance and specific occurrence of echinoderm *Leptopentacta elongata* in the outermost site of Budds station may indicate its success to tolerate the possible chromium-related stress despite its low impact on infaunal structuring. *L. elongata* lives buried in mud or muddy sand sediments (Picton & Morrow, 2016). The measured highest proportion of very fine particles (mean proportion: 47%) in this site support the relative preference of this burrowing species for very fine-grained sediments in keeping with the literature. Additionally, the grouping of *L. elongata* in particularly the outermost site of the area with no observation of the strong mephitis likely to be compatible with the habitat preference of this species as Larsen (1997) states the Echinoderms are generally sensitive the hypoxic water conditions and H_2S-related disturbance. The particular occurrence of the tubeworms *Sabella pavonina* in higher contaminated muddy sediments of Salterns and Budds may indicate the success of these organisms in the face of possible metal-related stress. The sediments of soft-bottom habitats could serve as a refuge for macroinfaunal organisms by enabling them to penetrate into the sediment layers below the maximum penetrating depth of the disturbant (Woodin, 1978). The organisms with tube building ability, therefore, could have the advantage to survive by becoming distant to contaminated part of the sediments (Woodin, 1978). *Ampelisca brevicornis*, an amphipod species sensitive to contaminants in estuary systems (Podlesińska & Dąbrowska, 2019), could indicate the relatively metal-related good condition of the harbour once more, by characterising Salterns and Milton stations having different contamination levels.

The contribution by multiple species to community pattern along with increasing infaunal diversity and richness gradients towards the western coast of the harbour (Figure 6b) may demonstrate the relative healthier ecological status of this side in the harbour. A disturbance that is not frequent or severe could increase the diversity due to competing species for the resources present in that marine environment (Huston, 1979) and thus, this competitive environment precludes the dominance of any single species (Ritz et al., 1989). The particular occurrence of invasive species *Crepidula fornicata*, *Corella eumyota* and native *Carcinus maenas* in high numbers at western part, moderately contaminated stations Salterns and Milton, may denote the present competitive environment in these stations. Besides the toleration to environmental stress, predation and interspecific competition are the other major determinants of the distributions of infaunal macroinvertebrates (Ryu et al., 2011). Non-native species common slipper shell, *C. fornicata,* and the orange-tipped sea squirt, *C. eumyota,* could affect these predation and competition paths by creating biological stress on infaunal communities represent these stations. American slipper limpet, *C. fornicata,* is reported in high-risk priority species lists based on its impacts on predation and trophic competition whereas there is no risk assessment concerning *C. eumyota* (Stebbing et al., 2015). The occurrence of this mollusc species in also other stations, alongside high abundances in westerns stations, differently from their reported detection in only the west side of the harbour in 2015 (Thomas et al., 2016) could be a critical signal of their over and continuing invasion. This invasion may have structuring power on spatial infaunal distribution in the harbour.

The observed polychaeta density of 57.1% across the harbour and the grain size analysis from the subtidal samples shows the fine sand dominance hosting mostly polychaeta species. They are in general the most abundant group of benthic communities and frequently used to assess the effects of stressors present in sediments and water columns on the benthic ecosystem (Dean, 2008; Pini et al., 2015). Saiz-Salinas and González-Oreja (2000) found that chemical contamination of sediments triggers the growth of polychaeta group within. Polychaetas exist with a great variety of species in estuaries and human-made harbours (Fauchald & Jumars, 1979). The occurring proportion of 57.1% in among the infaunal groups of the harbour seems reasonable considering their general abundance in benthic infaunal communities. The absence of oligochaetes and the near absence (SaA1- two individuals) of polychaeta capitellids which are known as the pollutant tolerant annelid groups (Pearson & Rosenberg, 1978) may also indicate the relative health of the harbour regarding metal contamination.

The dominance of interface feeders with the ability to switch the feeding modes seems to be adapted the environmental conditions of inner stations with more contaminated heterogeneous sediments and likely to prevent the possible competition between the deposit and filter feeder organisms in this area. Coarser-grained sediments are mostly preferred by infaunal suspension-feeders (Gray, 1974), whereas the deposit feeders dominate the finer-grained sediments with silt-clay particles (Rhoads & Young, 1970). The heterogeneous sediment structure of the inner stations Budds and Salterns could provide these two different niches for both two feeding modes. The study by Knott et al. (2009) shows the substantial decrease in numbers of filter feeder species stemming from the disturbance of contaminated sediments through the dredging, storms and tides in an estuary. The authors correlate this result with larvae mortalities due to possible back release of the toxicants into the water column. In this study, there is no observation regarding a substantial decrease of filter feeders in specified inner stations.

The present study demonstrates that heavy metal contamination in areas of the Langstone Harbour seems to have no potential to result in biological detrimental effects in local infaunal benthic organisms of the harbour. However, the behaviour of heavy metals- mobility, bioavailability and toxicity- are essential to evaluate the environmental impacts of the metal-polluted sediments and to focus on only measuring the total metal concentrations is inadequate for an environmental impact assessment (Usero et al., 1998; ANZECC & ARMCANZ, 2000; Statham, 2000) which likely to obtain solely superficial impact assessments of heavy metals on infaunal community structure in this harbour. Nevertheless, Hseu et al. (2002) state that the total concentration analysis of heavy metals in sediments could be used to assess the overall degree of contamination in a specified marine environment. This study could be extended with heavy metal analysis of the pore water to assess better the effects of these toxicants on infaunal distributions. The pore water is a crucial exposure route for infaunal species and an option to eliminate the grain size differences of the samples (Chapman et al., 2002). Warwick (1988) reports that analysing higher taxonomic groups rather than the species level in multivariate analyses provide clarity in the results to evaluate the pollution impact on fauna. Further studies, therefore, may design to analyse the distributional responses of major infaunal groups.

In reply to the hypothetical scenarios: (1) The specified stations in the harbour significantly differed in infaunal compositions and were characterised by certain species, however, could not be explained by the observed gradient of heavy metal pollution in the sediments. The multivariate models indicated the presence of other structuring pressures for these communities in these stations that were not addressed in the scope of this study, and (2) The estuary positions and grain size greatly affected the heavy metal accumulation. There was a pattern of increasing metal deposition in direct proportion to very fine and silt/clay particle percentages towards the shallower inner parts of the harbour. Because the model did not explain an important structuring impact of heavy metals or other factors on infaunal variation, to evaluate the indirect and direct effects of estuary position and the sediment grain size on distributions of infauna is unsuitable and redundant.

An attempt is made here to define and analyse the environmental conditions and biological infaunal patterns of the Langstone Harbour in company with the principles of benthic ecology in estuaries for better understanding of transitional estuarine behaviours.

The data obtained by predictive model-based studies similar to presented here could improve the predictability of environmental impact monitoring programs in transitional estuarine environments. Heavy metal contamination is a particular threat for these marine areas due to surrounding anthropogenic activities as the sediments could remain contaminated by accumulated heavy metals for years. The recovery of a marine environment with its complex nature could be the most compelling environmental process. Therefore, the biological monitoring of the estuaries periodically to assess the impacts of heavy metals on the estuarine health is crucial for the conservation of these fragile marine environments before the occurrence of undesirable effects.

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Extended Turkish Abstract
(Genişletilmiş Türkçe Özet)

Langstone Limanı (Birleşik Krallık) İçfaunal Komünitesinin Ağır Metal Değişimlerine Tepkileri

Haliçler, etraflarını çevreleyen yerleşim alanları ve endüstriyel alanlardan kaynaklı çeşitli kontaminantlara yoğun ölçüde maruz kalan oldukça kompleks ve dinamik ekosistemlerdir. Atık suların yoğun olarak karıştığı bu ortamlar, insan kaynaklı kirleticiler için nihai depolama yeri olarak görev gördüğünden, diğer denizel ortamların arasında yönetim önceliği bakımından kritik öneme sahiptir. Bu kıyısal deniz ortamlarının başlıca kirlilik kaynağı evsel ve endüstriyel atıksu deşarjlarının taşıdığı çeşitli kirletici girişleridir. Çalışmanın kapsamında yer alan kirletici, denizel çevrelerde biyolojik çeşitlilik için ana tehditlerden biri olan ağır metallerdir. Doğada doğal olarak belirli miktarlarda bulunan ve deniz organizmaları tarafından zorunlu olarak belirli oranda düşük miktarına ihtiyaç duyulan bu maddeler, kıyılarda çoğalan insan aktivitelerine bağlı olarak artan konsantrasyonları, deniz ekosistemlerinin biyolojik dengesi üzerinde büyük baskı oluşturmaktadır.

Görece uzun yaşam süresiyle kumun içerisinde kısıtlı hareket kabiliyeti veya hareketsiz şekilde yaşam sürdüren bentik içfaunal organizmalar, değiştirilmiş ve bozulmuş çevresel koşullara verdikleri tepkilerin güvenilirliği ve kuvveti ile diğer izlenebilir biyolojik gruplar arasında öne çıkmaktadırlar. Sedimanlar, su sistemlerine giren ağır metaller için lavabo görevi görürler. İçfaunal canlılar sediman ile beslenme ve yaşam alanları olması dolayısıyla sürekli etkileşim halindedir ve bu etkileşim komünite yapılarını etkilemesi için büyük bir gerekçedir. Yarı kapalı forma ve açık deniz sistemlerine kıyasla düşük tür çeşitliliğine sahip olan haliç sistemleri, makrobentik biota ve çevresel faktörler arasındaki olası interaksiyonları incelemek için uygun su kütleleri olarak değerlendirilebilir. Langstone Limanı'nda gerşekleştirilen mevcut çalışmada, stres etkenine maruz kalma karşısında oluşan infaunal tepkiler, topluluk yapılarındaki alansal değişimler baz alınarak araştırılmıştır. Geçişsel denizel çevrelerde daha gelişmiş bir anlaşılma için, çeşitli abiyotik faktörlerin etkisi altındaki yapısal bentik komünite farklılıklarına dayanarak, çok değişkenli istatistiksel analiz teknikler kullanılarak muhtemel yaklaşımlar gerçekleştirmek amaçlanmıştır.

Çalışmanın hedefleri: (1) Limanın yüzey sedimanlarındaki ağır metal yüklerindeki alansal varyasyonlara ilişkin makroiçfaunal türler paternini gözlemlemek; (2) İstasyon pozisyonu ve sediman tanecik büyüklüklerinin limandaki ağır metal konsantrasyon derecelenmeleri ve dolayısı ile makroiçfaunal komünite dağılımı üzerindeki muhtemel etkilerini değerlendirmektir. Çalışma, kıyı geçiş ekosistemlerindeki sediman içerisinde ikamet eden hassas bentik organizmaların dağılımını etkileyen faktörlerin daha iyi anlaşılması için belirlenen hedefler doğrultusunda iki hipotetik senaryo ile desteklenmektedir: (1) İstasyonlar arası farklı seviyelerde metal kontaminasyonlarına sahip sedimanlar, fizyolojik ve fonksiyonel toleranslarına bağlı olarak belirli içfaunal türler tarafından karakterize edilerek belirtilen istasyonlarda farklı içfaunal kompozisyonlara neden olabilir. (2) Alansal pozisyon ve sedimanın çok ince boyutlu partikül oranı çevresel değişkenleri, haliç ortamında istasyonlar arasındaki bentik makroiçfauna komünite varyasyonlarına, komünite yapılarını doğrudan etkileyerek ve de sediman metallerinin dağılımına etki ederek dolaylı bir şekilde katkıda bulunabilir.

Çalışmada, İngiltere'nin güney kıyısında İngiliz Kanalı'nda yer alan Langstone Limanı'nda, kirlilik girişi farklılıklarının gerçekleştiği düşünülen 4 farklı gelgit altı istasyonda, toplam 36 noktada örnekleme yapılmıştır. Bu noktalarda sırasıyla; Van Veen grab örnekleyicisi ile içfauna (>0.5 mm); Cr,

Cu, Ni, Pb ve Zn metallerinin toplam sediman konsantrasyonlarını izleme ve tanecik fraksiyon analizi için yüzeysel sediman toplanımı gerçekleştirilmiştir. Analiz proseslerinden sonra elde edilen veri seti, Primer versiyon 6 ve PERMANOVA istatistiksel yazılım paketleri kullanılarak, çok değişkenli analizler aracılığıyla incelenmiştir. Biyota ve tüm abiyotik verilerin ilişki desenleri çıkarılmış, ilişkili abiyotik verilere bağlı içfaunal komünite varyasyon oranları modellenmiş ve açıklanmıştır. Çalışma sonuçlarının daha iyi yorumlanabilmesi için belirli komunite karakteristikleri olan tür çeşitliliği ve zenginliği, ana içfaunal grup oranları, beslenme tiplerine göre sınıflandırma gibi tek değişkenli ölçümler istasyonlara uygulanmış, ilişkili olabilecek fırsatçı ve/veya istilacı yumuşak dip bentik omurgasız tür verileri de incelenmiştir.

Örneklenen makroiçfauna, Poliketler tarafından domine edilen toplam 48 takson içermiştir. İstasyonlar arasında ve bazen de istasyon içi ayırtedici varyasyonlar ve bu varyasyonlara en çok katkısı olan türler belirlenmiştir. Ekinoderm türü Leptopentacta elongata, Poliket türleri ve aileleri Nephtys cirrosa, Nephtys hombergii, Sabellidae ve Nereididae, çalışmadaki abiyotik faktörler tarafından en iyi açıklanan taksonlardır. Bazen düşük etki eşik değerini de aşan ve çalışma boyunca ölçülen en yüksek sediman ağır metal konsantrasyonlarına sahip olan havzanın kuzeydoğu iç bölge sedimanları, bölge yakınında yer alan atıksu arıtma tesisinin, halicin metal kirliliğine katkısının muhtemel işaretidir. Modelleme sonuçlarında, çalışmanın kapsamındaki abiyotik faktörler ve interaksiyonlarının, bentik içfaunal komünite yapısını %29.4 oranda açıkladığı, ve bu açıklamaya en büyük katkı yapan çevresel faktörün %6.6'lık oranı ile krom metali olduğu belirlenmiştir.

Elde edilen bulgulara dayanılarak çalışmanın hipotetik senaryolarına cevaben: (1) Limanın belirtilen istasyonları, içfaunal kompozisyonlarında anlamlı farklılıklar göstermiş ve belirli türler tarafından ifade edilmiş, fakat bu farklılıklar limanın gözlenen sediman ağır metal kontaminasyon değişimleri tarafından açıklanamamıştır. Analizlerde yapılandırılan modeller, limandaki içfaunal komüniteleri yapılandıran ve bu çalışmanın kapsamında işaret edilmeyen farklı çevresel baskıların muhtemel kontrolünü işaret etmektedir; ve (2) Haliç içi pozisyonlar ve sediman tanecik boyutları ağır metal birikimini önemli derecede etkilemiştir. Çok ince kum ve silt-kil partiküllerinin gelgit havzasının durgun sulara sahip sığlaşan iç alanlarına gidildikçe çamurlu kum karakterinde artışıyla birlikte yükselen sediman ağır metal birikimi, karakterize çevresel patern olarak dikkat çekmektedir. Modelin, ağır metallerin limandaki infaunal varyasyon üzerinde önemli bir yapılandırıcı etkisi olduğunu açıklayamaması nedeniyle, haliç içi pozisyonlar ve sediman tanecik granülometrisinin infaunal dağılım üzeri dolaylı ve doğrudan etkilerini değerlendirmek uygun olmayacaktır.

Çalışmada sunulan paternler, Langstone Limanı içfaunal komünitesinin olası stres değişimlerini anlayabilmek için gerçekleştirilebilecek gelecek çalışmalara temel oluşturarak katkıda bulunabilir. Limitli sayıda girişimden dolayı, belirli abiyotik ve biyotik faktörler arası ilişkiler bu gelgit havzası sedimanları için literatürde henüz açıklığa kavuşturulamamıştır. Burada sunulana benzer kestirimci model bazlı çalışmalardan elde edilen verilerin, kıyı denizel ortamlarında gerçekleştirilen çevresel etki izleme programlarında öngörülebilirliği geliştirebileceği düşünülmektedir.