

Chapter 5

Sediment Quality

5.1. Introduction

Particulate material that lies below the sea surface, such as shell hash, gravel, sand, mud and organic detritus, is collectively referred to as sediment. Sediment is an important component of marine ecosystems as it provides essential habitat for many bottom-dwelling organisms. In other words some organisms can only live in or on sediment, and often only in or on sediment of a relatively specific composition (*e.g.* sand or mud).

Sediment is an important fate for many contaminants introduced into marine ecosystems. This is because the contaminants have a low solubility and/or are particle reactive, and once introduced into marine waters rapidly adsorb onto suspended sediment and particulate organic matter and are in this manner ‘scavenged’ from the water column by flocculation, coagulation and/or sedimentation (De Groot *et al.* 1976, Förstner and Wittman 1979, Olsen *et al.* 1982, Huh *et al.* 1992, Honeyman and Santschi 1988, Mwanuzi and De Smedt 1999, Hatje *et al.* 2003, Moon *et al.* 2008). Consequently, the concentration of these contaminants in sediment usually exceeds their concentration in the overlying water column by several orders of magnitude (Horowitz, 1991; Daskalakis and O’Connor, 1995). In low energy environments such as estuaries and sheltered bays, where currents and other forms of turbulence are too weak to redistribute sediment, contaminants can accumulate in the sediment to such high concentrations they adversely affect sediment-dwelling organisms directly through toxic effects and indirectly by altering community and food web structure (Chapman, 1989).

It is for these reasons the measurement of contaminant concentrations in sediment constitutes an important component of outfall monitoring programmes in many parts of the world. The accumulation of contaminants in sediment near marine outfalls depends on several factors, including the proportion of fine-grained material

(especially mud) on the seabed (because many contaminants preferentially attach to mud), the concentrations and types of contaminants in the effluent (their properties affect their fate), and the deposition and accumulation on the seabed of contaminated particulate organic matter in the effluent.

This chapter discusses findings of the physical and chemical analysis of sediment collected in the Green Point, Camps Bay and Hout Bay areas in 2015/2016. The results are compared to findings of previous studies in these areas, where possible.

5.2. Materials and Methods

5.2.1. Fieldwork

The CSIR (2003) analysed sediment collected at 97 sites in the Table Bay, Camps Bay and Hout Bay areas for particulate organic carbon and nitrogen, stable isotopes of carbon and nitrogen, and concentrations of a suite of metals. Based on the findings the CSIR (2003) concluded there was no evidence for the excessive accumulation of effluent-derived particulate organic matter and metals in the sediment, and where there was evidence of metal contamination this was unlikely to pose a toxic risk to sediment-dwelling organisms. The CSIR (2003) recommended that future sediment quality measurements for the Cape Town outfalls monitoring programme be restricted to sediment collected at three sites in Table Bay and two sites in Hout Bay at six month intervals, these sites representing areas where it was considered there was a high possibility for effluent-derived contaminants to accumulate in the sediment. This approach was followed in surveys performed in 2005/2006 (CSIR, 2006) and 2011 (CSIR, 2011) for the Cape Town outfalls monitoring programme. Although there is logic in the recommendation for a pared down sediment sampling effort, a decision was made to expand the scope of sediment monitoring for the 2015/2016 survey compared to 2005/2006 and 2011 surveys based on public



Figure 5.1. Aerial view of the Table Bay area, showing the positions where sediment was collected for physical and chemical analysis for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The Green Point outfall is denoted by the red line.

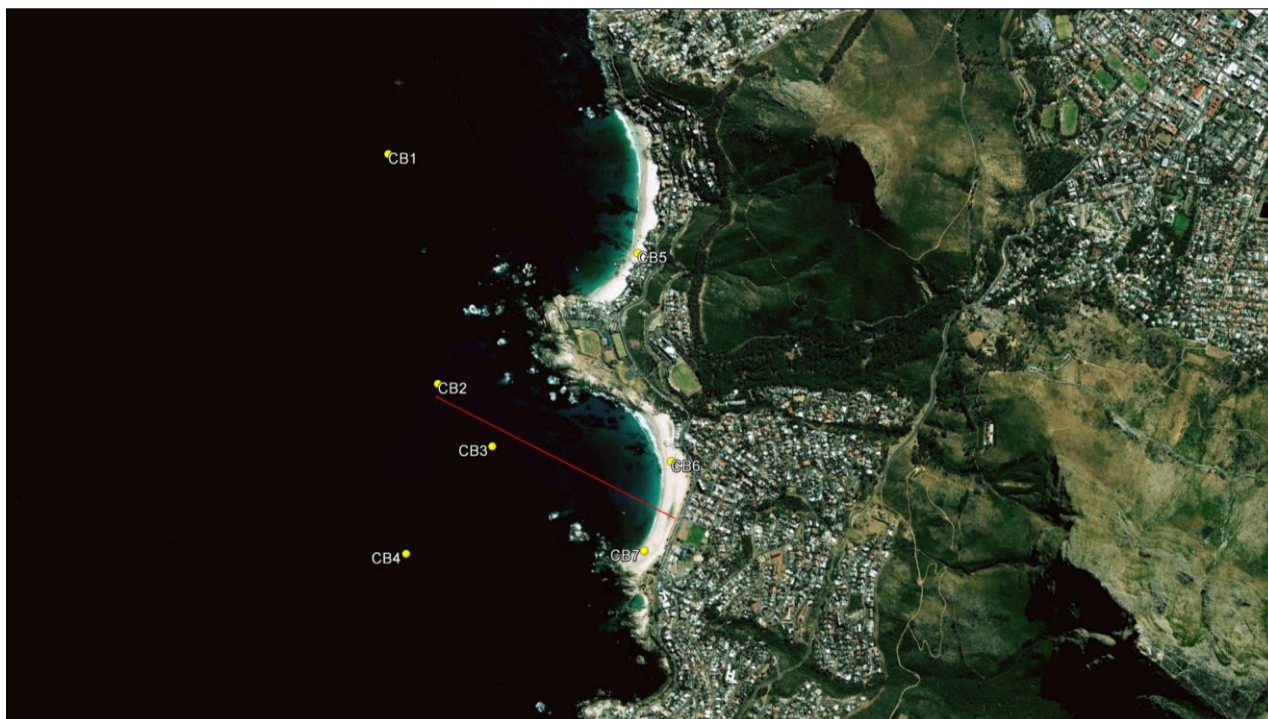


Figure 5.2. Aerial view of the Camps Bay area, showing the positions where sediment was collected for physical and chemical analysis for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The Camps Bay outfall is denoted by the red line.

concern following the publication of images in the printed and electronic (including social) media of effluent reaching the sea surface near the Green Point, Camps Bay and Hout Bay outfalls. The intent was to collect sediment at 67 of the sites sampled in 2003, these sites identified on the basis of the

contribution of mud to the bulk weight of sediment and their spatial representation in terms of potential near- and farfield depositional zones for effluent constituents. The CSIR (2003) could not collect sediment at a large proportion of the sites during the 2003 survey, using the conventional



Figure 5.3. Aerial view of the Hout Bay area, showing the positions where sediment was collected for physical and chemical analysis for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The last part of the Hout Bay outfall is denoted by the red line.

approach of a grab sampler due to the presence of exposed bedrock (reef) on the seabed. Therefore, in areas where the grab was ineffective divers were employed to collect sediment (*e.g.* from small pockets of sediment in reef gullies). The intent of the 2015/2016 survey was to focus largely on sites where a grab sampler was more likely to be effective in collecting sediment, but to attempt to collect sediment in certain areas even if the likelihood of success was low. As expected from the 2003 survey (and indeed previous surveys; *e.g.* CSIR, 1985), the collection of sediment in the 2015/2016 survey using a grab sampler was challenging, particularly near the Green Point and Camps Bay outfalls but also in some areas near the Hout Bay outfall. An attempt was, therefore, made to collect sediment in key areas near the Green Point and Camps Bay outfalls using divers, but this confirmed there were only small pockets of sediment in reef gullies near the outfalls. Commercial divers were employed to collect sediment at some deepwater sites where sediment could not be collected using a grab, but this also proved unsuccessful or challenging at most sites. As a result sediment was collected at 40 of the 67 sites identified in the offshore environment (Figures 5.1 and 5.2). Although the sediment collected at these

sites does not provide the most comprehensive understanding of the physical and chemical characteristics of sediment or the seabed across the Table Bay and Camps Bay areas and to a lesser degree the Hout Bay area, the sites are situated in near- and farfield areas considered suitably representative of areas where effluent-derived material would conceivably accumulate in sediment in the receiving environment. The sediment collected offshore was supplemented by sediment collected at two sites in the sandy intertidal in the Green Point and Sea Point area (Sites TB27 and TB28), at three sites in the sandy intertidal in the Clifton and Camps Bay area (Sites CB5, CB6 and CB7), at two sites in sandy intertidal in Hout Bay (Sites HB13 and HB14), at a site in the Disa (Hout Bay) River (Site HB15), and at two sites in Hout Bay Harbour (Sites HB1 and HB2; Figures 5.1 and 5.2).

Where appropriate, sediment was collected using a van Veen grab that sampled a surface area of 0.1 m². The grab has hinged top screens that permit the removal of relatively undisturbed surface sediment from the grab. Following retrieval of the grab an inspection of the contents was made. Undisturbed and level sediment inside the grab was required for the grab to be accepted. If these

conditions were not met the contents were discarded and the grab was again deployed. For the successful grabs, any water overlaying the sediment was siphoned off. The sediment was then inspected for texture, colour, aroma and the presence of obviously anomalous matter. Approximately 150 cm³ of surface sediment was removed and homogenised in a stainless steel bowl using a high-density polyethylene scoop. Aliquots of sediment were then transferred to pre-cleaned high density polyethylene and amber glass containers and stored on ice until return to the laboratory, where the sediment was frozen (-4°C) until further processing and analysis. The grab and sediment processing equipment was rinsed with site water, scrubbed with a hard brush and sprayed with hexane before re-deployment.

Sediment collected by divers was scooped into sampling jars and then sealed underwater. Sediment from the sandy intertidal areas was also scooped into sampling jars and then sealed immediately. Sediment from the Disa River was collected using a small van Veen grab, deployed from a bridge. In all of these cases the sediment was processed and stored in the field in the same manner described for sub-surface sediment grab samples above. Sampling equipment was also cleaned following the same procedure discussed above.

5.2.2. Laboratory Analyses

5.2.2.1. Grain Size Composition

The grain size composition of sediment was determined by wet and dry sieving into seven grain size classes according to the Wentworth Scale, namely: mud (<0.063 mm), very fine-grained sand (0.063 - 0.125 mm), fine-grained sand (0.125 - 0.250 mm), medium-grained sand (0.25 - 0.50 mm), coarse-grained sand (0.5 - 1.0 mm), very coarse-grained sand (1.0 - 2.0 mm) and gravel (>2.0 mm).

5.2.2.2. Total Organic Content

Sediment samples were oven dried, weighed, and particulate organic debris degraded using hydrogen peroxide. The sediment was washed in distilled water, re-dried and re-weighed, and the difference in dry weight before and after degradation used to

determine the total organic content.

5.2.2.3. Metals

The sediment was first freeze dried and ball milled. Approximately 1 g of freeze dried sediment was weighed into a digestion vessel and digested in a mixture of HNO₃-HCl-H₂O₂ according to USEPA method 3050B. This is a 'near-total' digestion method that dissolves most elements that could become 'environmentally available' but is not designed to analyse for metals tightly incorporated in silicate structures. The digestate was filtered (0.45 µm), diluted to volume with Milli-Q water, and the concentrations of various major, minor and trace metals detected and quantified using Inductively Coupled Plasma Optical Emission (ICP-OES) and Mass Spectroscopy (ICP-MS). Mercury was analysed using a direct mercury analyser (DMA).

5.2.2.4. Organic Chemicals

The sediment was first freeze dried and ball-milled. The sediments were analysed for various phenolic compounds, total petroleum and recoverable hydrocarbons, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls. Organic chemicals were extracted from freeze dried sediment using methods based on those recommended by the United States Environmental Protection Agency. Extracts were subjected to a clean-up procedure to remove interfering substances if necessary, and concentrated. Analytes were identified using a Gas Chromatograph-Mass Spectrometer, Gas Chromatograph with Electron Capture Detector, or Gas Chromatograph-Inductively Coupled Plasma Mass Spectrometer. Quantification was relative to internal and external standards.

5.3. Results and Discussion

5.3.1. Grain Size Composition

An understanding of the grain size composition of sediment in marine environments that receive contaminants from effluent and other sources is important for several reasons. First, the grain size provides indirect information on the strength of currents and other forms of turbulence near the seabed. Sediment in areas where currents are strong and/or there is significant wave action, such as on beaches, is sandy (coarse-grained), while that

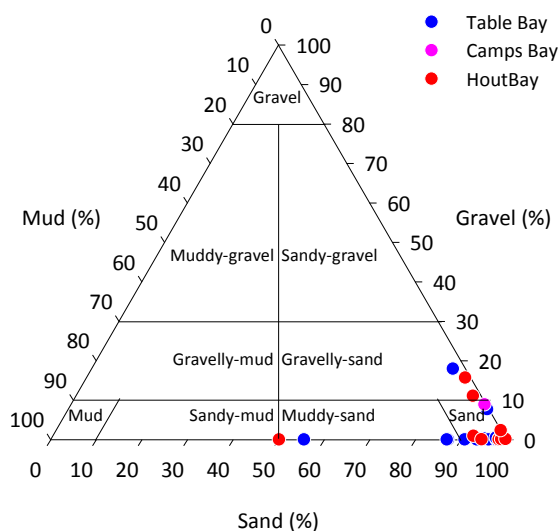


Figure 5.4. Ternary plot illustrating the contribution of gravel, sand and mud to the bulk weight of sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

in sheltered water bodies, such as estuaries, tends to have a higher mud (fine-grained) content. This has implications for understanding the potential dispersion, dilution and deposition of particulate matter (including contaminants adsorbed onto these particles) in effluent in a marine receiving environment. Second, the grain size provides important information for interpreting particulate organic matter and concentrations of particle reactive and hydrophobic contaminants in sediment. This is because particulate organic matter and mud, being of similar mass, compared with, for example, heavier sand particles, tend to accumulate in or be winnowed from sediment in the same areas depending on the prevailing current strength. The relationship between these variables can thus be used to identify sediment with an anomalously high or low total organic content (see below). Fine-grained sediment also sequesters more contaminants than coarse-grained sediment because of the greater surface area to volume ratio provided by the grains for contaminant adsorption. The surface of silt and clay (mud) grains is also electrically charged, rendering them more chemically reactive (Power and Chapman, 1995). Concentrations of particle-reactive and associated contaminants (such as metals) tend, therefore, to be highest in fine-grained sediment and lowest in coarse-grained sediment. Effluent discharge has also been shown to alter the grain size composition of sediment through the input of significant

amounts of fine-grained particulate matter (e.g. Read, 1989; Gray, 1997; Arvai *et al.*, 2002).

From a textural perspective the sediment collected at most sites in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme is classified as sand (Figure 5.2). Sand contributed $\geq 76.5\%$, and usually $>90\%$ of the bulk weight of sediment at all but three sites (Figure 5.3). At Sites HB1 and HB2 in Hout Bay Harbour the sediment is texturally classified as sandy-mud and muddy-sand, with mud contributing 50.3 and 49.9% of the bulk weight of the sediment respectively (note that the symbol for one of these sites is shielded by that for the other in Figure 5.4). At Site TB25, situated about 1 200 m to the south-southwest of the near the Green Point outfall terminus in Table Bay, the sediment is classified as muddy-sand, with mud contributing 44.4% of the bulk weight of the sediment.

Closer inspection of the data shows that while the sediment at most offshore sites was classified as sand or gravelly-sand there were fairly pronounced differences in the contribution of various grain size classes to the bulk weight of sediment between the marine receiving environments (Figure 5.5). The contribution of coarse material, that is, very coarse-grained sand, coarse-grained sand and medium-grained sand, to the bulk weight of sediment in the Hout Bay and particularly Camps Bay area was generally higher than in the Table Bay area. The contribution of fine-grained sand and very-fine grained sand was, in turn, generally higher in the Table Bay area. The sediment at all but one site in the Camps Bay area, including shoreline sites, was in fact dominated by coarse-grained sand (Figure 5.5). The exception was Site CB5 on the sandy shoreline at Clifton 4th Beach, where the sediment was dominated by medium-grained sand. The difference in the grain size composition of sediment between the receiving environments infers indirectly that currents in Table Bay area are weaker than in the Camps Bay area, and indeed also much of the Hout Bay area, where currents impinging on the seabed are clearly sufficiently and persistently strong enough to limit the significant settling and accumulation of fine-grained material on the seabed. There was considerable variability in the grain size composition of sediment amongst

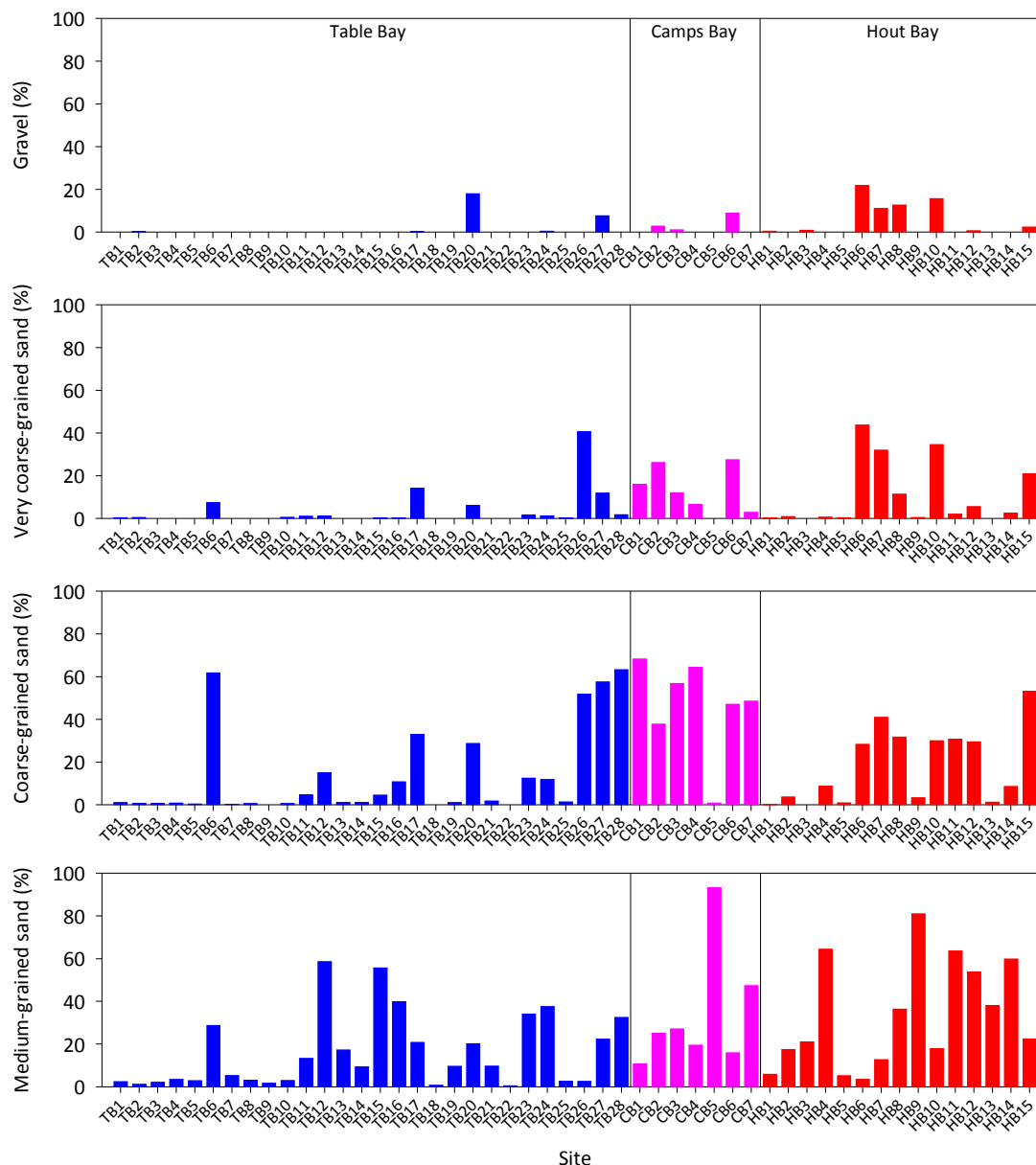


Figure 5.5. Contribution of various grain size classes to the bulk weight of sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The y-axis of the graphs is set at the same scale to highlight similarities and differences in the contribution of various grain size classes to the bulk weight of sediment between sites and areas.

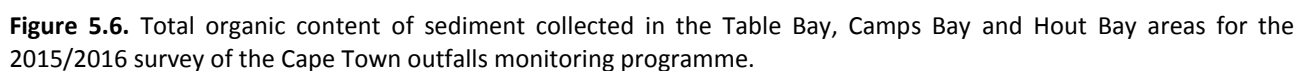
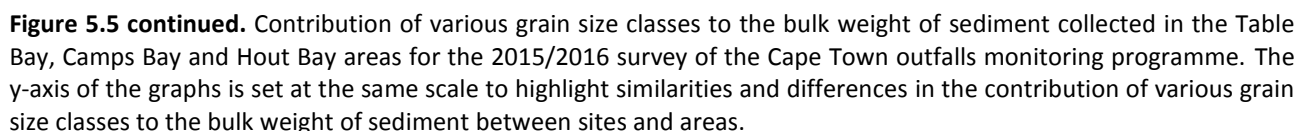
sites within each receiving environment, including sites separated by a relatively short distance (Figure 5.5). This may reflect the influence of seabed morphology (*e.g.* presence of reef) on current strength and turbulence, and hence on sediment transport and deposition. As stated above, sediment was collected from reef gullies by divers at some sites in the Table Bay area and this was usually dominated by very-coarse material.

The most significant finding arising from the grain size analysis of sediment is that the Table Bay, Camps Bay and Hout Bay marine receiving environments, or at least those parts where

sediment was collected are not depositional in nature. Currents and other forms of turbulence clearly limit the significant accumulation of fine-grained material on the seabed. The low contribution of mud to the bulk weight of sediment collected in each marine receiving environment is consistent with previous surveys in the Cape Town outfalls study area (*e.g.* CSIR, 1982; Woodborne, 1983; CSIR, 1985; CSIR, 1993; CSIR, 1995; CSIR, 2003; CSIR, 2006; CSIR, 2011; MacHutchon, 2012).

5.3.2. Total Organic Content

Total organic content is a measure of the amount of (generally particulate) organic matter present in



proliferation of bacteria. In extreme cases the complete loss of benthic macrofaunal communities can occur (Pearson and Rosenberg, 1978; Gray *et al.*, 2002; Hyland *et al.*, 2005). These impacts are driven by the depletion of dissolved oxygen and an increase in the concentration of sulphide by-products in porewater and at the sediment-water interface (Diaz and Rosenberg, 1995; Gray *et al.*, 2002; Hyland *et al.*, 2005; Wildish and Pohle, 2005; Hargrave *et al.*, 2008; Pelletier *et al.*, 2011). Dissolved oxygen depletion occurs when bacteria

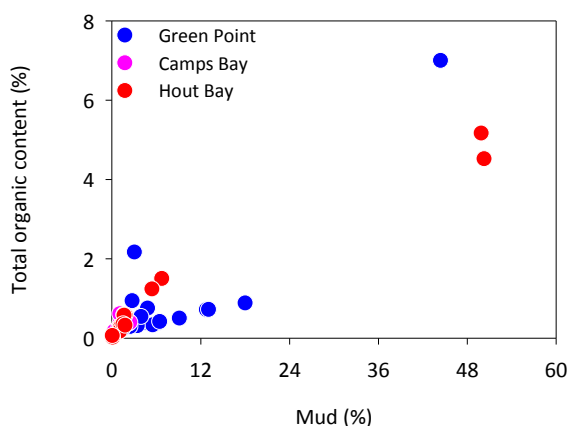


Figure 5.7. Relationship between the total organic content and mud fraction of sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

that degrade particulate organic matter proliferate to such a degree they consume all of the available oxygen in sediment porewater and at the sediment-water interface. This leads to the gradual loss of benthic macrofauna as the dissolved oxygen concentration decreases, based on their tolerance of low dissolved oxygen concentration (hypoxia). In extreme cases the sediment may become anoxic and this may result in the complete loss of benthic macrofauna. When the sediment becomes hypoxic or the dominant role in the decomposition of particulate organic matter is assumed by bacteria that are able to survive at low dissolved oxygen concentrations. Sulphide by-products are produced by sulphate-reducing bacteria when they metabolise under hypoxic and particularly anoxic conditions (Hyland *et al.*, 2005). Hydrogen sulphide is toxic to most aquatic organisms at low concentrations. Some sediment-dwelling organisms (*e.g.* certain species of polychaete worms) are able to tolerate elevated hydrogen sulphide and low dissolved oxygen concentrations and may proliferate and dominate communities under these conditions. This has made them useful indicators of the excessive enrichment of sediment by particulate organic matter. Such impacts are well documented for the Southern Works outfall off Durban (*e.g.* CSIR, 2016b). However, as sulphide production increases, even sulphide-tolerant faunal taxa are unable to survive and the sediment becomes progressively depauperate with respect to benthic macrofaunal organisms, until eventually only single celled organisms such as protozoae,

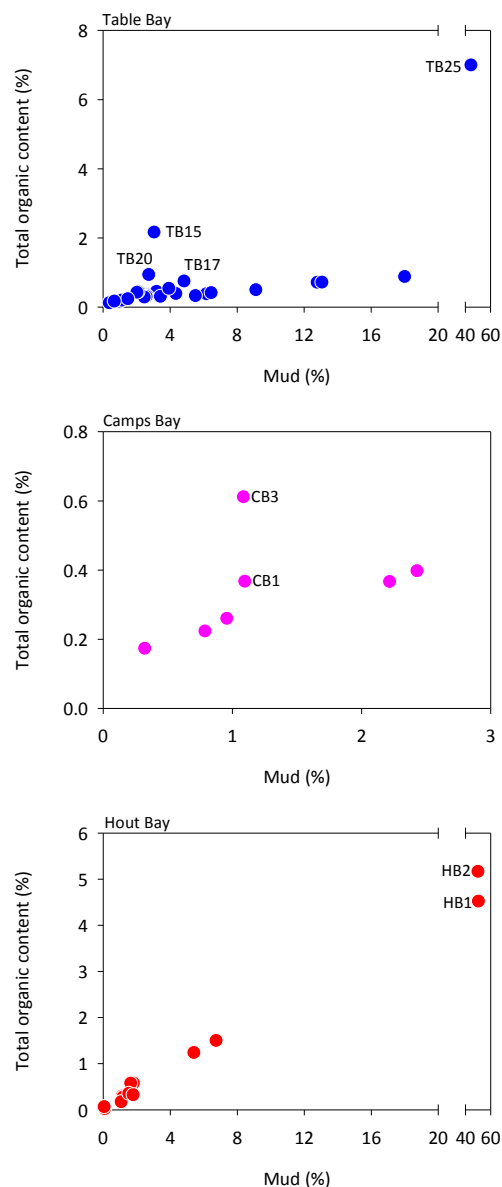


Figure 5.8. Relationship between the total organic content and mud fraction of sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. Data points highlighted by site identifiers are potentially enriched with particulate organic matter.

ciliates and flagellates that are able to live in sulphide-rich sediment remain (Fenchel and Riedl, 1970; Pelletier *et al.*, 2011).

An understanding of the total organic content of sediment has further implications in the context of the Cape Town outfalls monitoring programme since many toxic chemicals found in effluent preferentially adsorb onto particulate organic matter and eventually settle on the seabed with this matter. The amount of particulate organic matter can thus account for trends in their concentration in sediment.

The total organic content of sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme varied widely, from 0.02% at Site HB14 on the Hout Bay shoreline to 6.99% at Site TB25 situated about 1 200 m to the south-southwest of the Green Point outfall terminus in Table Bay (Figure 5.6). In addition to this site the total organic content of sediment collected at both sites in Hout Bay Harbour was high, while that for sediment collected at Site TB15 near the Oceana Power Boat Club near Granger Bay was fairly high. The total organic content of sediment at most sites was low, typically $\leq 0.94\%$.

There are no prescriptive values to define if the total organic content of sediment can be construed as low, moderate or high as this is unique to sediment in different aquatic ecosystems. The total organic content of sediment in sheltered, biologically productive estuarine ecosystems tends, for example, to naturally be higher than in sediment in nearshore marine ecosystems. This is because the nearshore marine environment is generally characterised by lower biological productivity and more importantly stronger currents and other forms of turbulence that limit the settling and significant accumulation of fine particulate organic matter on the seabed. Because of the sorting effect of currents and turbulence on particulate organic matter it is not valid to directly compare the total organic content between sediment samples of a different granulometry and conclude that the sediment with the higher total organic content is more 'contaminated' than that with a lower total organic content.

In aquatic ecosystems, or parts thereof where there is little enrichment of sediment with particulate organic matter from anthropogenic sources there is often a strong linear relationship between the mud fraction and total organic content of the sediment. This is because these fine-grained materials are similarly winnowed from or deposited on sediment depending on prevailing currents and turbulence. This relationship is beneficial as it can be used to identify sediment with an anomalously high or low total organic content. Figures 5.7 and 5.8 provide the relationship between the total organic content and mud fraction of sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2015,

inclusive of sediment from the sandy intertidal and the Disa (Hout Bay) River. There is a strong linear relationship between the total organic content and mud fraction of sediment in each of the marine receiving environments if the data for certain sites are considered to be outliers based on their deviation from the relationship for other sites (Figure 5.8). Pearson correlation analysis provides a correlation coefficient (r) of 0.899 ($p < 0.001$) for the Table Bay area if the data for sites TB15, TB17, TB20 and TB25 are considered outliers, of 0.873 ($p = 0.023$) for the Camps Bay area if the data for Site CB3 is considered an outlier, and of 0.974 ($p < 0.001$) for the Hout Bay area if the data for Sites HB1 and HB2 in Hout Bay Harbour are considered outliers. There is, however, uncertainty on the nature of the relationship for the Hout Bay area because of the skewed data distribution. It is uncertain if data for the two sites in Hout Bay Harbour should be included in the relationship because there are no data points intermediate between these and the data for other sites. Nevertheless, the relationship between the total organic content of sediment in the Hout Bay area and possibly also the Camps Bay area appears to differ from that for the Table Bay area when trimmed of outliers (shallower slope in latter area; see Figure 5.8).

Outlier sites in the Table Bay and Camps Bay area's represent sites where the total organic content of the sediment was higher than that for sediment at other sites based on the mud fraction of the sediment. Apart from Site TB25 situated about 1 200 m to the south-southwest of the Green Point outfall terminus and Site TB15 near the Oceana Power Boat Club near Granger Bay, the sediment in Table Bay was not enriched with particulate organic matter. A similar situation applies to the Camps Bay area even though the total organic content of sediment at Site CB3, about 380 m to the southeast of the outfall terminus, was identified as an outlier. This is because the total organic content of sediment at the latter station deviated only slightly from the relationship for other sites. In the case of Hout Bay the total organic content of sediment at Sites HB1 and HB2 in Hout Bay Harbour was either slightly lower than expected if the relationship for other sites is extrapolated, but which should be done with caution, or the total organic content at

Sites HB3 and HB5 is anomalous and that for Sites HB1 and HB2 is not. As stated above, the highly skewed data distribution make it difficult to conclude which situation is more likely.

The low total organic content of sediment collected at most offshore sites for the 2015/2016 survey of the Cape Town outfalls monitoring programme is consistent with the findings of previous surveys in the offshore part of the Cape Town outfalls study area (e.g. CSIR, 1982; CSIR, 1985; CSIR, 1992; CSIR, 1993; CSIR, 1997; CSIR, 2003). The surveys provided little to no evidence for the excessive accumulation of effluent-derived particulate organic matter on the seabed. The CSIR (1985, 1997, 2003) concluded that effluent discharged through the Green Point and Camps Bay outfalls, and river and stormwater runoff to the marine receiving environments were insignificant sources of particulate organic matter in sediment in Table Bay (about 1% in the case of effluent). Based on coprostanol (faecal steroid) concentrations in sediment collected between Granger Bay and the end of the western breakwater for the Port of Cape Town in 1982, the CSIR (1985) concluded that the higher particulate organic matter content of sediment in this area may have reflected the accumulation of effluent-derived material. At this time the Green Point outfall discharged effluent about 1 km nearer the shoreline than the present outfall.

Surveys at Hout Bay when effluent was discharged into the surf zone at Badtamboer provided evidence for the enrichment of shoreline sediment by organic matter (Eagle *et al.*, 1980; Bartlett *et al.*, 1981). This was attributed to a combination of effluent and fish factory waste discharges. Similar studies at Camps Bay revealed no enrichment of shoreline sediment (Eagle *et al.*, 1980; Bartlett, 1981).

It is impossible to determine if the higher total organic content of sediment collected at some sites for the 2015/2016 survey of the Cape Town outfalls monitoring programme, or indeed at all sites was derived from effluent apart from Sites HB1 and HB2 in Hout Bay harbour and Site HB15 in the Disa (Hout Bay) River, where it almost certainly was not derived from effluent. As stated above, the CSIR (2003) concluded there was no evidence for the excessive accumulation of effluent-derived

particulate organic matter in sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2003. However, analysis of the sediment for stable isotopes of nitrogen and carbon did provide evidence for a spatially variable amount of particulate organic matter in the sediment derived from effluent/terrestrial sources. Plankton was identified as an additional significant source of particulate organic matter in sediment in all areas.

Based on the total suspended solids concentration in, and volume of effluent discharged through the Green Point, Camps Bay and Hout Bay outfalls (see Chapter 2), the load of particulate organic matter introduced into the marine receiving environments by effluent is clearly considerable. Thus, even though the total organic content of sediment in the marine receiving environments was typically very low, it is illogical to conclude no effluent-derived particulate organic matter is settling on the seabed. However, particulate organic matter is not accumulating significantly on the seabed and its contribution is probably less than that derived from natural sources (e.g. phytoplankton). There is a possibility that effluent-derived particulate organic matter is being exported further offshore than the Cape Town outfalls study area and may be accumulating in sediment in low bed shear stress (deep) areas in the farfield (e.g. on the Benguela Shelf; CSIR, 2003), but has not yet been demonstrated.

5.3.3. Metals

Determining if sediment is contaminated by certain chemicals is easy as they only have a human origin (e.g. synthetic chemicals such as polychlorinated biphenyls). The mere presence of these chemicals in sediment is indicative that it is contaminated. Determining if sediment is metal contaminated is more complicated, for several reasons. First, metals are a ubiquitous naturally occurring component of sediment. The mere presence of metals in sediment does not thus imply the sediment is contaminated. Second, metal concentrations in uncontaminated sediment can vary by orders of magnitude over relatively small spatial scales depending on sediment mineralogy, granulometry and organic content amongst other factors (Wangersky, 1986; Windom *et al.*, 1989; Loring and Rantala, 1992; Thomas and Bendell-Young, 1999; Kersten and

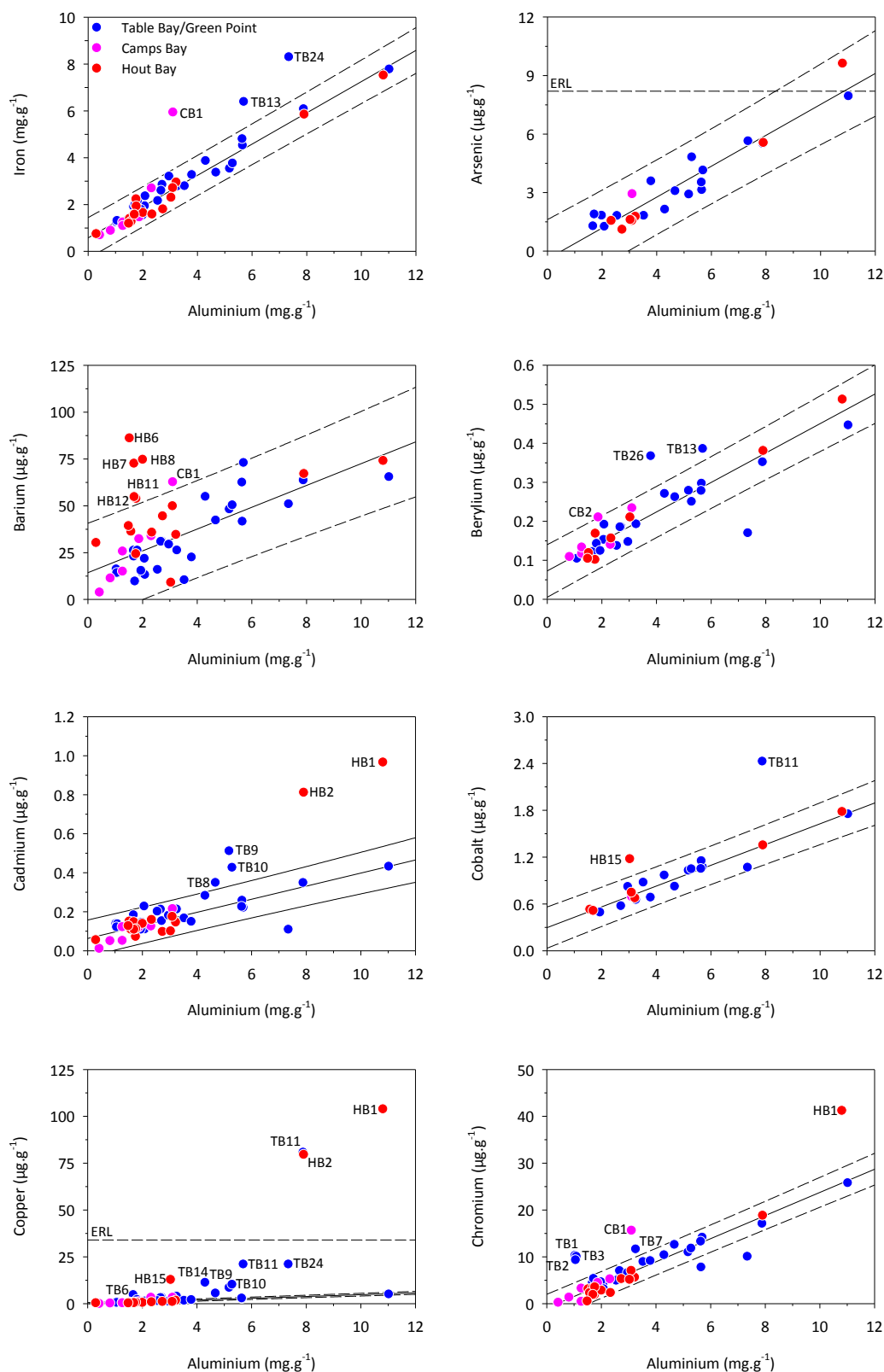


Figure 5.9. Baseline metal concentration models for sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme, with metal concentrations in all sediment samples superimposed. Selected data points are highlighted by site identifiers. The horizontal dashed lines represent the Effects Range Low (ERL) of the sediment quality guidelines defined by Long *et al.* (1995) (only included if guideline falls within the y-axis range).

Smedes, 2002). Within a geologically homogenous area, grain size is the most important factor that controls natural metal concentrations in sediment (Förstner, 1989). This is because aluminosilicates,

the dominant natural metal-bearing phase of sediment, predominate in clay. Sand, in contrast, is comprised predominantly of metal deficient quartz. Particulate organic matter is an additional host for

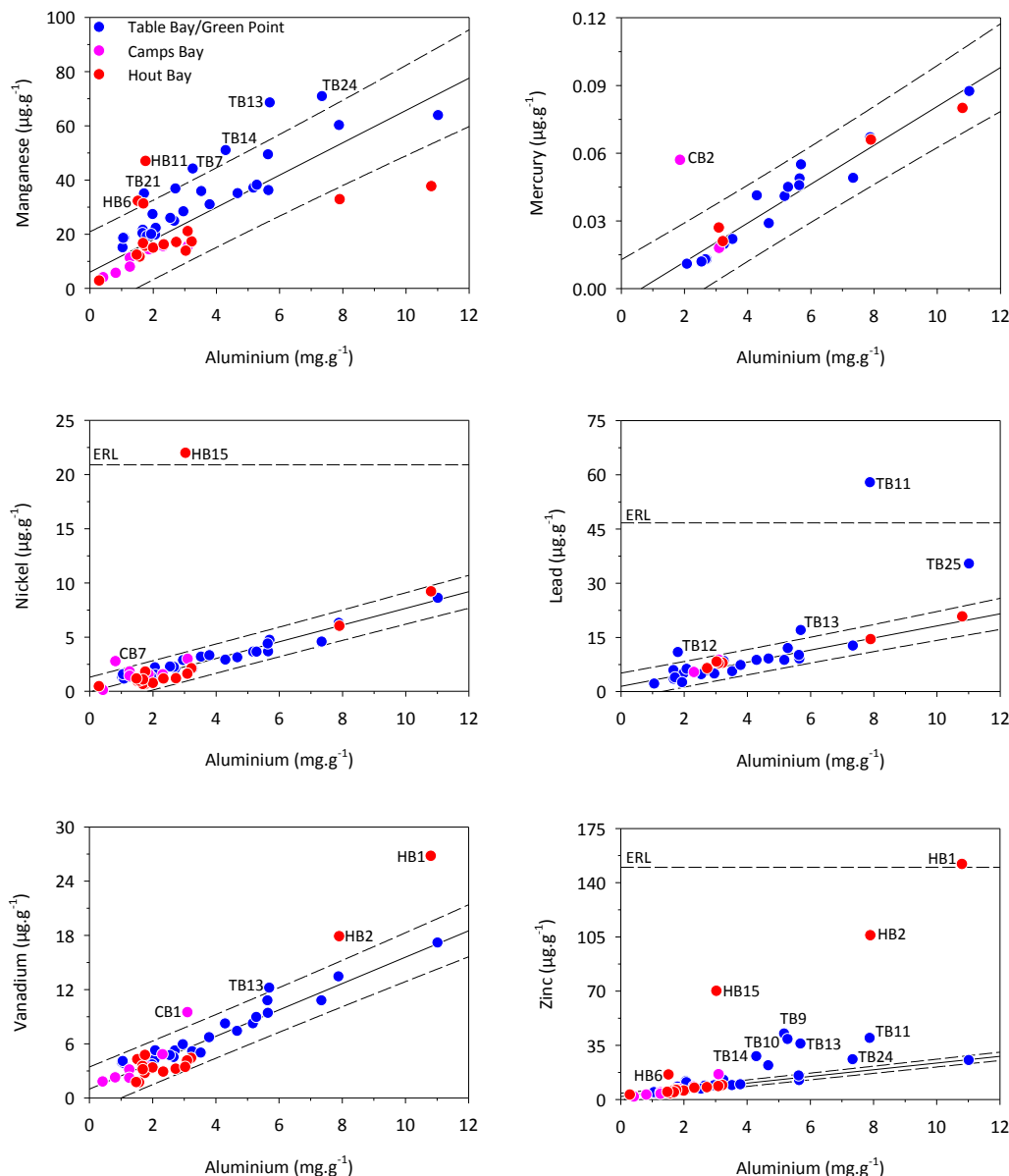


Figure 5.9 continued. Baseline metal concentration models for sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme, with metal concentrations in all sediment samples superimposed. Selected data points are highlighted by site identifiers. The horizontal dashed lines represent the Effects Range Low (ERL) of the sediment quality guidelines defined by Long *et al.* (1995) (only included if guideline falls within the y-axis range).

metals. High metal concentrations in sediment may thus simply reflect the mineralogy of the sediment parent material and/or granulometry and organic content of the sediment, and not necessarily contamination. Third, despite input and transport dissimilarities naturally occurring and anthropogenically introduced metals tend to accumulate in the same areas (Loring, 1991; Hanson *et al.*, 1993). Because of these complexities an identical metal concentration in two sediment samples from the same aquatic ecosystem may reflect contamination in one instance and not the other. To meaningfully interpret metal concentrations in sediment, factors that influence their natural variation must be

compensated for before natural concentrations can be differentiated from anthropogenically-enhanced concentrations. This can be accomplished by the procedure of geochemical normalisation, which involves the mathematical normalisation of metal concentrations to a co-occurring element that provides a conservative tracer of crustal decomposition (Hanson *et al.*, 1993; Kersten and Smedes, 2002).

Within geologically homogenous areas metals in sediment tend to occur in relatively constant proportions. This permits the modelling of relationships between metals and conservative

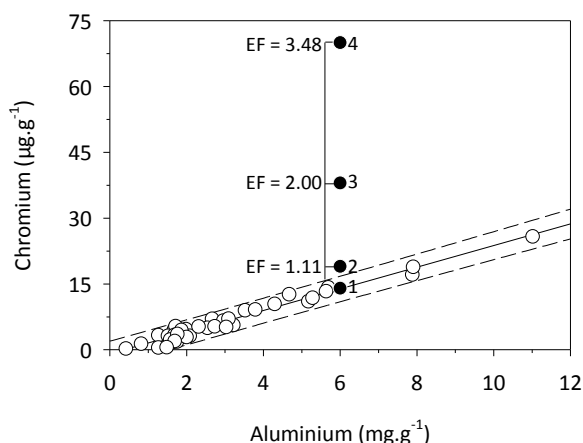


Figure 5.10. Baseline model for chromium in sediment in the Table Bay, Camps Bay and Hout Bay areas. The open symbols represent concentrations used to define the baseline model. The solid symbols represent four hypothetical scenarios: 1. concentration falls within baseline model prediction limits (dashed lines flanking solid regression line) and is interpreted as not enriched; 2, 3 and 4. concentrations exceed baseline model upper prediction limit and are interpreted as reflecting various levels of enrichment that can broadly be defined as very low (2) through to high (4). Enrichment Factors (EF) for hypothetical concentrations 2, 3 and 4 are provided. Concentrations 3 and 4 would be interpreted as reflecting enrichment through an anthropogenic contribution with a high level of confidence. Concentration 2 would be interpreted as reflecting enrichment through an anthropogenic contribution with a low level of confidence.

tracers of crustal decomposition through simple or multiple-linear regression. Simple linear regression models defined in this manner are referred to as baseline metal concentration models (or more simply as baseline models).

Metal concentrations in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme were used to define baseline models. Since there was a possibility some metal concentrations in the sediment reflected contamination the approach followed for baseline model definition was different to that which ordinarily would be followed were the sediment collected in an anthropogenically unimpacted area. Thus, none of the sediment samples were excluded based on their position relative to known or strongly suspected sources of metals. A linear regression and 99% prediction limits were fitted to scatter plots of each metal-aluminium concentrations. Metal concentrations that fell outside the prediction limits were deemed outliers and trimmed, starting with the concentration furthest

from a prediction limit and continuing sequentially until all concentrations fell within the prediction limits.

Aluminium was used as the normaliser of metal concentrations because it is a major constituent of fine-grained aluminosilicates, with which the bulk of trace metals are naturally associated. It thus shows a strong positive correlation with the mud fraction of sediment. Aluminium concentrations are, as a result, also strongly positively correlated to co-occurring metal concentrations. Aluminium is, furthermore, stable and not affected by early diagenetic processes and strong redox effects that are commonly observed in sediment (Schiff and Weisberg 1999, Kersten and Smedes 2002), and is highly refractory.

Figure 5.9 presents the baseline models, with aluminium normalised metal concentrations in all sediment samples collected for the 2015/2016 survey superimposed. The way that baseline models are used to interpret metal concentrations in sediment is provided in Figure 5.10. Briefly, metal concentrations that fall within the baseline model prediction limits are considered to fall within the baseline range, which may not necessarily reflect uncontaminated sediment but is considered indicative of minimally contaminated sediment. Metal concentrations that fall above the baseline model upper prediction limit are higher than expected (enriched) and may reflect natural enrichment or contamination.

The definition of metal baseline models was complicated by the fact that the dataset was relatively small, and, importantly, skewed to low concentrations. This reflects the fact the sediment at most sites was comprised predominantly of sand, which as stated above naturally has a low metal content. Consequently, metal concentrations at the few 'high' co-occurring aluminium concentrations exerted a relatively strong influence on the strength of baseline models, and through their leverage effect also a strong influence on model slopes. Although the baseline models are as a result not without limitations and uncertainties they are useful for interpreting metal concentrations in the sediment.

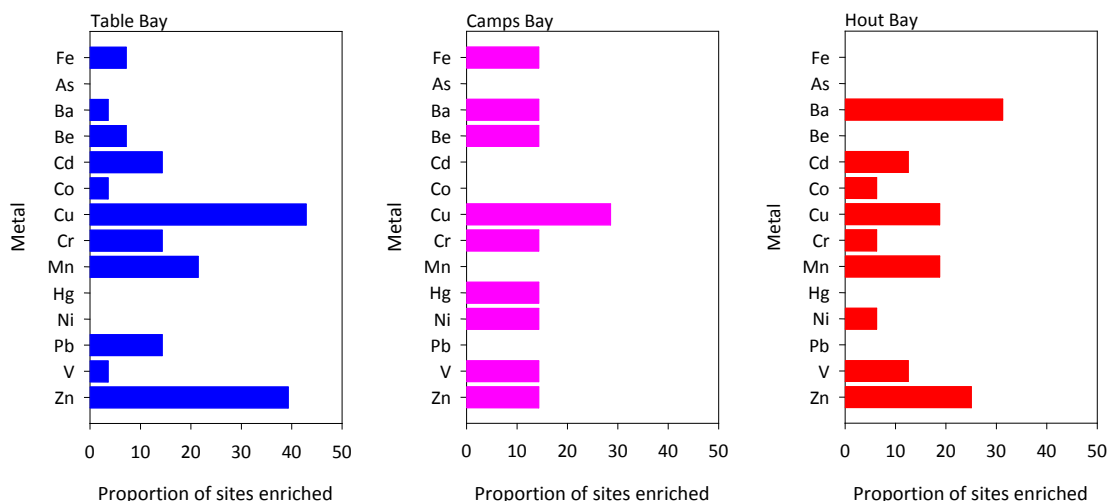


Figure 5.11. Proportion of sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme with various metals at a higher than expected concentration. The x-axis of the graphs is set to the same scale to highlight differences and similarities between areas.

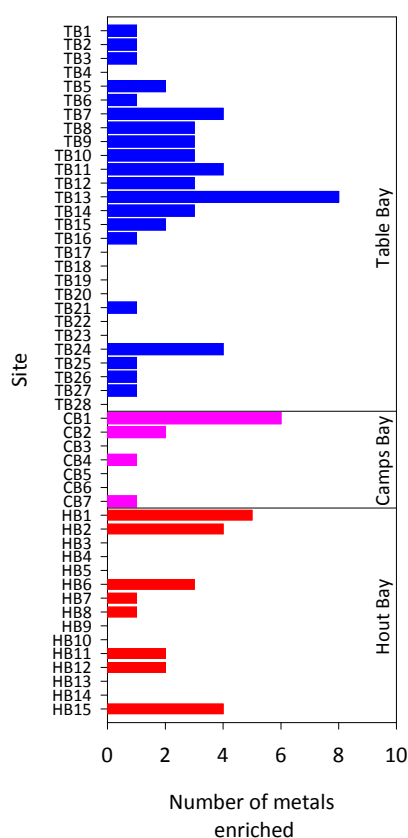


Figure 5.12. The number of metals at a higher than expected concentration in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

Of the 700 metal concentrations (excluding aluminium) that were analysed in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme, including intertidal sites and the Disa River site, only 80 (or 11.4%) exceeded a baseline model upper

prediction limit (*i.e.* were higher than expected). If the receiving environments are considered separately the proportion of metal concentrations that were higher than expected was 12.2% for the Table Bay area, 10.2% for the Camps Bay area, and 9.8% for the Hout Bay area (note the small sample size [seven sites] for the Camps Bay area makes the use of proportions somewhat spurious). The metals most often at a higher than expected concentration were (in order) copper, zinc and manganese in the Table Bay area, copper in the Camps Bay area, and barium, zinc, copper and manganese in the Hout Bay area (Figure 5.11). The more frequent detection of copper and zinc at higher than expected concentrations could reflect the impact of effluent discharge considering these metals were detected in all effluent samples from the Green Point, Camps Bay and Hout Bay wastewater works analysed between 1 March 2015 and 30 September 2016, and were at a relatively high concentration in Green Point and Camps Bay effluent (see Chapter 2). However, copper and zinc are also amongst the most frequent and significant contaminants of stormwater in urban areas (*e.g.* Schiff *et al.*, 2002; MoT, 2003; Kelly, 2010; Revitt *et al.*, 2014). Copper, for example, is a constituent of vehicle brake pads while zinc is included in tyres and roofing material amongst its many uses. Also, as discussed below the sediment that was most contaminated by copper and zinc was usually at sites situated a considerable distance from the outfall diffuser sections.



Figure 5.13. Bubble plot representation of the number of metals at a higher than expected concentration in sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents eight metals. The Green Point and Camps Bay outfalls are denoted by the red lines.

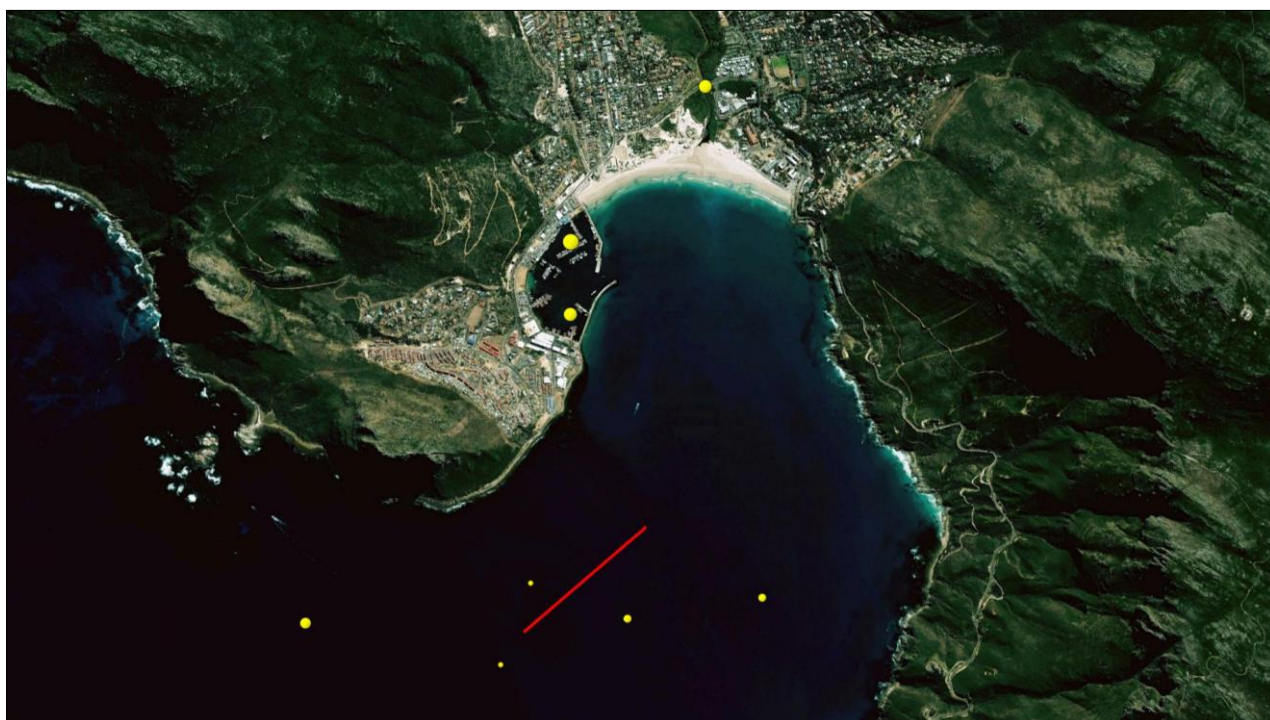


Figure 5.14. Bubble plot representation of the number of metals at a higher than expected concentration in sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents five metals. The Hout Bay outfall is denoted by the red line.

Manganese enrichment of sediment in the Table Bay and Hout Bay areas was always of a low magnitude (*i.e.* slight exceedance of baseline model upper prediction limit; Figure 5.9). Manganese was also found to be enriched in sediment collected in

these areas in studies for surveys in 2005/2006 and 2011 (CSIR, 2006, 2011). Although manganese was always detected in effluent from each wastewater works (see Chapter 2), attributing the enrichment to effluent is tenuous. This is because manganese is

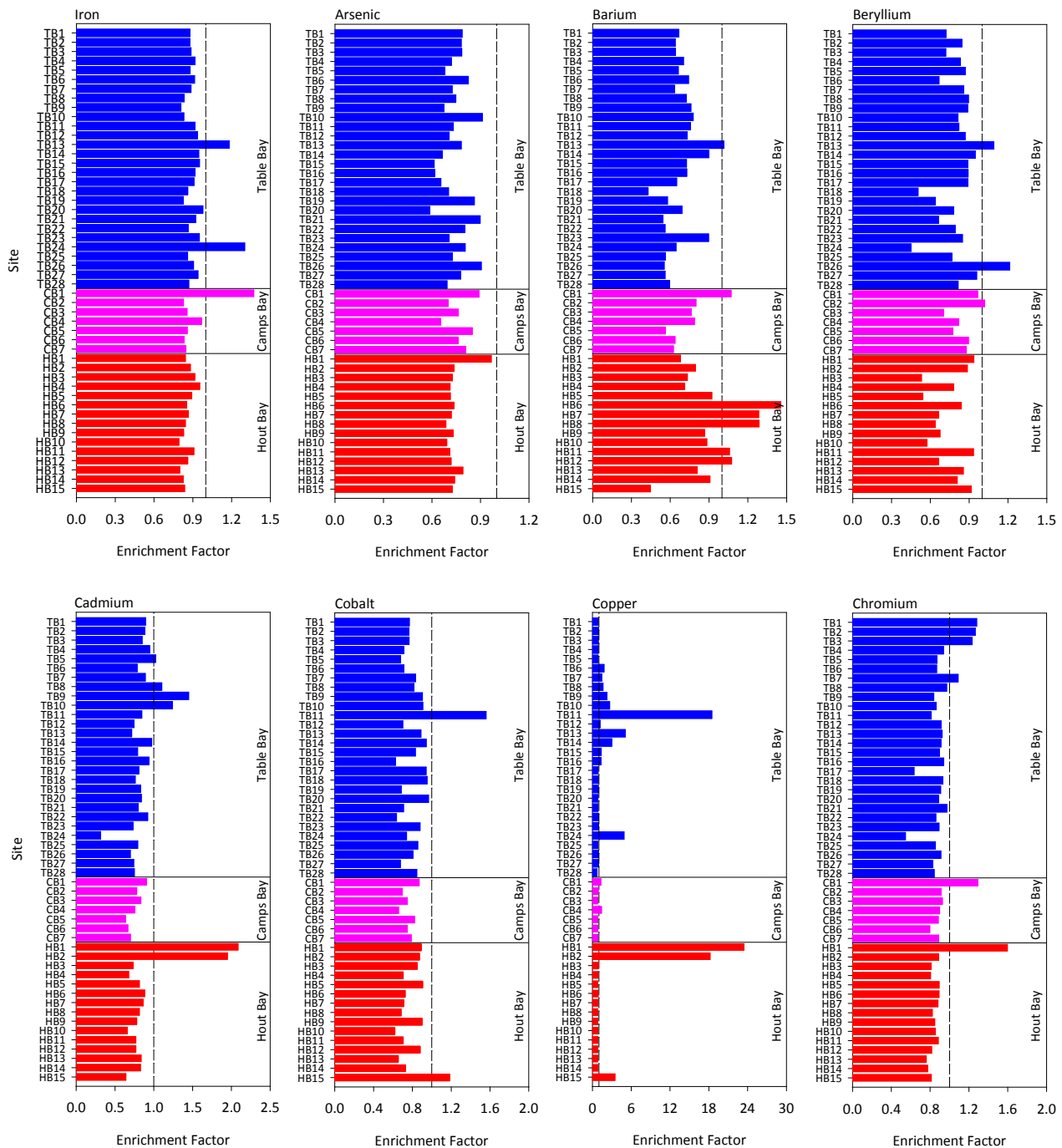


Figure 5.15. Enrichment Factors and the cumulative Enrichment Factor for metals in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The vertical dashed lines represent an Enrichment Factor of one.

highly mobile in sediment under certain conditions (e.g. hypoxia and anoxia), and can result in its natural enrichment at the sediment surface. This said, there was no evidence the sediment at any site was anoxic based on its colour and smell.

The number of metals at a higher than expected concentration in sediment collected at each site for the 2015/2016 survey of the Cape Town outfalls monitoring programme is provided in Figure 5.12. To facilitate interpretation the data are also

presented as bubble plots in Figures 5.13 and 5.14. The bubbles are scaled to the number of metals at a higher than expected concentration in the sediment. The sediment collected at eight of the 28 sites in the Table Bay area, at three of the seven sites in the Camps Bay area, and at seven of the 15 sites in the Hout Bay area was not metal enriched. The greatest number of metals at a higher than expected concentration in sediment at any site was eight (of 14 metals), at Site TB13 near the western breakwater for the Port of Cape Town (Figures 5.12

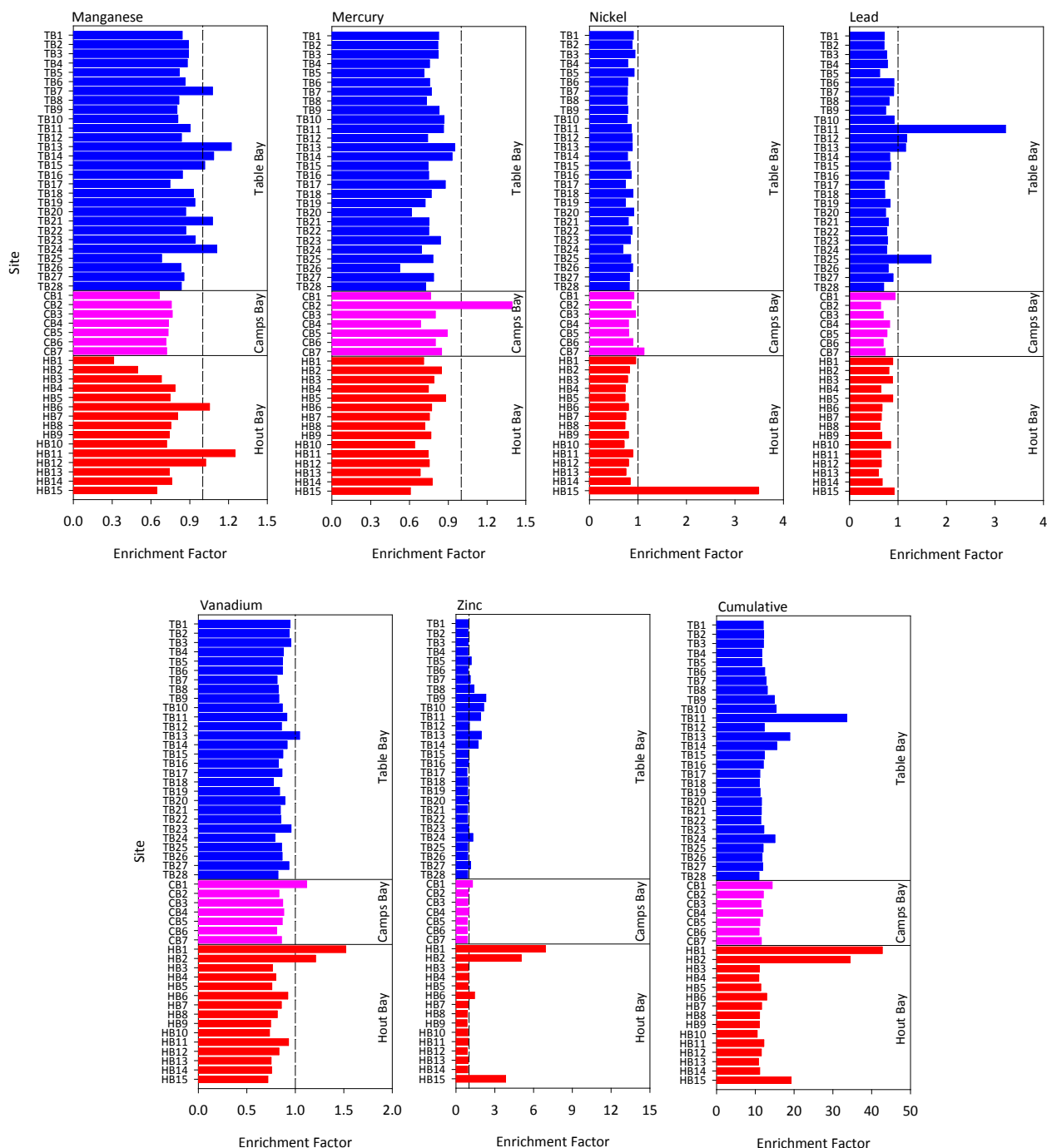


Figure 5.15 continued. Enrichment Factors and the cumulative Enrichment Factor for metals in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The vertical dashed lines represent an Enrichment Factor of one.

and 5.13), followed by six metals at Site CB1 situated about 1 200 m to the north of the Camps Bay outfall terminus, and five metals at Site HB1 in Hout Bay Harbour (Figures 5.12 and 5.14). The sediment at all sites between the Granger Bay Marina and western breakwater for the Port of Cape Town (*i.e.* sites TB13, TB14, TB15 and TB16) was enriched by at least one metal, and as stated previously by eight metals at Site TB13. Sediment at several sites in the southeastern part of Table Bay near the eastern breakwater for the Port of Cape

Town and mouth of the Salt River (*i.e.* sites TB7, TB8, TB9, TB10, TB11, TB12) was enriched by three or four metals.

Some metals, including barium, beryllium, cobalt, mercury and vanadium were enriched in sediment at one to a few sites, and, as discussed further below, usually to such a low magnitude (*i.e.* slight exceedance of baseline model upper prediction limit) that it is difficult or impossible to conclude this reflects contamination (Figures 5.15 - 5.42).

Certain other metals, such as copper and zinc, were enriched to a magnitude in sediment at numerous sites in Table Bay and Hout Bay Harbour that reflects contamination.

The sediment at three sites ‘near’ the Green Point outfall diffuser section, at two sites near the Camps Bay outfall diffuser section, and at three sites near the Hout Bay outfall diffuser section was metal enriched, but only by one or two metals with the exception of Site TB24 near the Green Point outfall, where the sediment was enriched by four metals (Figures 5.12 - 5.14).

The number of metals that are at a higher than expected concentration in sediment at a particular site provides important information for reaching a conclusion on whether the enrichment reflects contamination. This is because anthropogenic sources of metals to aquatic ecosystems, such as effluent and stormwater, are usually contaminated by more than one metal (see for example Chapter 2). As a result sediment is usually also contaminated by more than one metal. Counting the number of metals in sediment at a higher than expected concentration does not, however, consider the magnitude of enrichment. Thus, a metal concentration that marginally exceeds a baseline model upper prediction limit is accorded the same score (count) as a concentration that substantially exceeds an upper prediction limit, yet the toxicological significance of the concentrations may be very different. To contextualise the magnitude of metal concentration exceedance of a baseline model upper prediction limit an Enrichment Factor was calculated for each metal concentration in sediment at each site. For this purpose, metals at a concentration below the method detection limit were replaced by a surrogate concentration equal to one-half the detection limit. Baseline model prediction limits are not linear but biconcave, being narrowest at the average value for the x-axis variable (in this case the aluminium concentration). If prediction limits have a considerable curvature it is difficult to calculate meaningful Enrichment Factors. Metal concentrations were thus adjusted to the average aluminium concentration using the baseline model parameters. The Enrichment Factor was then taken as the ratio between adjusted metal concentrations

in the sediment sample of interest and the concentration predicted at the baseline model upper prediction limit at the average aluminium concentration. The upper limit of the baseline concentration range for each metal was thus used to discriminate between metal enriched and non-enriched sediment.

However, inspection of Enrichment Factors for metals in sediment with low co-occurring aluminium concentrations (*i.e.* sandy sediment) showed they were often anomalously high. Spurious Enrichment Factors at low normaliser concentrations are a result of baseline model intercepts rarely, if ever, being zero. Also, the baseline model upper prediction limit, used in this study to discriminate between metal enriched and non-enriched sediment, will almost invariably not have a zero intercept. Enrichment Factors at low aluminium concentrations are thus magnified due to the small value for the denominator. Metal concentrations were thus adjusted to an aluminium concentration of 6 mg.g^{-1} , approximately one-half the highest aluminium concentration included in the baseline models. Enrichment Factors were then calculated in the manner discussed above.

The Enrichment Factor, which is unitless, indicates by how many times a metal concentration exceeds the concentration predicted at the baseline model upper prediction limit at the normaliser concentration to which metal concentrations were adjusted. An Enrichment Factor ≤ 1 denotes the concentration falls within or below the baseline concentration range while an Enrichment Factor > 1 denotes the metal was at a higher than expected concentration. Enrichment Factors can be visualised using the same hypothetical example used to demonstrate the way that baseline models are used to interpret metal concentrations in sediment (Figure 5.10). As expected, Enrichment Factors for hypothetical concentrations 2, 3 and 4 increase the further the concentration is from the baseline model upper prediction limit. An Enrichment Factor of 3.48, as is the case for hypothetical concentration 4, indicates the concentration is a little under three and a half times higher than the concentration at the baseline model upper prediction limit at the same aluminium concentration as that in the sediment sample of interest.

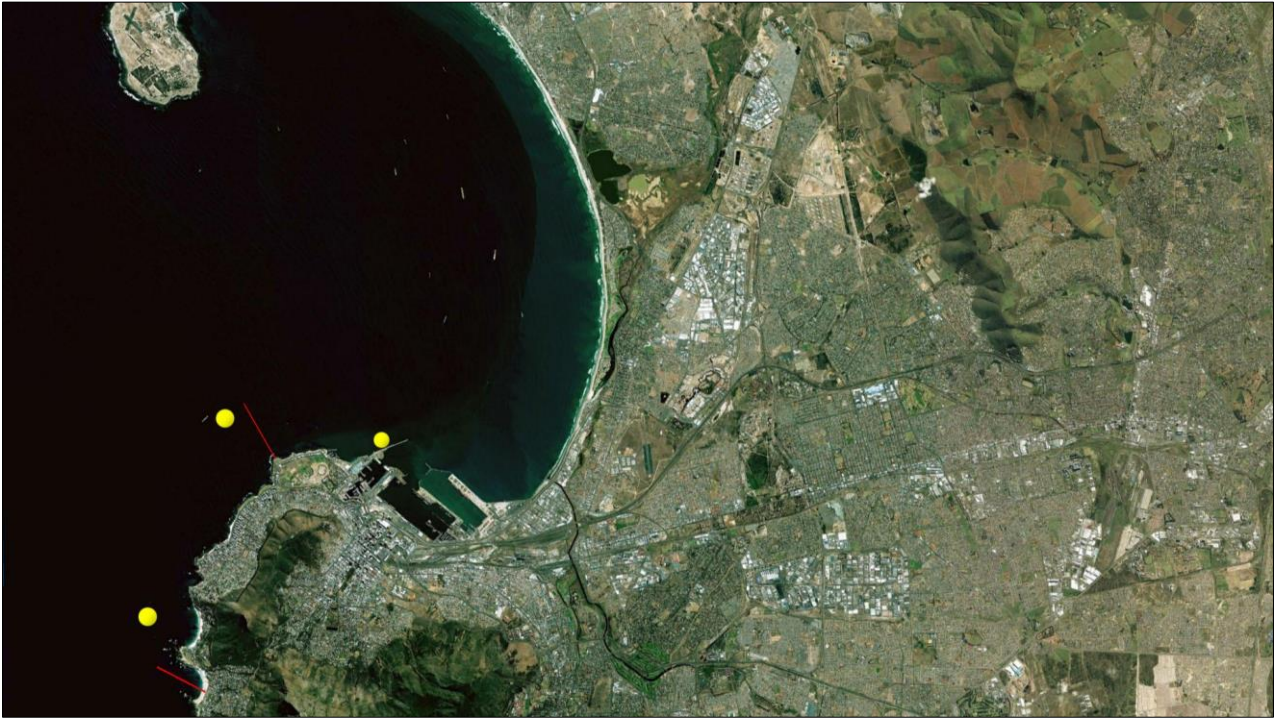
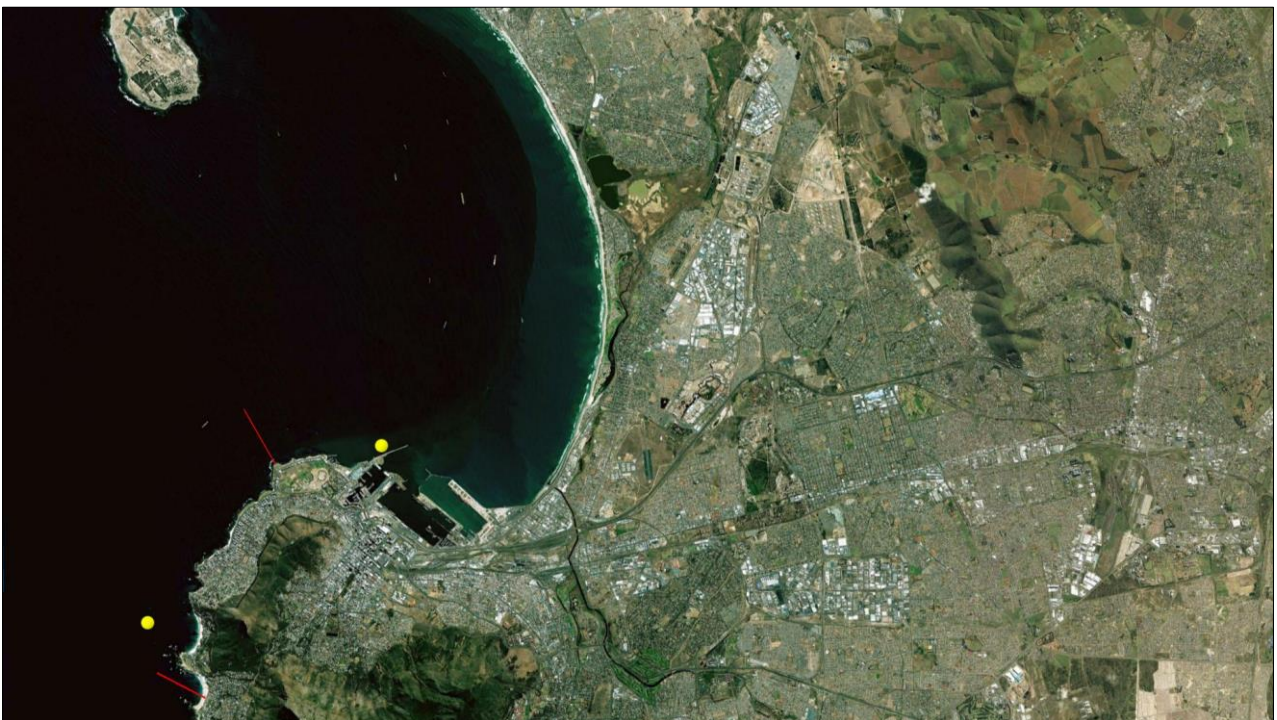


Figure 5.16. Bubble plot representation of iron Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 1.37. The Green Point and Camps Bay outfalls are denoted by the red lines.



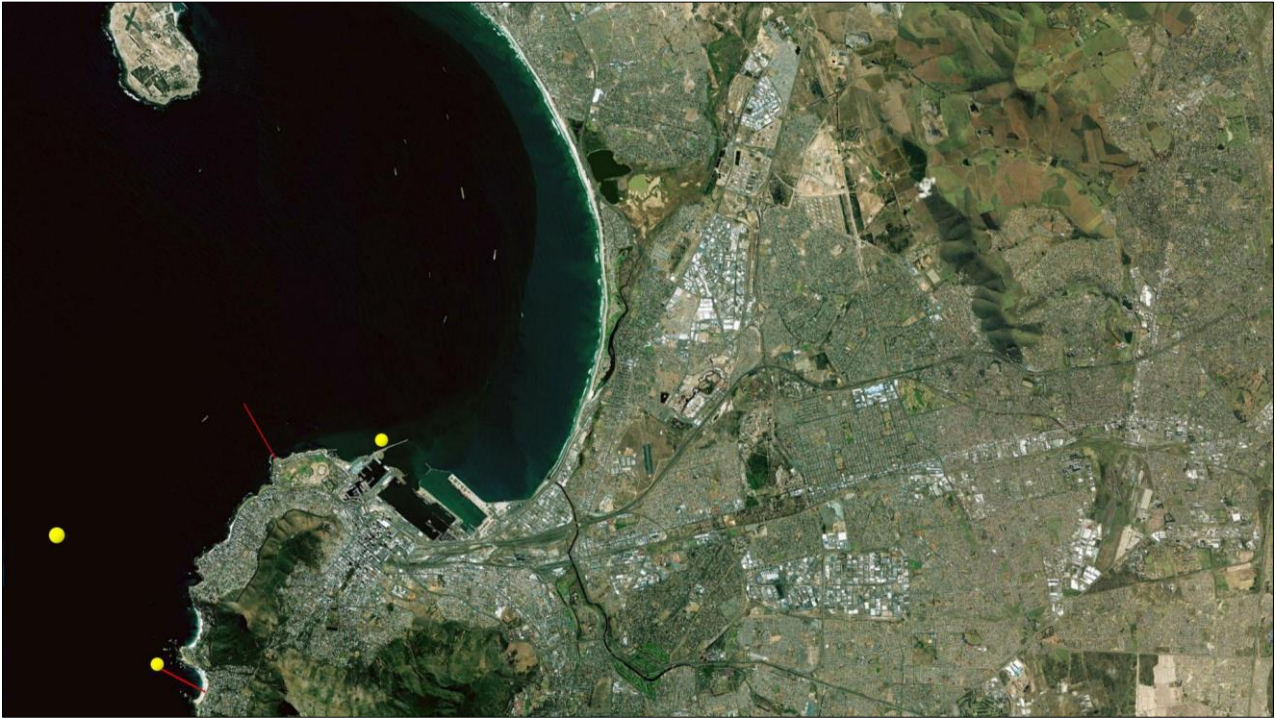
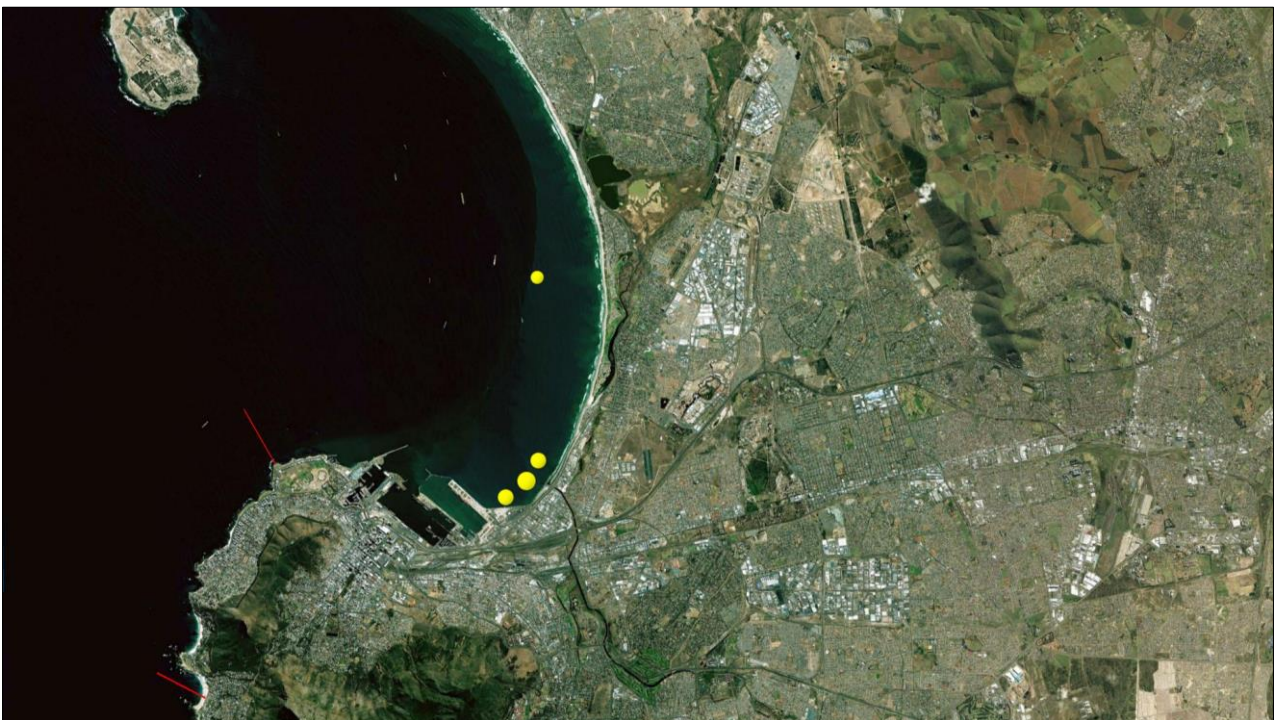


Figure 5.18. Bubble plot representation of beryllium Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 1.21. The Green Point and Camps Bay outfalls are denoted by the red lines.



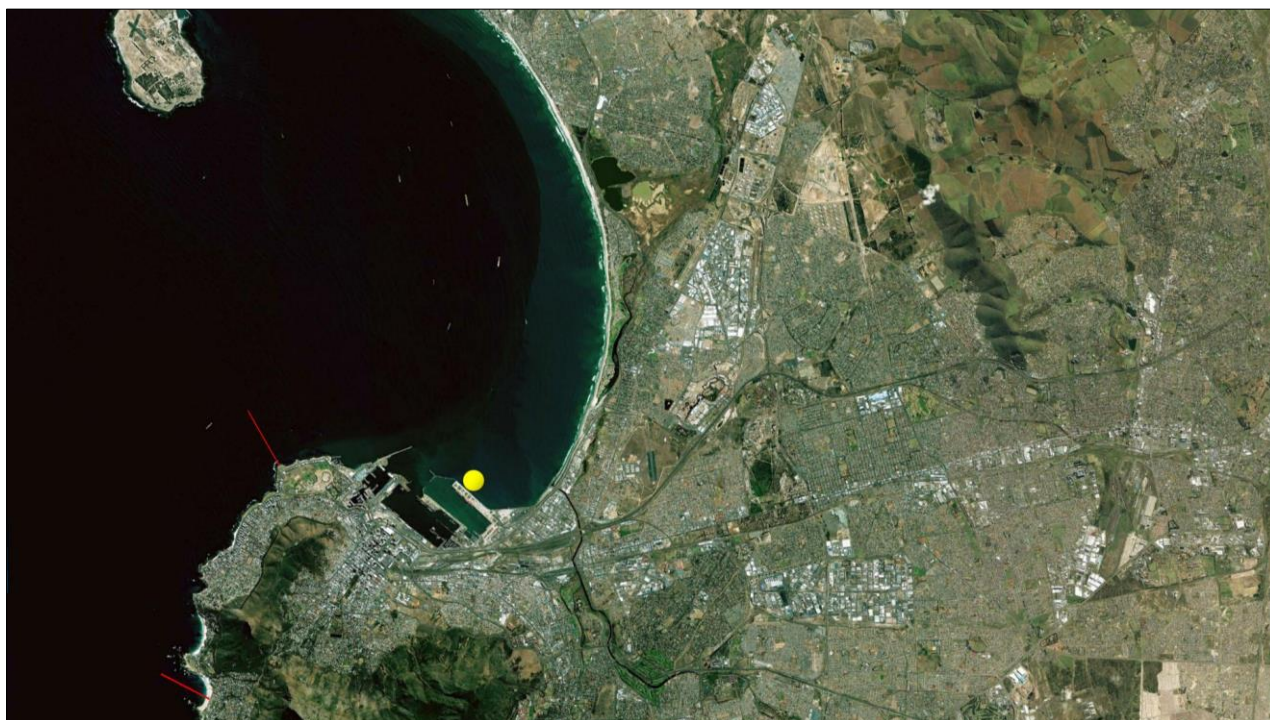


Figure 5.20. Bubble plot representation of cobalt Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 1.56. The Green Point and Camps Bay outfalls are denoted by the red lines.

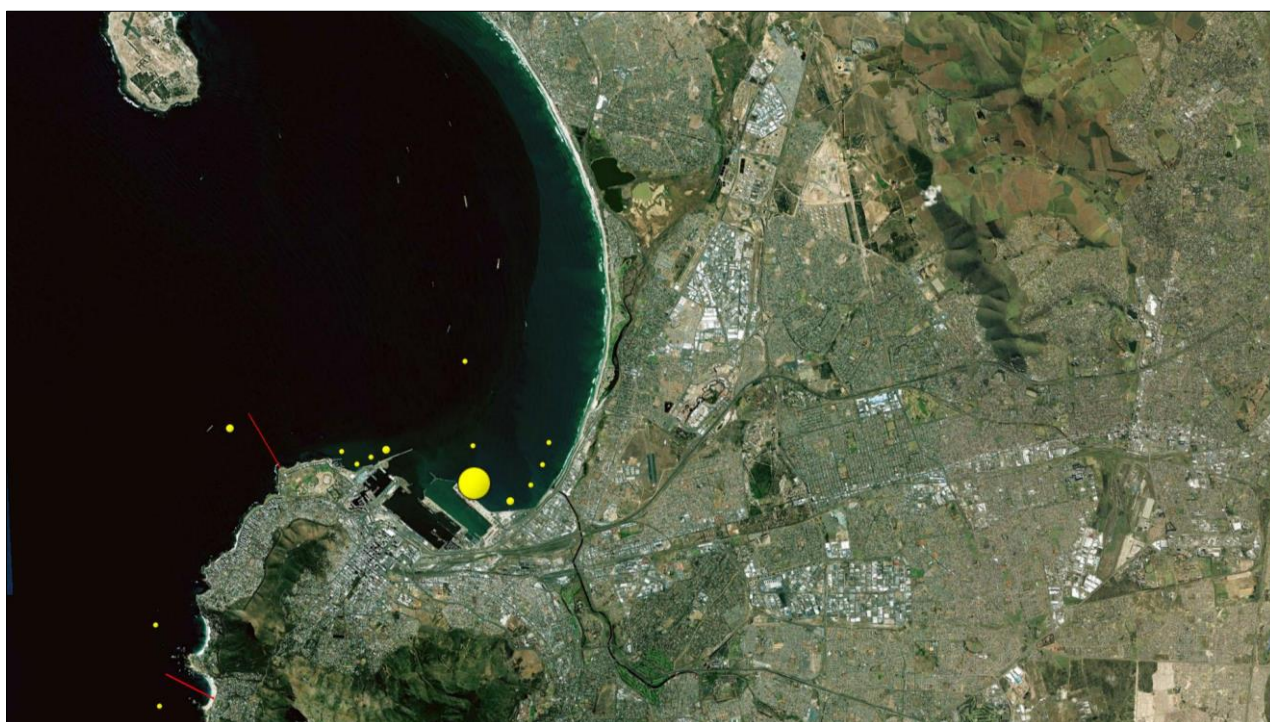
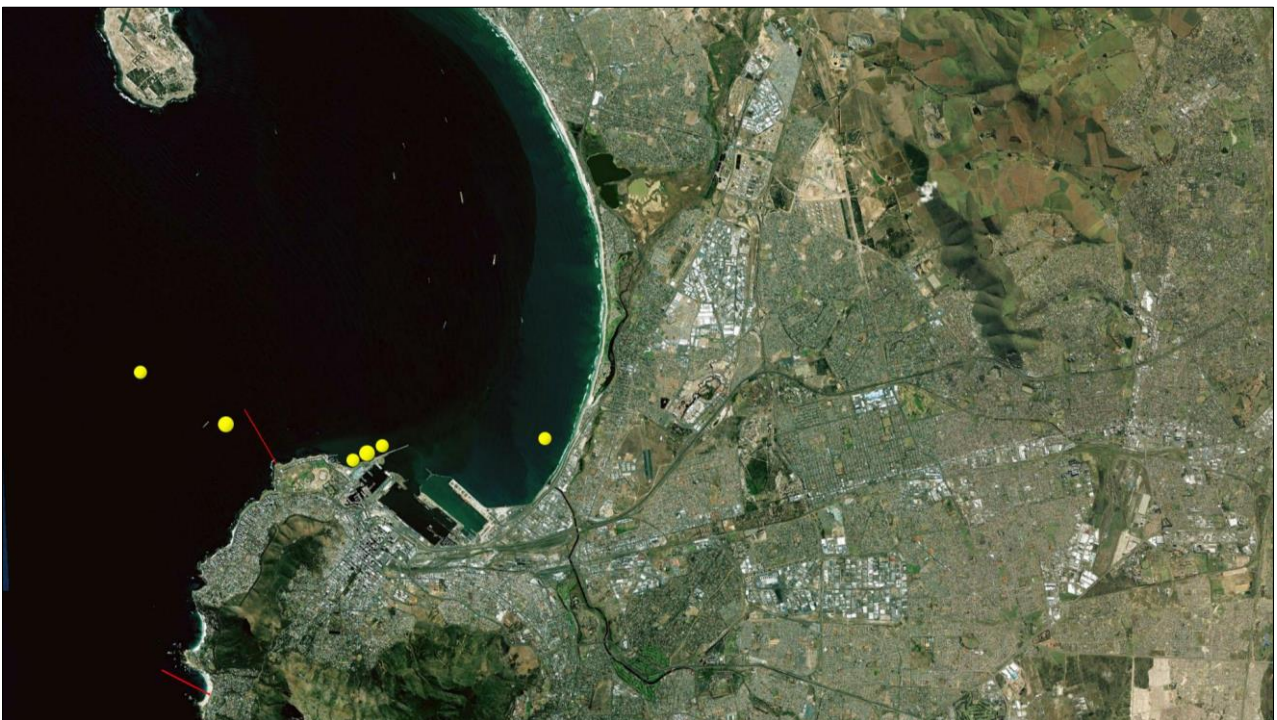




Figure 5.22. Bubble plot representation of chromium Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 1.29. The Green Point and Camps Bay outfalls are denoted by the red lines.



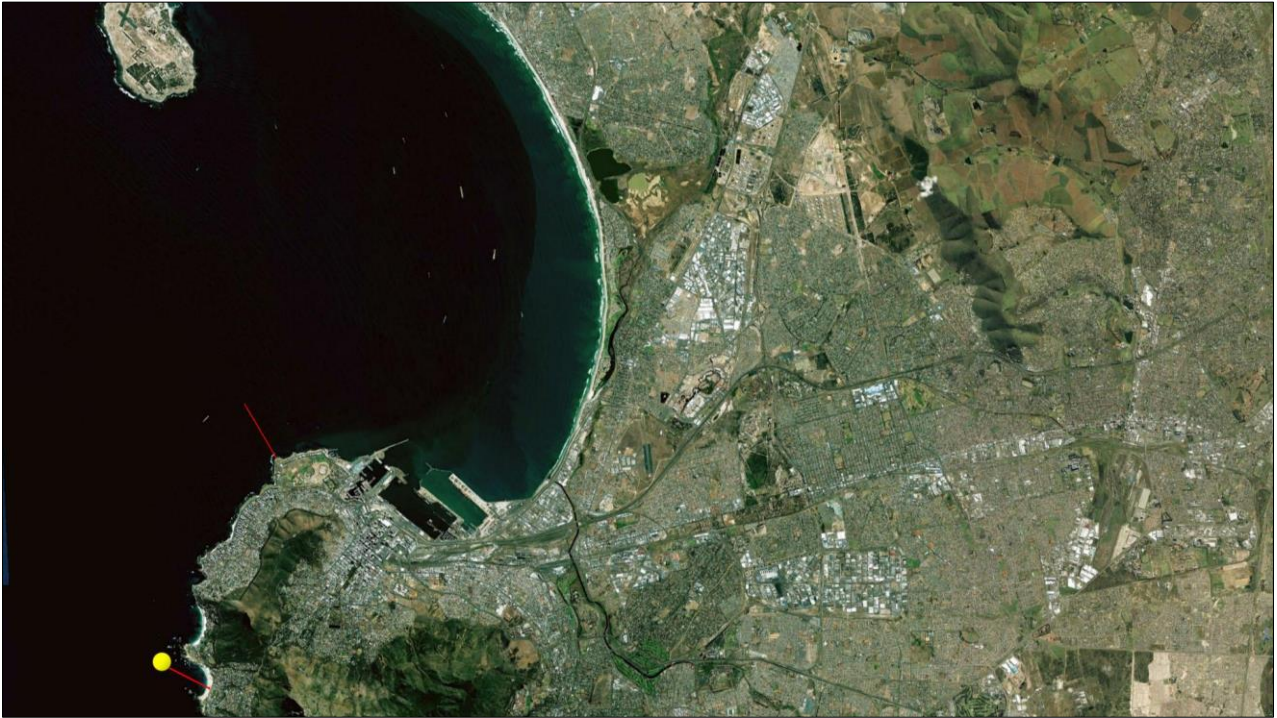
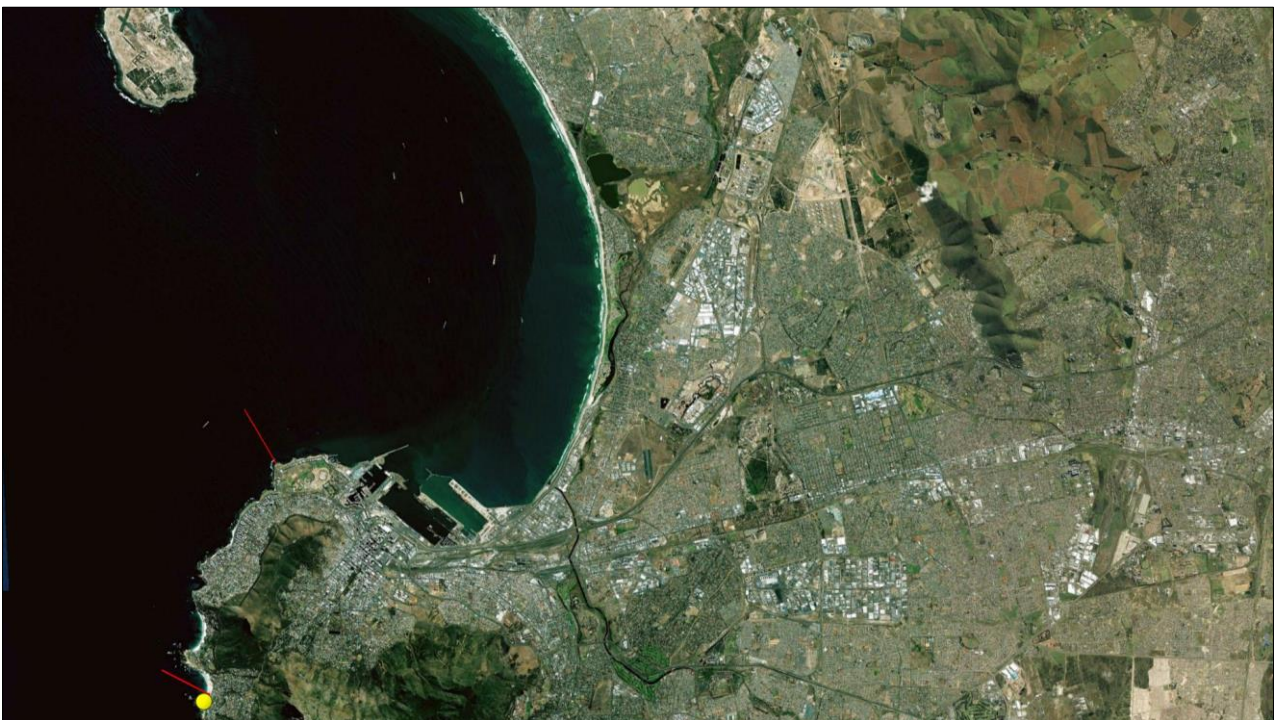


Figure 5.24. Bubble plot representation of mercury Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 1.39. The Green Point and Camps Bay outfalls are denoted by the red lines.



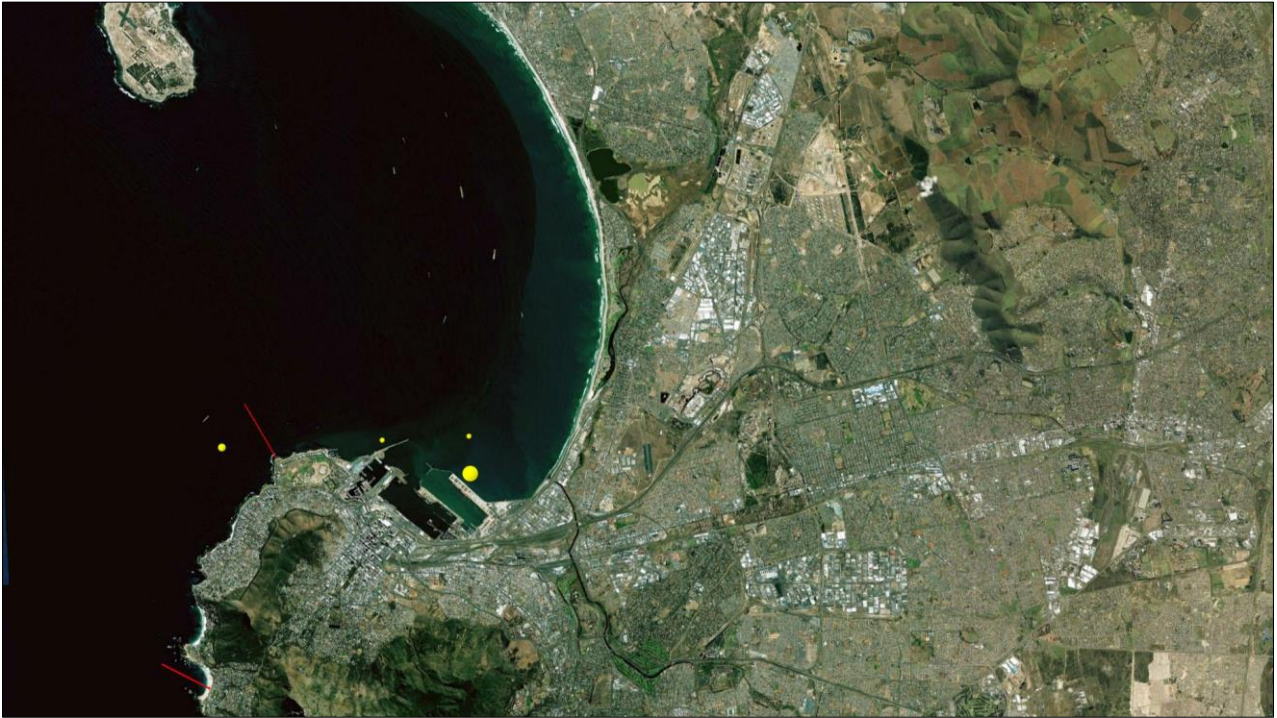
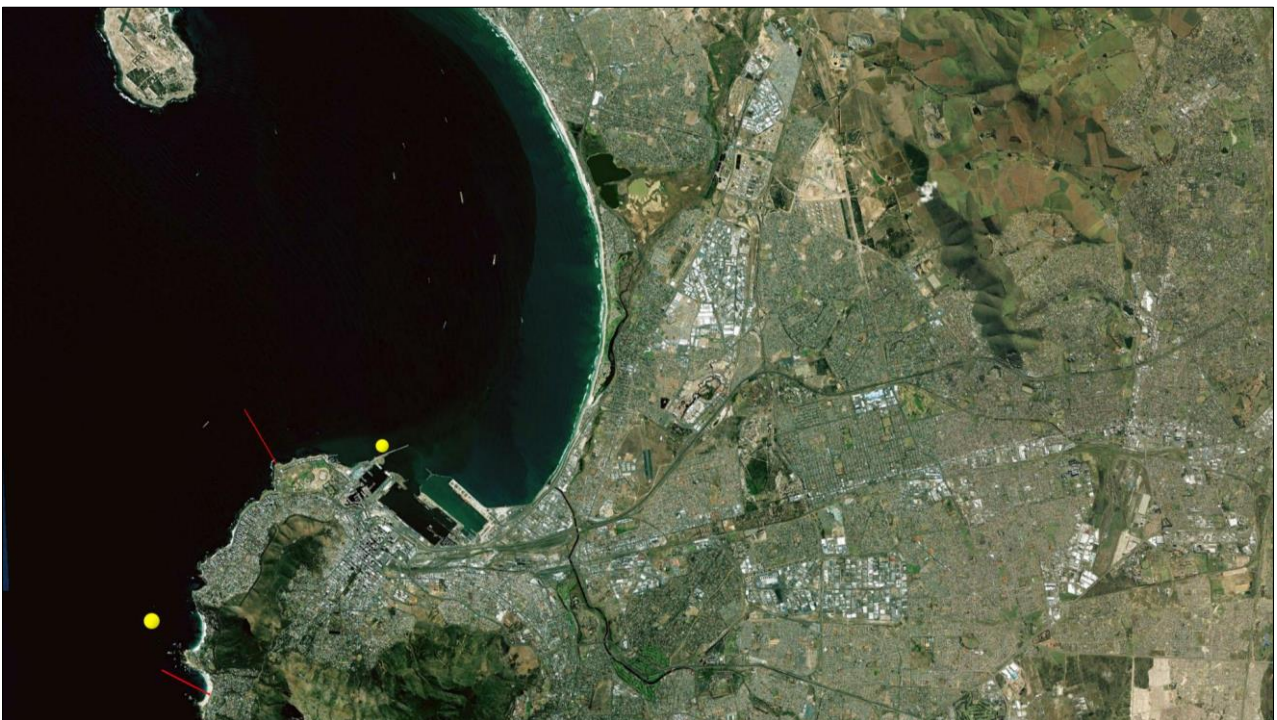


Figure 5.26. Bubble plot representation of lead Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 3.22. The Green Point and Camps Bay outfalls are denoted by the red lines.



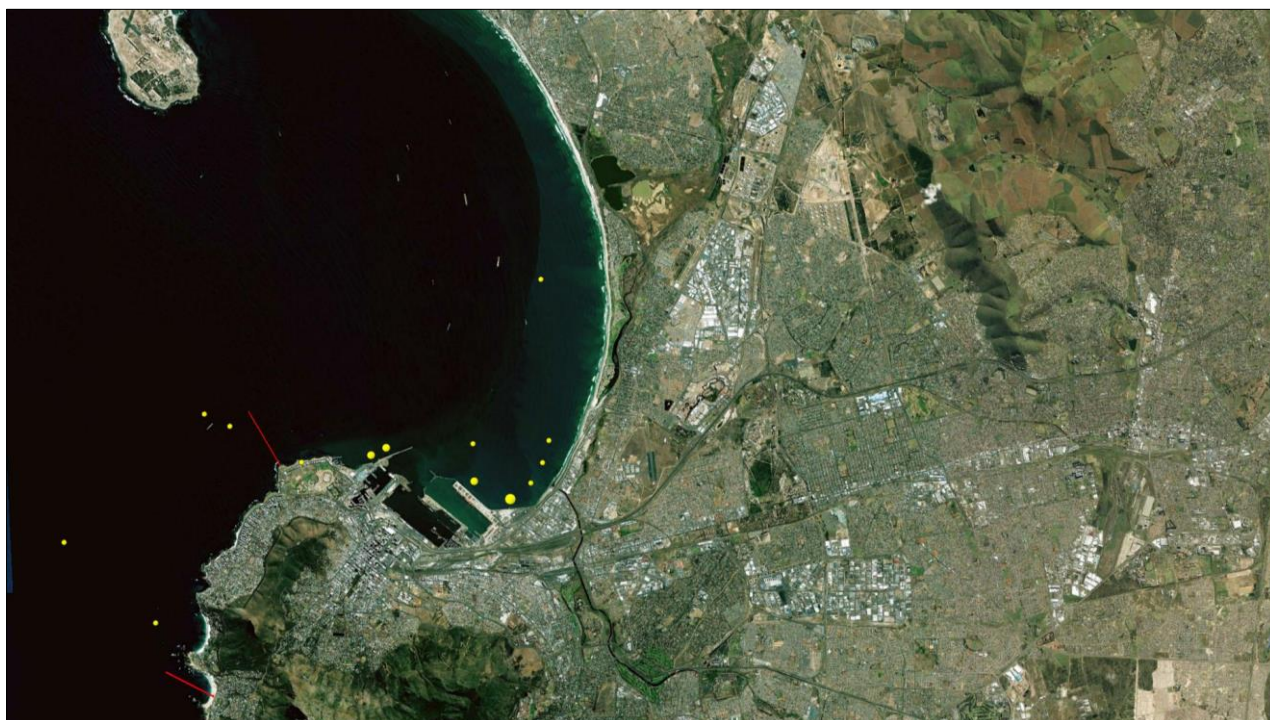


Figure 5.28. Bubble plot representation of zinc Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 2.30. The Green Point and Camps Bay outfalls are denoted by the red lines.

Enrichment Factors for each metal and the cumulative Enrichment Factor for all metals in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme are presented in Figure 5.15. For ease of interpretation Enrichment Factors are also presented as bubble plots in Figures 5.16 - 5.42. The bubbles are scaled to the magnitude of the Enrichment Factor, but only Enrichment Factors that exceed a value of one are shown, that is, only for concentrations that were higher than expected. Because of the wide range of Enrichment Factors for some metals the bubbles are not always scaled on a one to one basis. The plots nevertheless identify sites where metals were at a higher than expected concentration and provide an understanding on the difference in the magnitude of enrichment (note that Enrichment Factors should not be compared between Figures 5.16 - 5.42 since different bubble scales were used).

The highest Enrichment Factors were for the copper concentration in sediment collected at Site HB2 in Hout Bay Harbour, at 23.4 (Figures 5.15 and 5.35), at Site TB11 near the eastern breakwater for the Port of Cape Town, at 18.5 (Figures 5.15 and

5.21), and at Site HB1 in Hout Bay Harbour, at 18.2 (Figure 5.15 and 5.35). In other words, the copper concentration in sediment at these sites was about 23, 19 and 18 times higher than the highest concentration expected in uncontaminated sediment in the Cape Town outfalls study area. The highest, or amongst the highest Enrichment Factors for many metals were for Site TB11 near the western breakwater for the Port of Cape Town, for Sites HB1 and HB2 in Hout Bay Harbour, and for Site HB15 in the Disa (Hout Bay) River (Figure 5.15). The highest cumulative Enrichment Factors were also for these sites (Figure 5.15). Enrichment Factors for many metals at these sites, and indeed at certain other sites were high enough to conclude the enrichment reflects contamination. Enrichment Factors for some metals at the above sites and most metals in sediment at other sites rarely exceeded 1.5, that is, the magnitude of enrichment was relatively low. In many instances, in fact, Enrichment Factors were so low it is impossible to conclude the enrichment reflects contamination or a limitation of the baseline models.

The CSIR analysed metal concentrations in 57 sediment samples collected at 28 sites in 1980

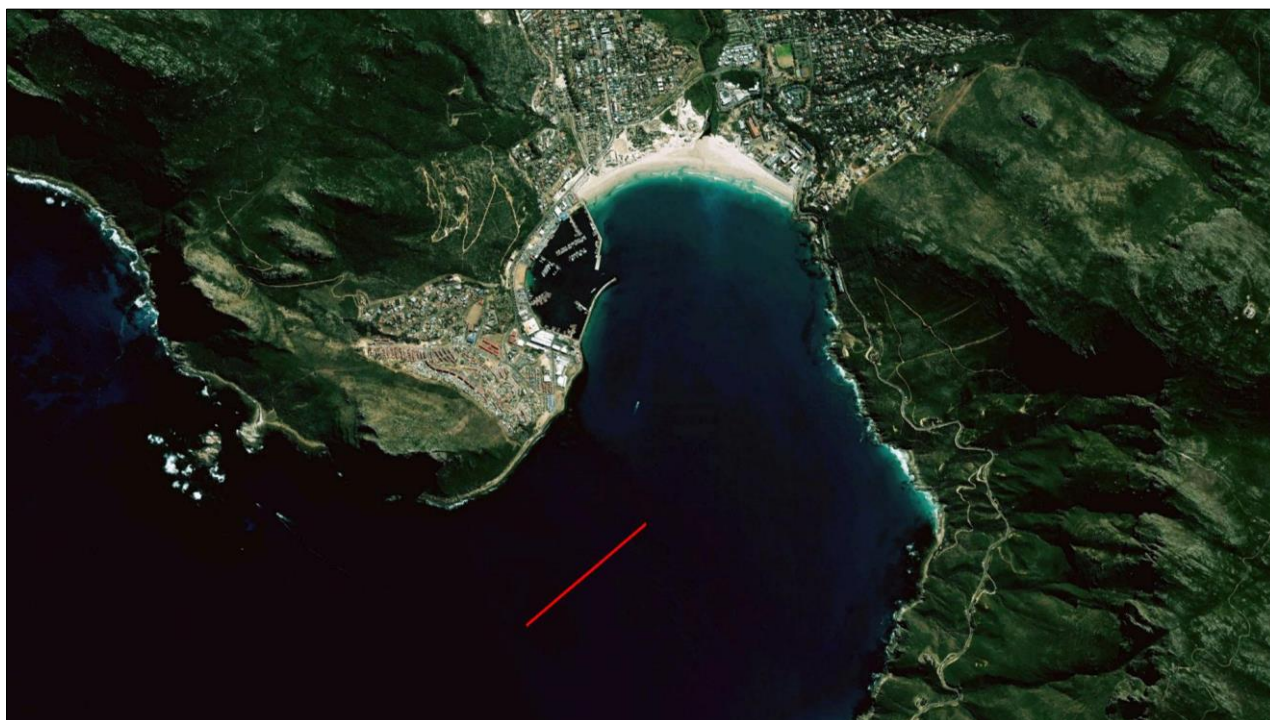


Figure 5.29. Bubble plot representation of iron Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. All Enrichment Factors were <1 . The Hout Bay outfall is denoted by the red line.

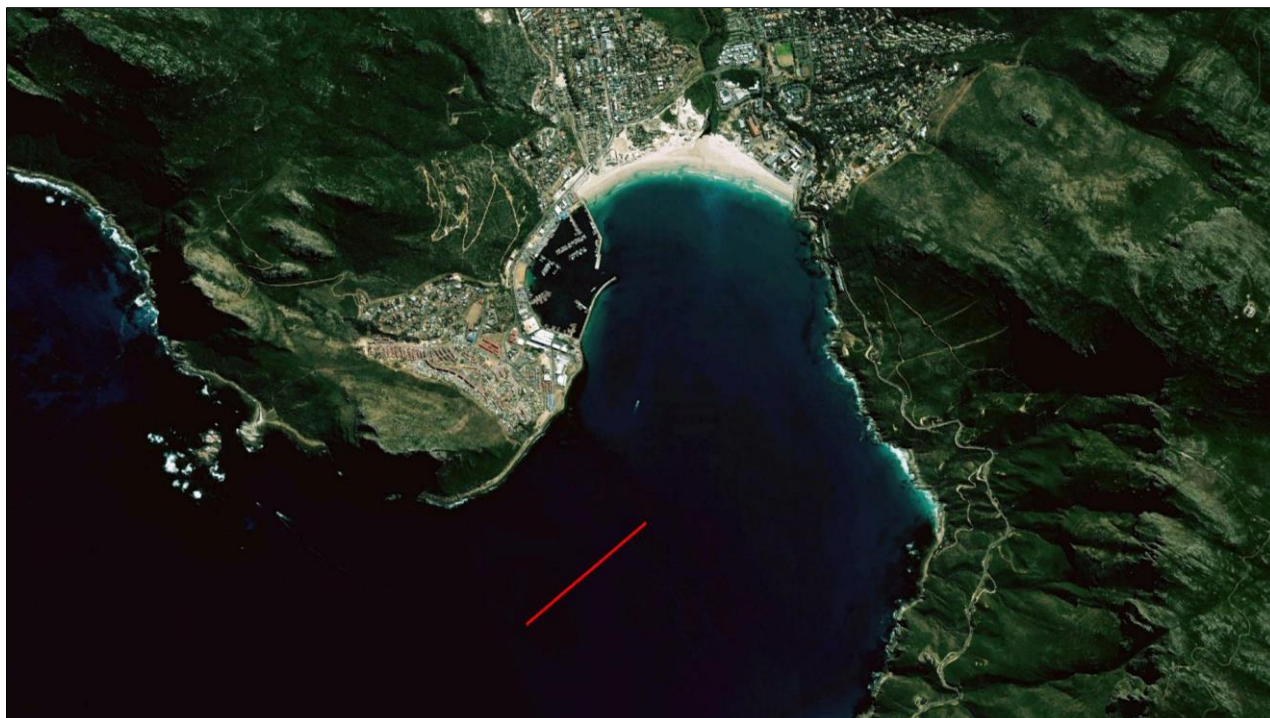


Figure 5.30. Bubble plot representation of arsenic Enrichment Factors exceeding a value of one for sediment collected



Figure 5.31. Bubble plot representation of barium Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 1.45. The Hout Bay outfall is denoted by the red line.

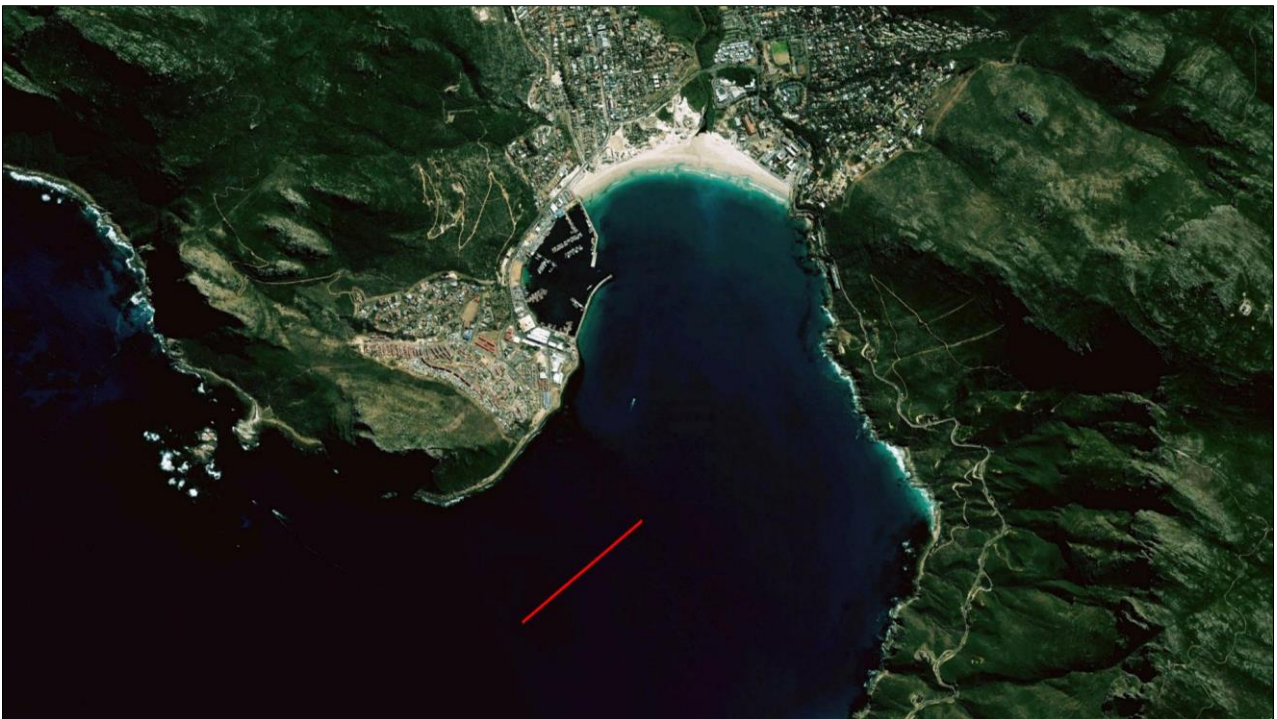


Figure 5.32. Bubble plot representation of beryllium Enrichment Factors exceeding a value of one for sediment

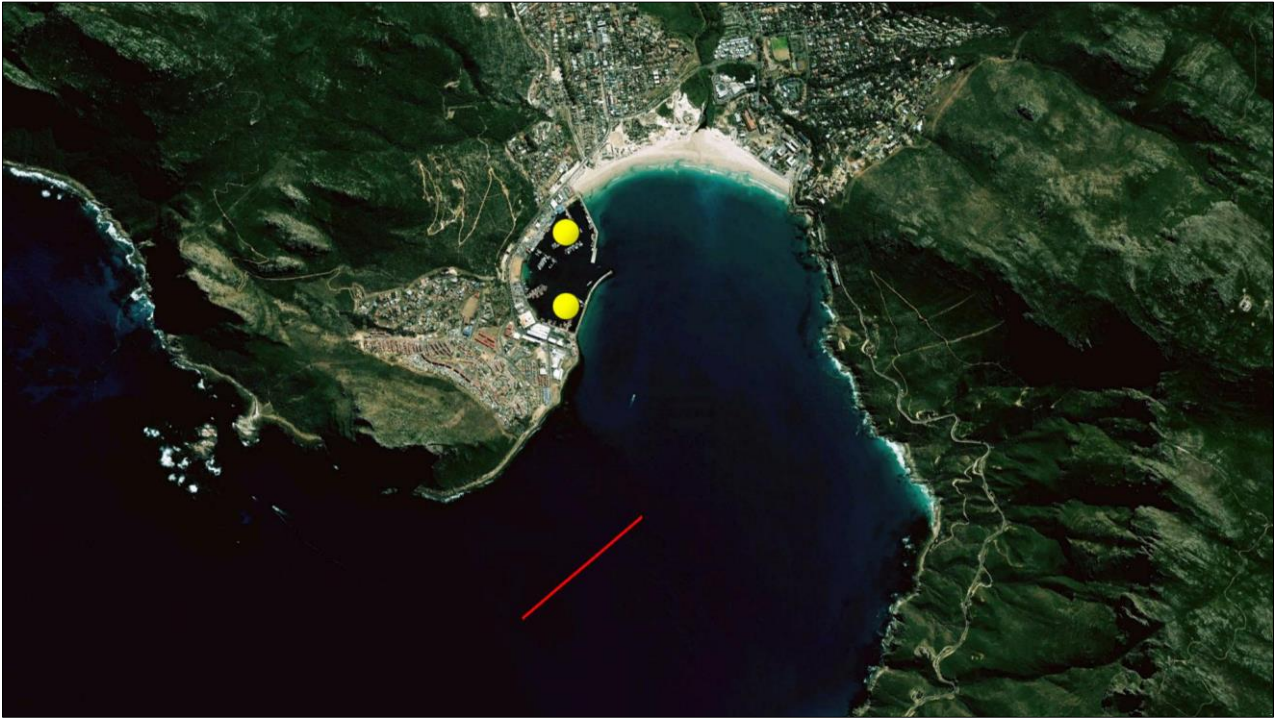


Figure 5.33. Bubble plot representation of cadmium Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 2.08. The Hout Bay outfall is denoted by the red line.

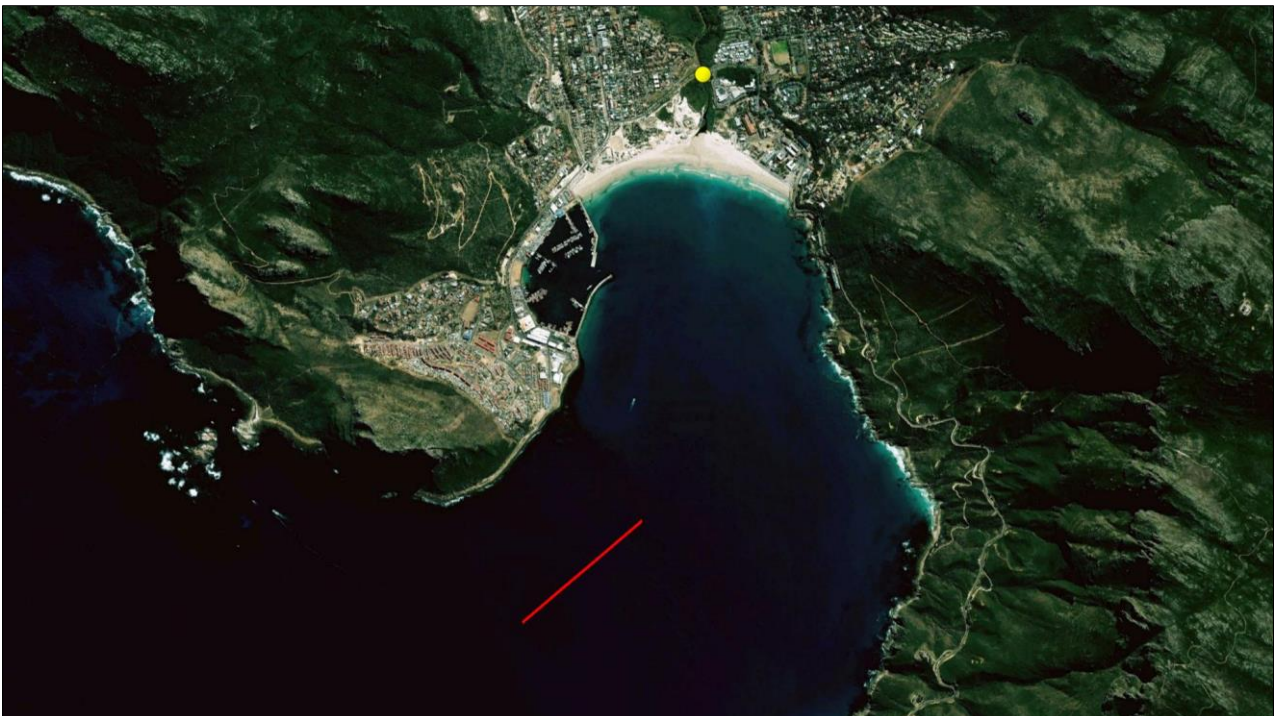


Figure 5.34. Bubble plot representation of cobalt Enrichment Factors exceeding a value of one for sediment collected

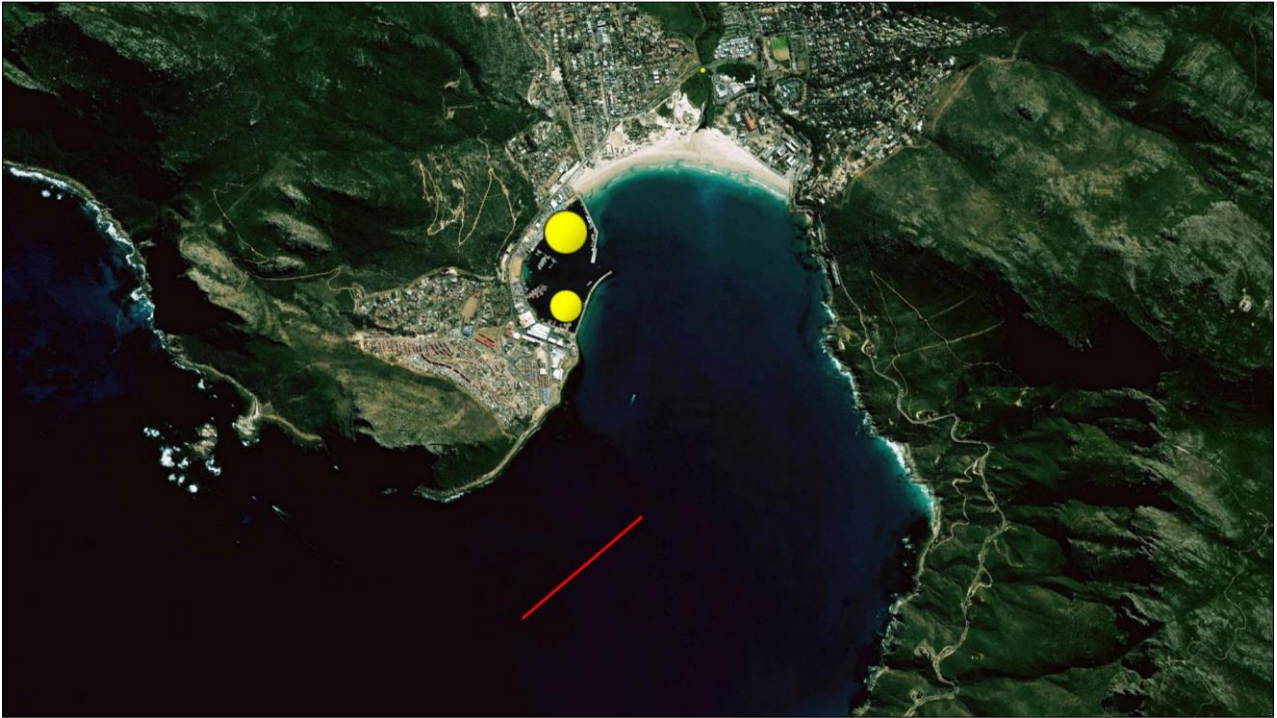


Figure 5.35. Bubble plot representation of copper Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 23.42. The Hout Bay outfall is denoted by the red line.

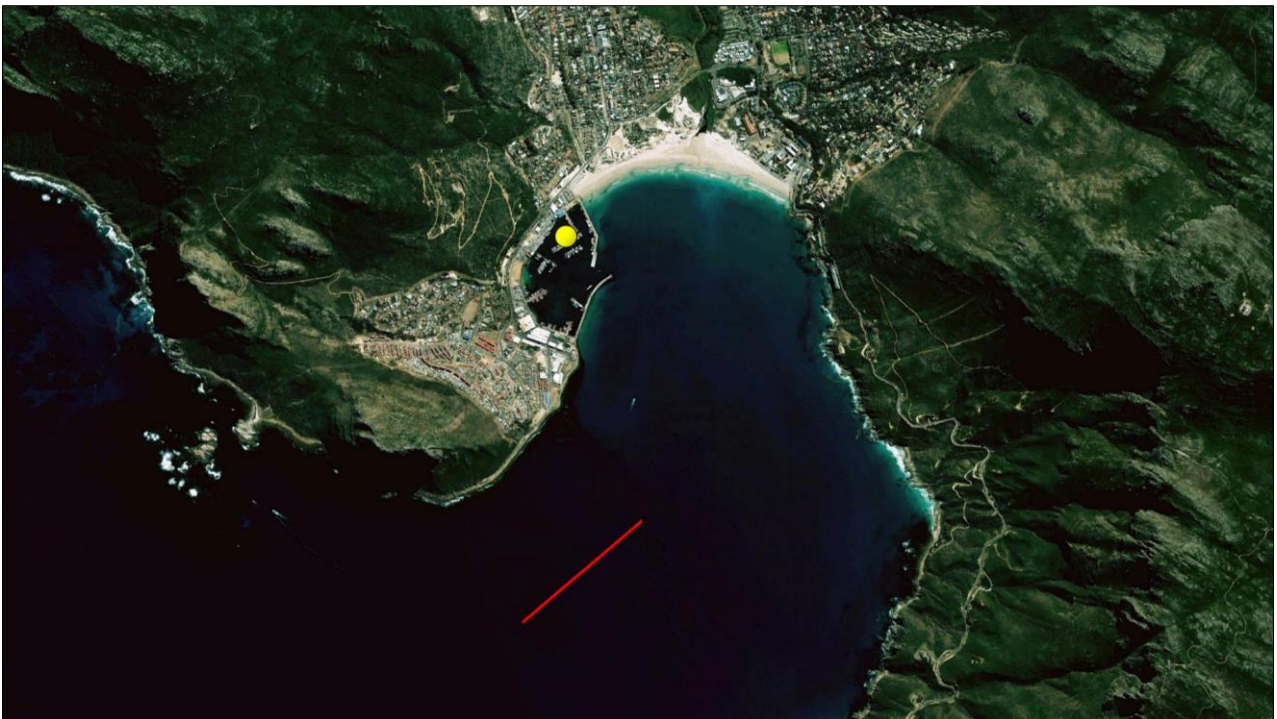


Figure 5.36. Bubble plot representation of chromium Enrichment Factors exceeding a value of one for sediment

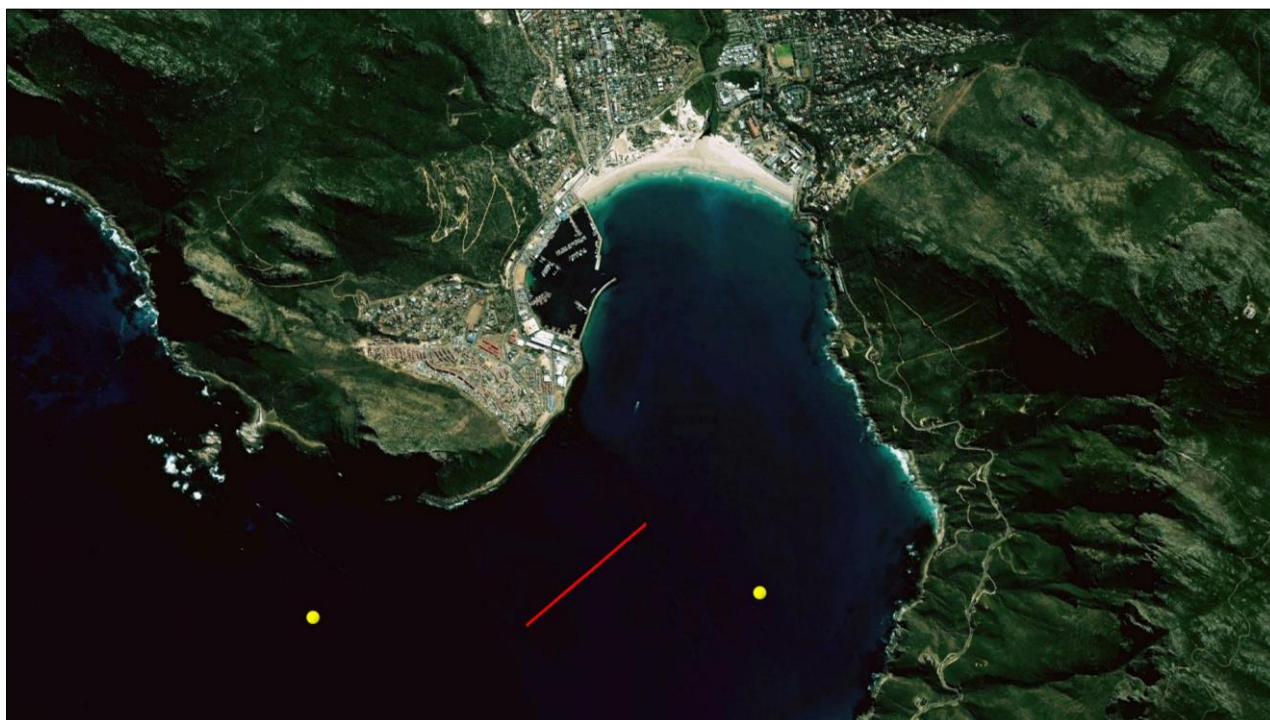


Figure 5.37. Bubble plot representation of manganese Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 1.25. The Hout Bay outfall is denoted by the red line.

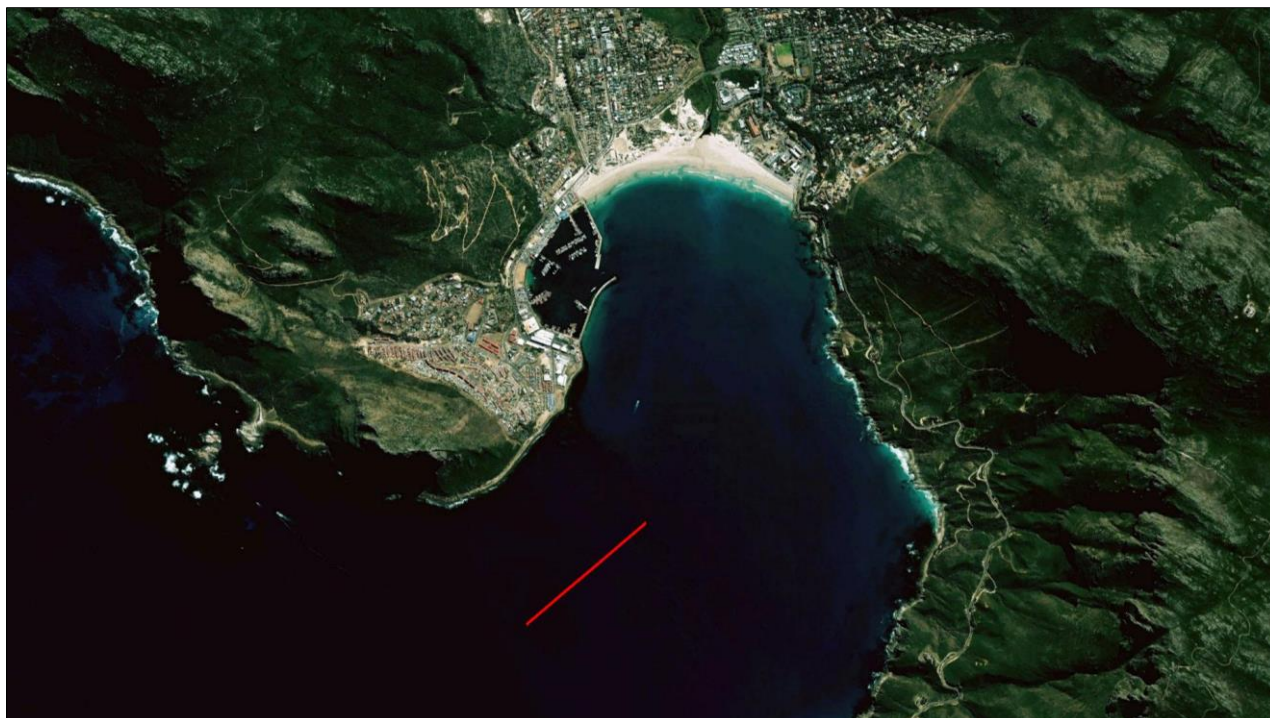


Figure 5.38. Bubble plot representation of mercury Enrichment Factors exceeding a value of one for sediment

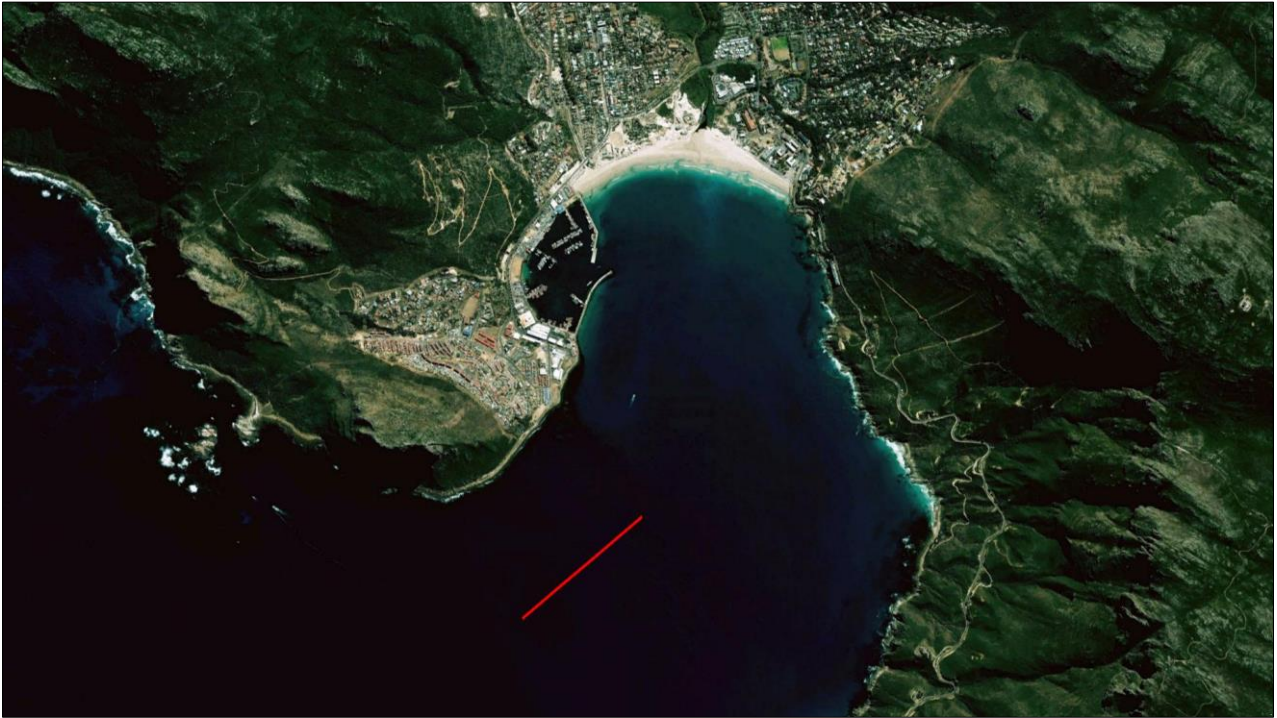


Figure 5.39. Bubble plot representation of nickel Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 3.49. The Hout Bay outfall is denoted by the red line.

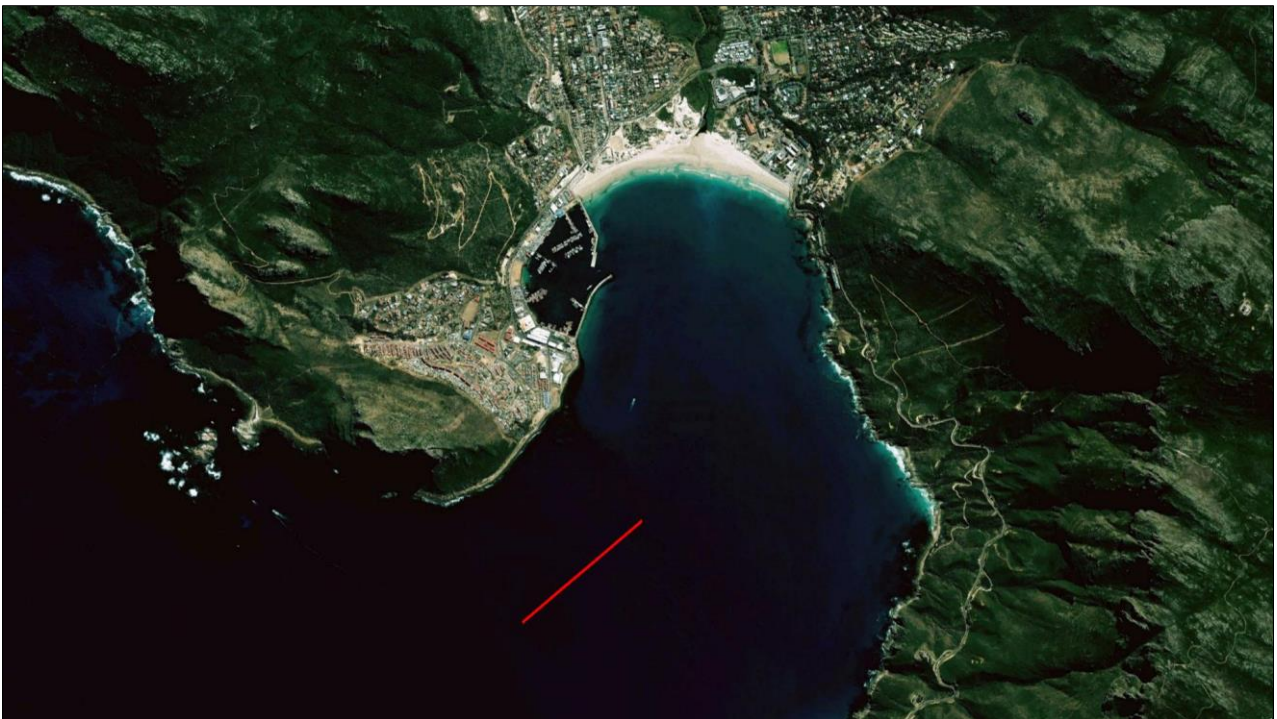


Figure 5.40. Bubble plot representation of lead Enrichment Factors exceeding a value of one for sediment collected in

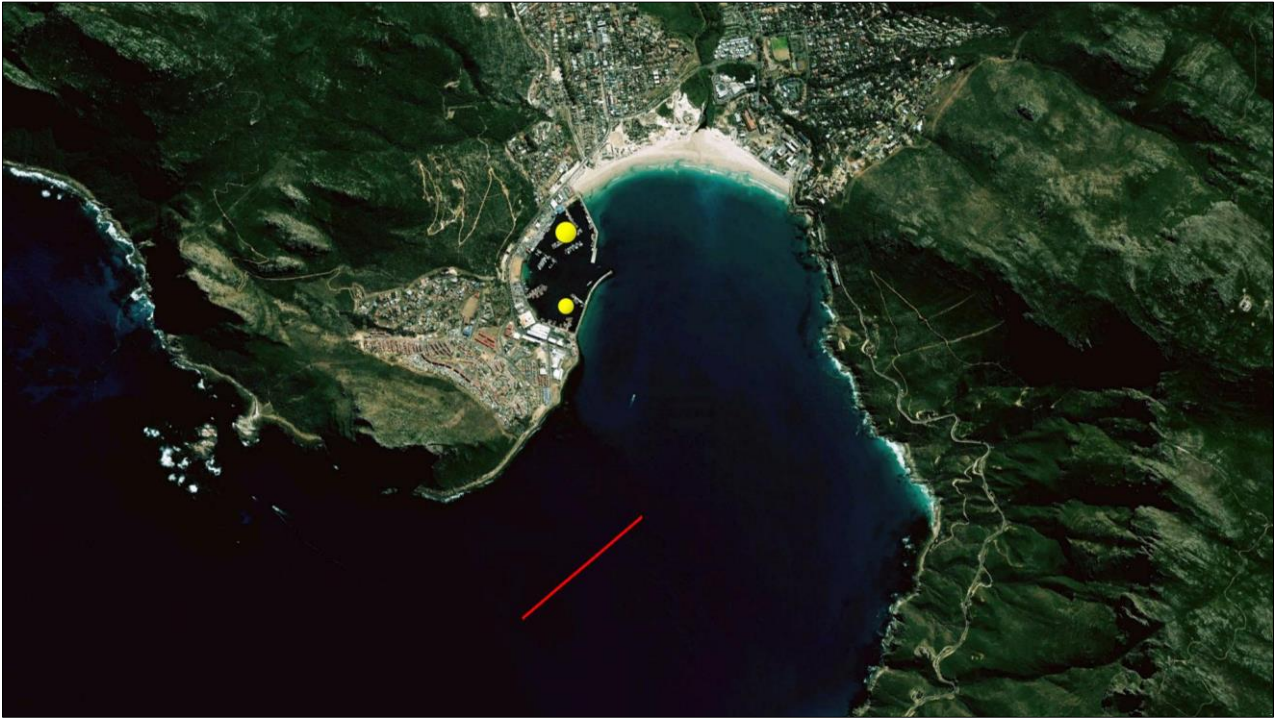


Figure 5.41. Bubble plot representation of vanadium Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents an Enrichment Factor of 1.52. The Hout Bay outfall is denoted by the red line.

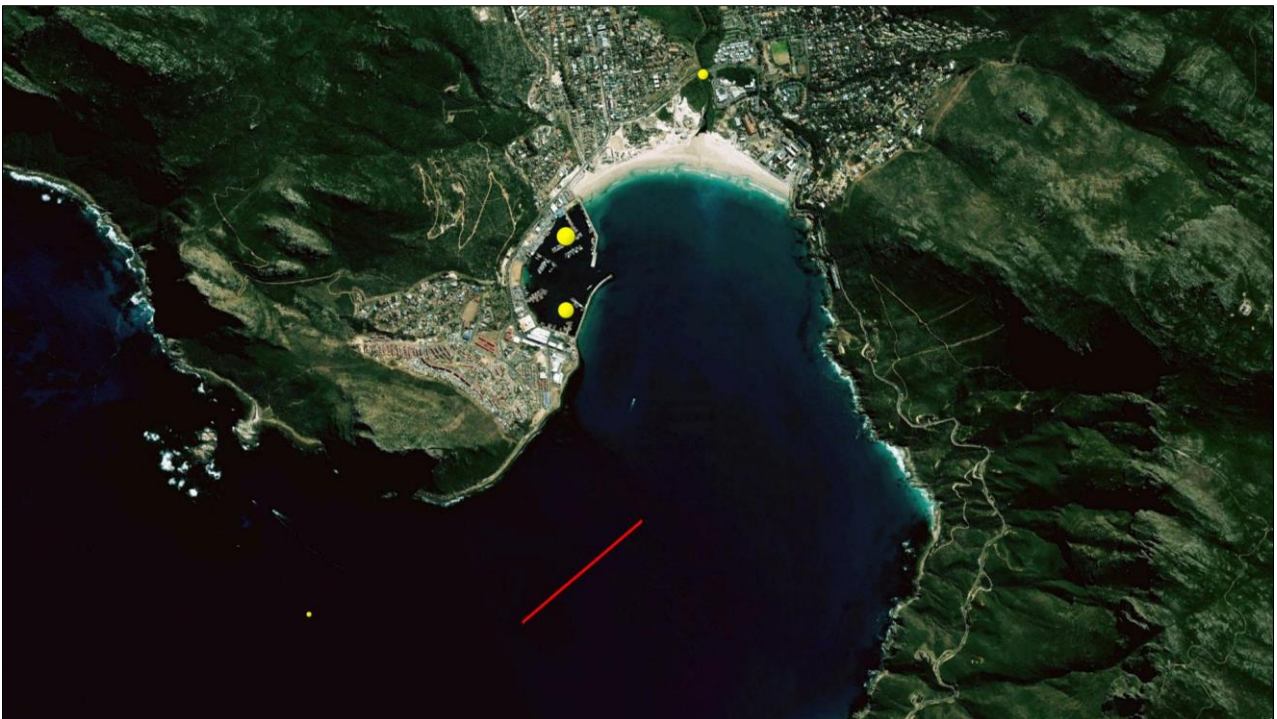


Figure 5.42. Bubble plot representation of zinc Enrichment Factors exceeding a value of one for sediment collected in

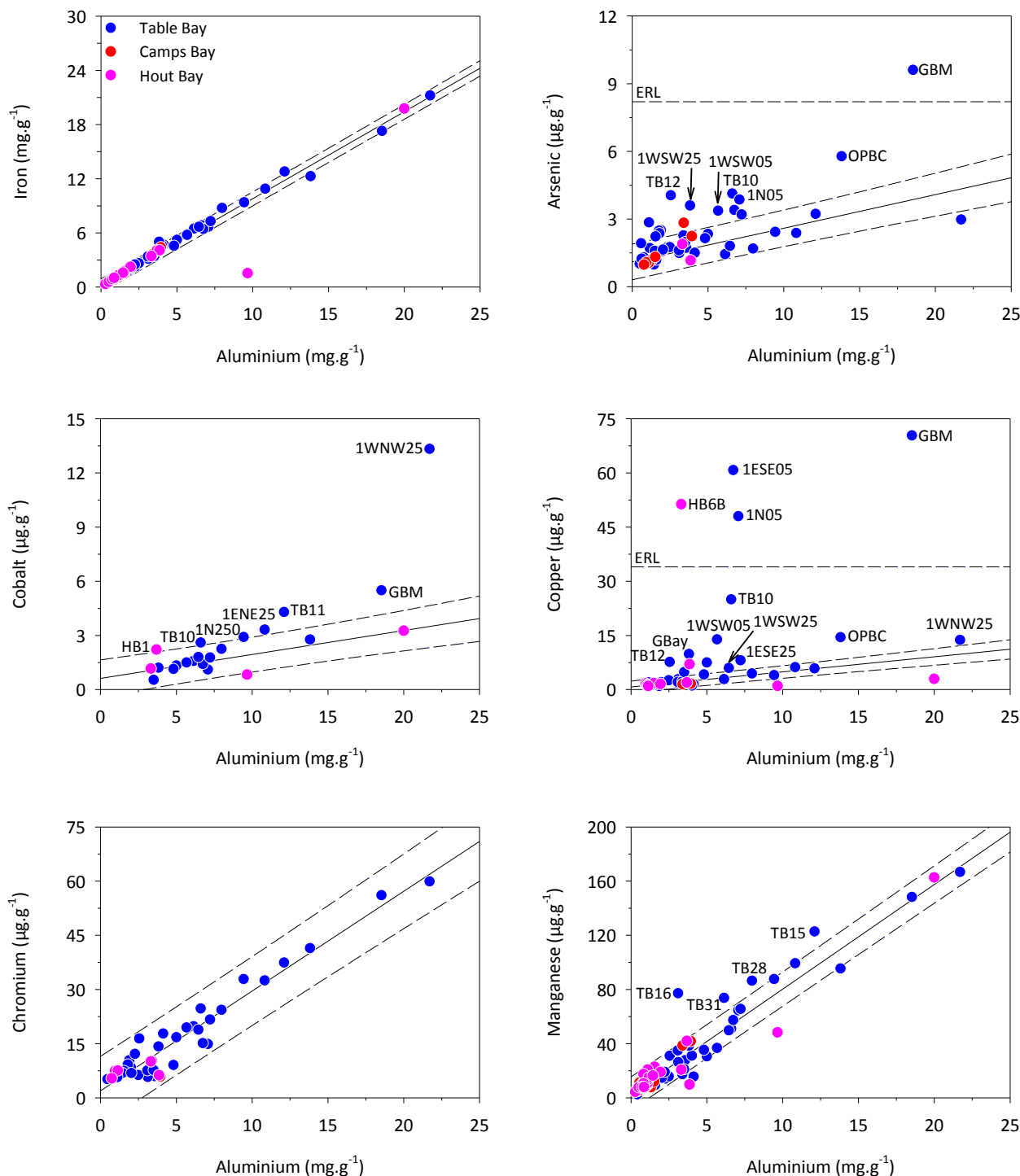


Figure 5.49. Baseline metal concentration models for sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2003 (CSIR, 2003), with metal concentrations in all sediment samples superimposed. Selected data points are highlighted by site identifiers. The horizontal dashed lines represent the Effects Range Low (ERL) of the sediment quality guidelines defined by Long *et al.* (1995) (only included if the guideline falls within the y-axis range).

(CSIR, 1982) and at 44 sites in 1982 in Table Bay (CSIR, 1985) (cores were collected at some sites) to assess the impact of effluent discharge through the Green Point outfall on the marine receiving environment (note the outfall operating at this time was replaced by the present outfall in 1993 and did not extend as far from the shoreline). Since Global

Positioning System coordinates were not provided for sites it is not possible to present their positions in a Google Earth image. The relationship between several metals and co-occurring iron concentrations (aluminium was only analysed in one survey) differed between surveys. This was commented on by the CSIR (1985), although the relationship

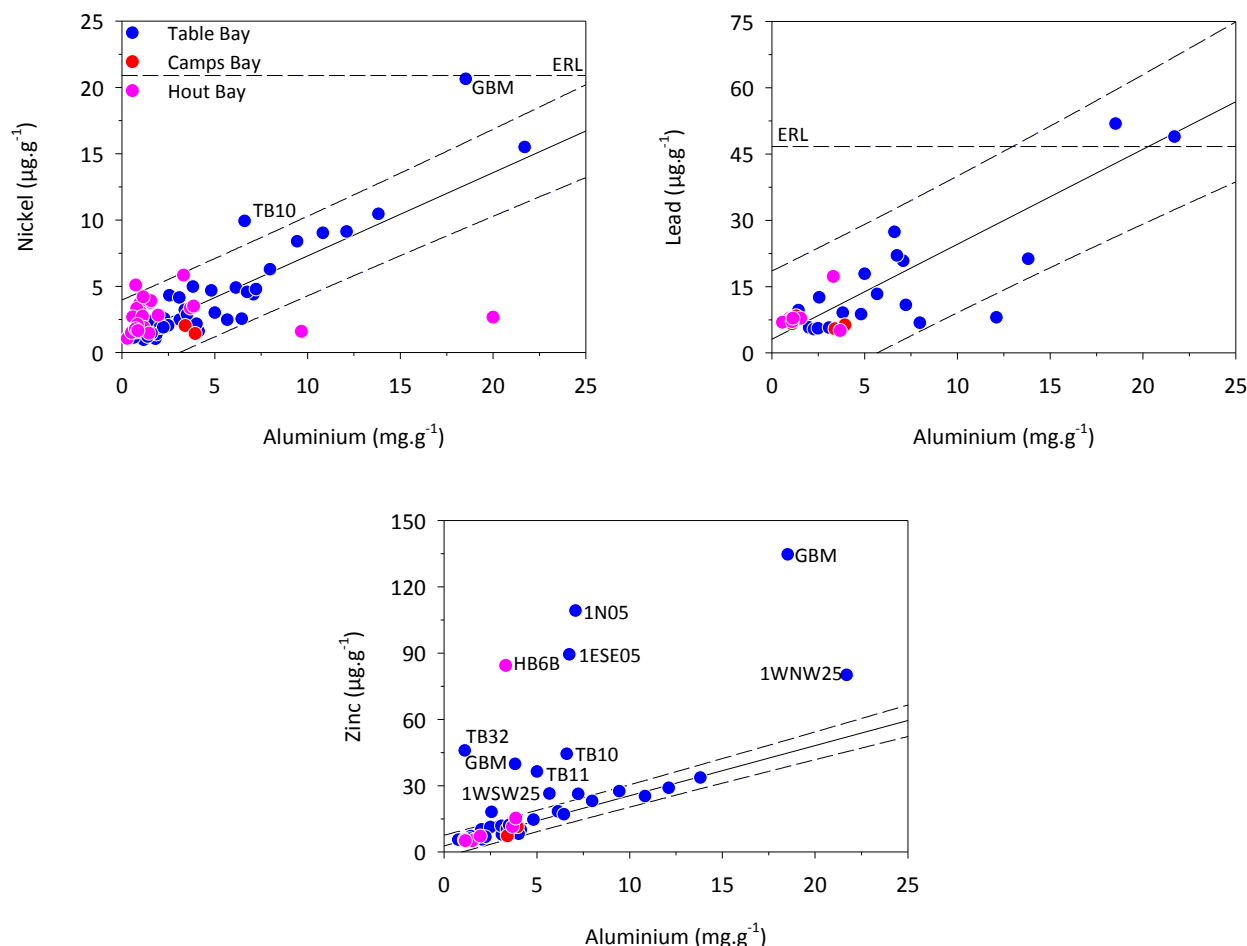


Figure 5.49 continued. Baseline metal concentration models for sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2003 (CSIR, 2003), with metal concentrations in all sediment samples superimposed. Selected data points are highlighted by site identifiers. The horizontal dashed lines represent the Effects Range Low (ERL) of the sediment quality guidelines defined by Long *et al.* (1995) (only included if the guideline falls within the y-axis range).

between metal concentrations was not used to interpret their concentrations in these studies. Because of the difference, baseline models were defined following the same procedure for this study but only using metal concentrations analysed in sediment collected for the 1980 survey. There were too few mercury concentrations exceeding the method detection limit to define a baseline model. The baseline models are provided in Figure 5.43, with metal concentrations analysed in all samples collected for the 1980 survey superimposed. To emphasise the difference in metal concentration relationships between the surveys, Figure 5.44 provides the same information as in Figure 5.43 but here with metal concentrations analysed in sediment collected in 1982 also superimposed. The difference in relationships for cadmium, mercury, nickel and zinc between surveys suggests the results for the 1982 survey were either anomalous as a result of a methodological issue or there was a marked increase in the spatial extent and

magnitude of contamination by these metals between surveys. Although the latter is unlikely, any conclusion in this context is complicated by the fact that relationships between most copper and manganese and to a lesser degree lead and co-occurring iron concentrations were comparable between the surveys. The relationship between baseline concentrations of several metals (*e.g.* copper and zinc) collected for the 1980 survey are comparable to iron normalised baseline models defined using sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme (not shown here). However, in the case of cadmium and nickel the differences are relatively pronounced.

For the 1980 survey there was evidence for minor to significant copper enrichment of sediment at seven of the 28 sites, minor to significant lead enrichment of sediment at five sites, minor to moderate manganese enrichment of sediment at

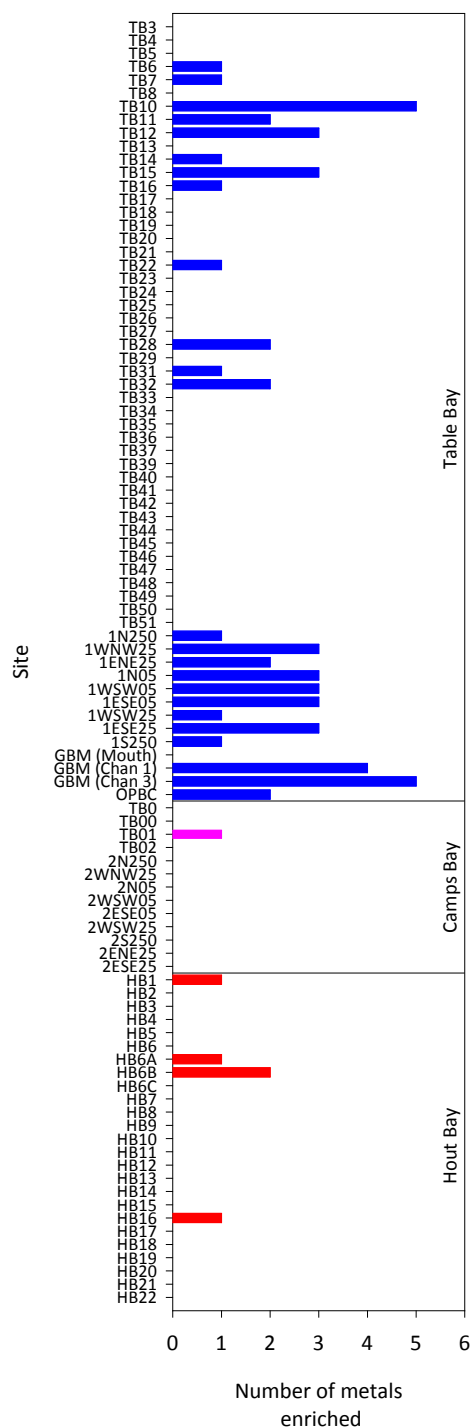


Figure 5.50. Number of metals at higher than expected concentrations in sediment samples collected in the Table Bay, Camps Bay and Hout Bay areas in 2003 (CSIR, 2003).

eight sites, minor cadmium and nickel enrichment of sediment at single sites, and minor to significant zinc enrichment of sediment at 14 sites (Figure 5.43). The sediment that was most frequently and/or significantly enriched by copper, nickel, lead and zinc was collected at three sites between Granger Bay Marina and the end of the western breakwater for the Port of Cape Town (Sites 13, 14 and 43 in Figure 5.43), opposite the entrance to the

port (Site 42 in Figure 5.43), and near the eastern breakwater for the port (Sites 40 and 41 in Figure 5.43). The only metal enriched in sediment near the Green Point outfall diffuser section was copper (Site 4 in Figure 5.43).

Although concentrations of some metals in sediment collected for the 1982 survey were anomalous compared to the 1980 survey, a similar trend was nevertheless evident in that the highest concentrations were usually in sediment collected in the area between Granger Bay and the end of the western breakwater for the Port of Cape Town, off the entrance to the port, and between the eastern breakwater for the port and the mouth of the Salt River. Based on the highest coprostanol (a faecal steroid) concentrations in sediment collected between Granger Bay and the end of the western breakwater for the Port of Cape Town in the 1982 survey, the CSIR (1985) concluded that the relatively higher organic content and concentrations of several metals in sediment in this area probably reflected an effluent discharge impact, but the contribution of metals from other sources, such as stormwater, was not discounted.

The CSIR analysed metal concentrations in sediment collected at 26 sites in Hout Bay prior to the commissioning of the Hout Bay outfall in 1993 (CSIR, 1993) and after its commissioning in 1994 (CSIR, 1995). All but one of the sites was within 500 m of the mid-point of the (proposed) outfall diffuser section, the remaining site about 1 000 m from the diffuser section. Since Global Positioning System coordinates were not provided for the sites it is not possible to present their positions in a Google Earth image. The only potential normaliser of metal concentrations analysed in sediment collected for the 1993 survey was iron and for the 1994 survey was aluminium. Metal concentrations analysed in the sediment are superimposed on aluminium and iron normalised baseline models defined using metal concentrations in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme in Figures 5.45 and 5.46. The reader should note that a smaller suite of metals was analysed in the 1993 and 1994 surveys compared to the 2015/2016 survey.

For the 1993 survey, concentrations of most metals



Figure 5.51. Bubble plot representation of the number of metals at higher than expected concentrations in sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The largest bubble represents 10 metals. The Green Point and Camps Bay outfalls are denoted by the red lines.

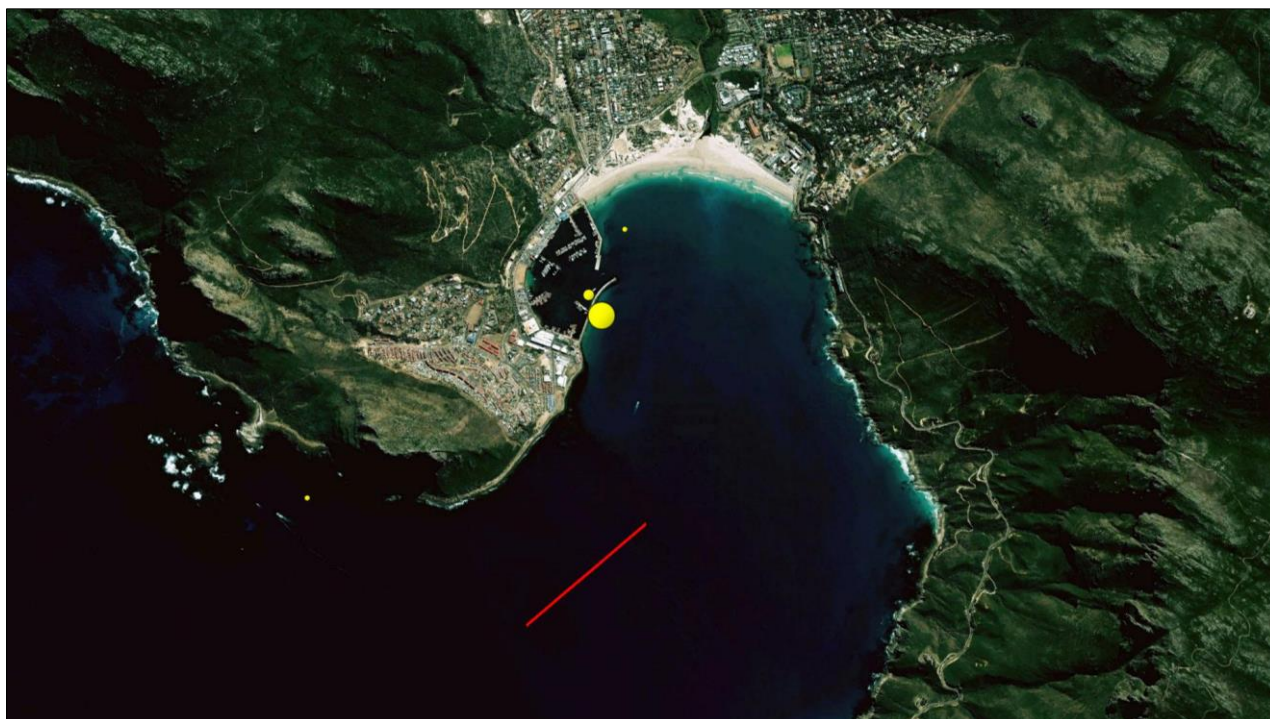


Figure 5.52. Bubble plot representation of the number of metals at higher than expected concentrations in sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The largest bubble represents 3 metals. The Hout Bay outfall is denoted by the red line.

fall within or near the baseline model prediction limits (Figure 5.45). Although all or most copper, mercury and nickel concentrations fall slightly above the relevant baseline model upper prediction limit it is doubtful this reflects contamination. This conclusion is based on the fact the outfall was not

operational at the time, although wastewater was discharged through a shoreline outfall at Badtamboer. The exceedances might reflect a difference in the extraction efficiency of some metals from sediment in the 1993 and 2015/2016 surveys, but in the absence of other information

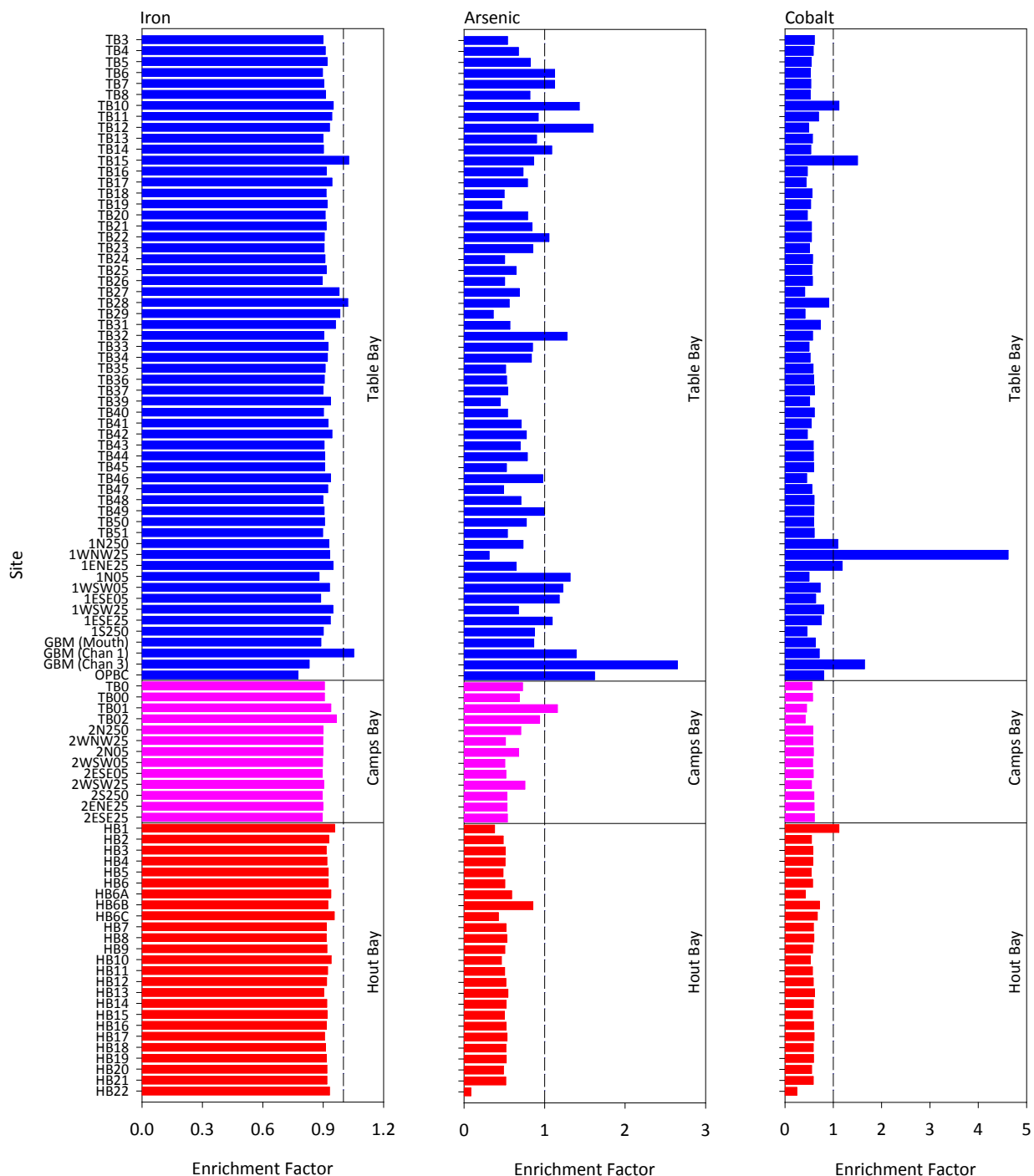


Figure 5.53. Enrichment Factors for metals in sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2003 (CSIR, 2003). The arrows denote the position of the outfall diffuser section relative to the sites. The vertical dashed lines represent an Enrichment Factor of one.

this conclusion is speculative. The only clear instances of contamination were for the mercury concentration in a sediment collected at the outfall terminus and zinc concentrations in sediment collected at sites 250 and 500 m from the mid-point of the diffuser section.

For the 1994 survey, the concentrations of most metals fall above the baseline model prediction limits, while most lead concentrations fall below

the lower prediction limit of the relevant baseline models (Figure 5.46). It is again uncertain if the exceedances reflect contamination or a difference in the extraction efficiency of metals from sediment between the 1993 and 1994 surveys, and between the latter survey and the 2015/2016 survey. If this is the case the only clear instances of contamination were for mercury and nickel in sediment collected at a site 250 m from mid-point of the outfall diffuser section. If not, then there was

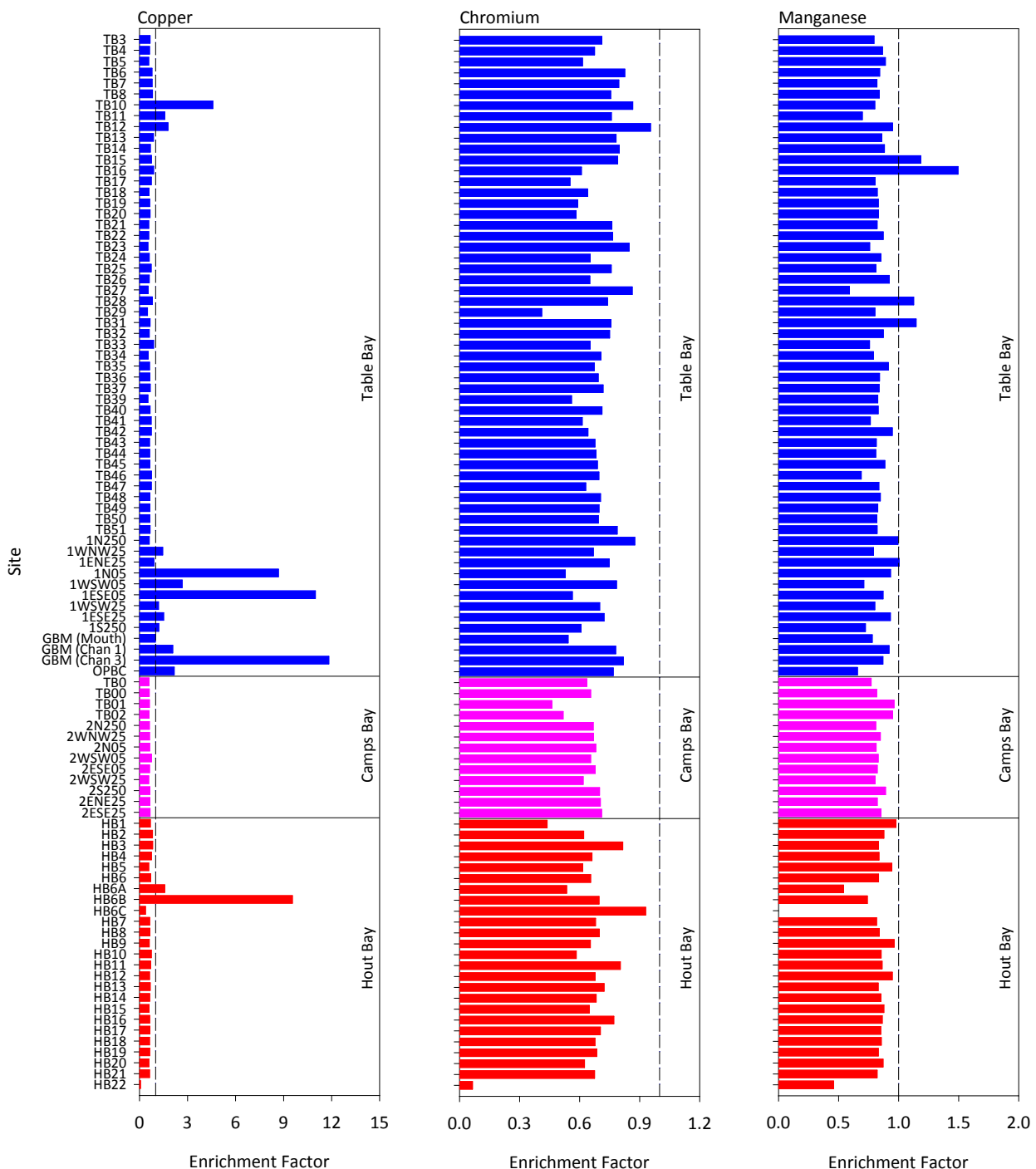


Figure 5.53 continued. Enrichment Factors for metals in sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2003 (CSIR, 2003). The arrows denote the position of the outfall diffuser section relative to the sites. The vertical dashed lines represent an Enrichment Factor of one.

evidence for low magnitude contamination of sediment at most sites by most metals.

The CSIR (2003) analysed metal concentrations in sediment collected at 97 sites in the Table Bay, Camps Bay and Hout Bay areas in 2003 (Figures 5.47 and 5.48). Figure 5.49 presents aluminium normalised baseline models defined using the metal concentrations, with metal concentrations analysed in all sediment samples superimposed.

The baseline models were defined using the same procedure as for the 2015/2016 survey. Baseline models were not defined using the combined 2003 and 2015/2016 survey data due to differences in the relationship between some metal and co-occurring aluminium concentrations between surveys. Although differences for most metals were minor this was not the case for arsenic, for which there was a marked difference. Also, the method detection limit for certain metals was considerably

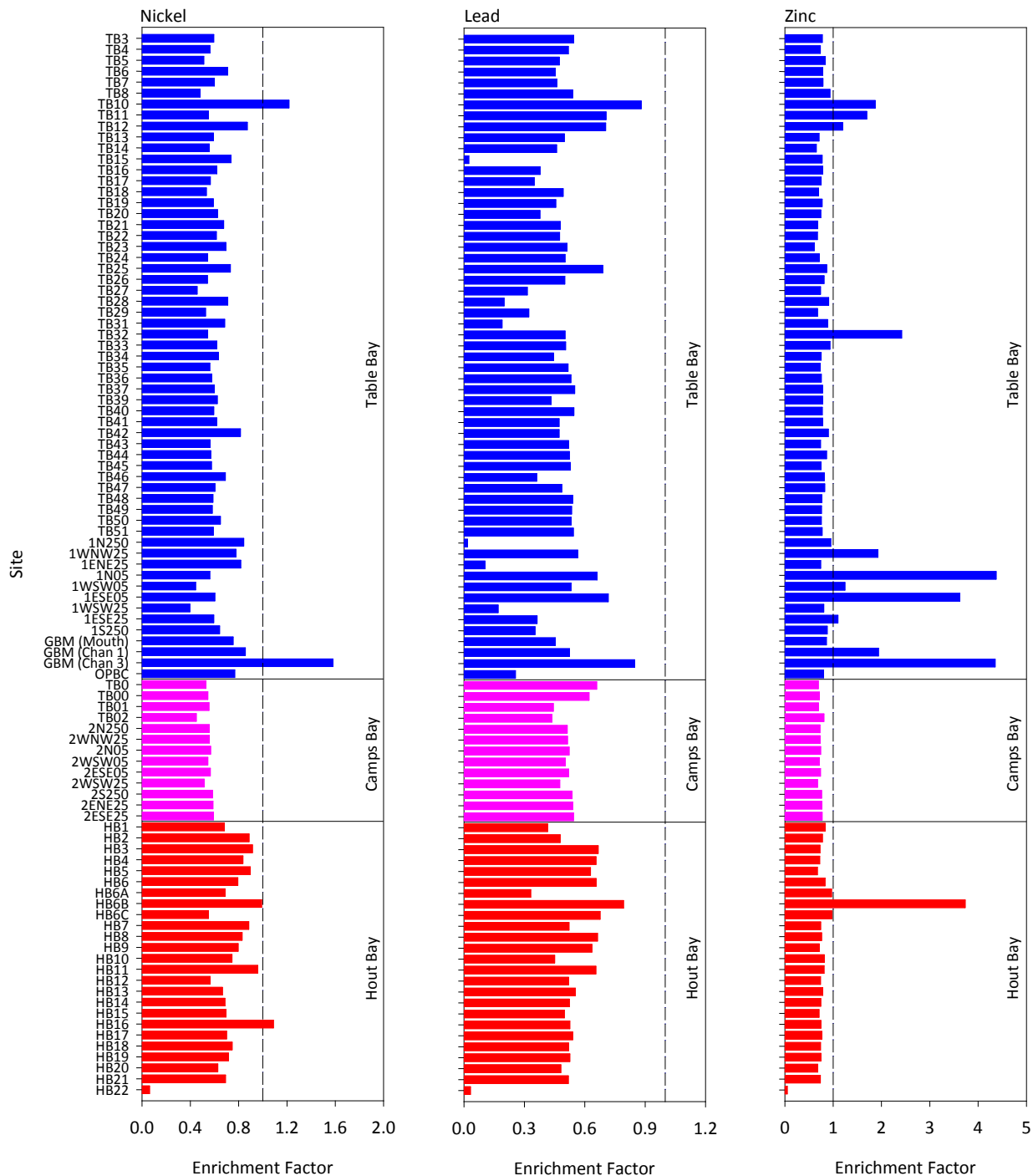


Figure 5.53 continued. Enrichment Factors for metals in sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2003 (CSIR, 2003). The arrows denote the position of the outfall diffuser section relative to the sites. The vertical dashed lines represent an Enrichment Factor of one.

higher in the 2003 survey. Thus, cadmium and mercury were at a concentration exceeding the method detection in only one and two of the 97 sediment samples respectively. Baseline models could not, therefore, be defined for these metals. The reader should note that a smaller suite of metals was analysed in the 2003 survey compared to the 2015/2016 survey.

in sediment at each site following the same procedure for the 2015/2016 survey. The number of metals at a higher than expected concentration in sediment collected in 2003 is provided in Figure 5.50, and for ease of interpretation as bubble plots in Figures 5.51 and 5.52. Enrichment Factors for metals are presented in Figure 5.53 and as bubble plots in Figures 5.54 - 5.71.

Enrichment Factors were calculated for each metal

For sediment collected in the Camps Bay area a

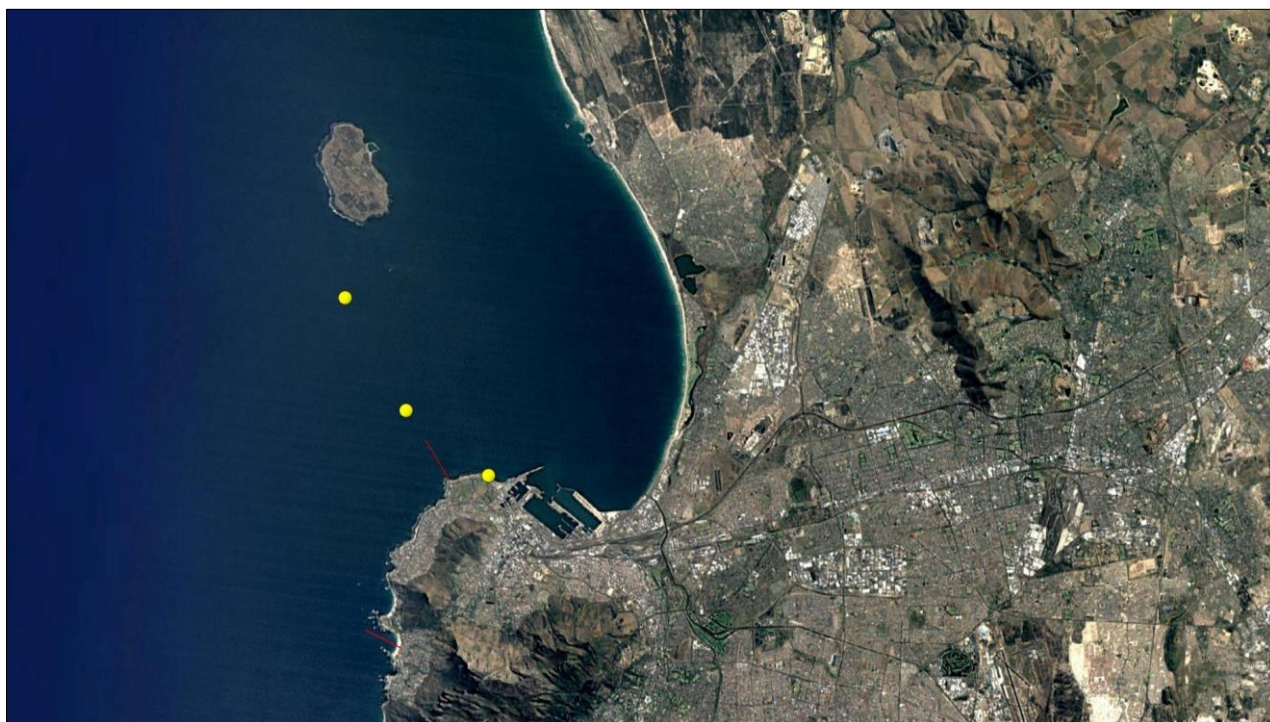


Figure 5.54. Bubble plot representation of iron Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The largest bubble represents an Enrichment Factor of 1.05. The Green Point and Camps Bay outfalls are denoted by red lines.

single metal was at a higher than expected concentration, while five metal concentrations in sediment at three sites in the Hout Bay area were higher than expected. Sediment at most sites within about 370 m of the Green Point outfall terminus was, in contrast, enriched by at least one metal, but usually by three metals (these sites denoted by the prefix 1 in Figures 5.49 and 5.50). Apart from certain of the latter sites the largest number of metals at a higher than expected concentration was in sediment at two sites in Granger Bay Marina (sites denoted with prefix GBM in Figure 5.50), at a site in the Oceana Powerboat Club basin (Site OPBC), at a site near the end of the western breakwater for the Port of Cape Town (Site TB10), at a site in the southeastern part of Table Bay about 1 000 m to the north of the mouth of the Salt River (Site TB12), and at a site about 1 400 m to the north-northwest of the Green Point outfall terminus (Site TB15). The sediment at these sites was sometimes enriched to a high magnitude by cobalt, copper and/or zinc (Figures 5.53 and 5.54 - 5.71). The highest Enrichment Factors were 11.5 for the copper concentration in sediment collected at a site in Granger Bay Marina and 11.0 for the copper concentration in sediment collected at a site near the Green Point outfall terminus (Figures 5.53

and 5.57). The sediment at ten other sites in Table Bay was metal enriched, but usually by a single metal (Figures 5.50 and 5.51) to a low magnitude (Figures 5.53 - 5.62). In Hout Bay, metals were at a higher than expected concentration in sediment at four sites (Figures 5.50 and 5.52). Sediment at Site HB6B near Hout Bay Harbour was enriched by five metals and that at Site HB6A in the harbour by two metals, and at the remaining sites by a single metal. Apart from copper and zinc in sediment collected at Site HB6B the magnitude of enrichment was low (Figures 5.53 and 5.63 - 5.71).

The CSIR (2006, 2011) analysed metal concentrations in sediment collected at five sites in Table Bay and four in Hout Bay in 2005 and 2006, and in 2010 and 2011 (Figures 5.72 and 5.73). These included sites recommended by the CSIR (2003) for assessing the long-term impact of effluent discharge through the outfalls, based on the findings of metal concentrations in sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2003 (as discussed above). The sites represent near- and farfield areas where the propensity for the accumulation of effluent-derived constituents in sediment was considered highest. Metal concentrations in the sediment are super-



Figure 5.55. Bubble plot representation of arsenic Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The bottom image provides a close up view of the area between the Green Point outfall and western breakwater for the Port of Cape Town. The largest bubble represents an Enrichment Factor of 2.65. The Green Point and Camps Bay outfalls are denoted by red lines.



Figure 5.56. Bubble plot representation of cobalt Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The bottom image provides a close up view of the area between the Green Point outfall and western breakwater for the Port of Cape Town. The largest bubble represents an Enrichment Factor of 4.61. The Green Point and Camps Bay outfalls are denoted by red lines.



Figure 5.57. Bubble plot representation of copper Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The bottom image provides a close up view of the area between the Green Point outfall and western breakwater for the Port of Cape Town. The largest bubble represents an Enrichment Factor of 11.82. The Green Point and Camps Bay outfalls are denoted by red lines.

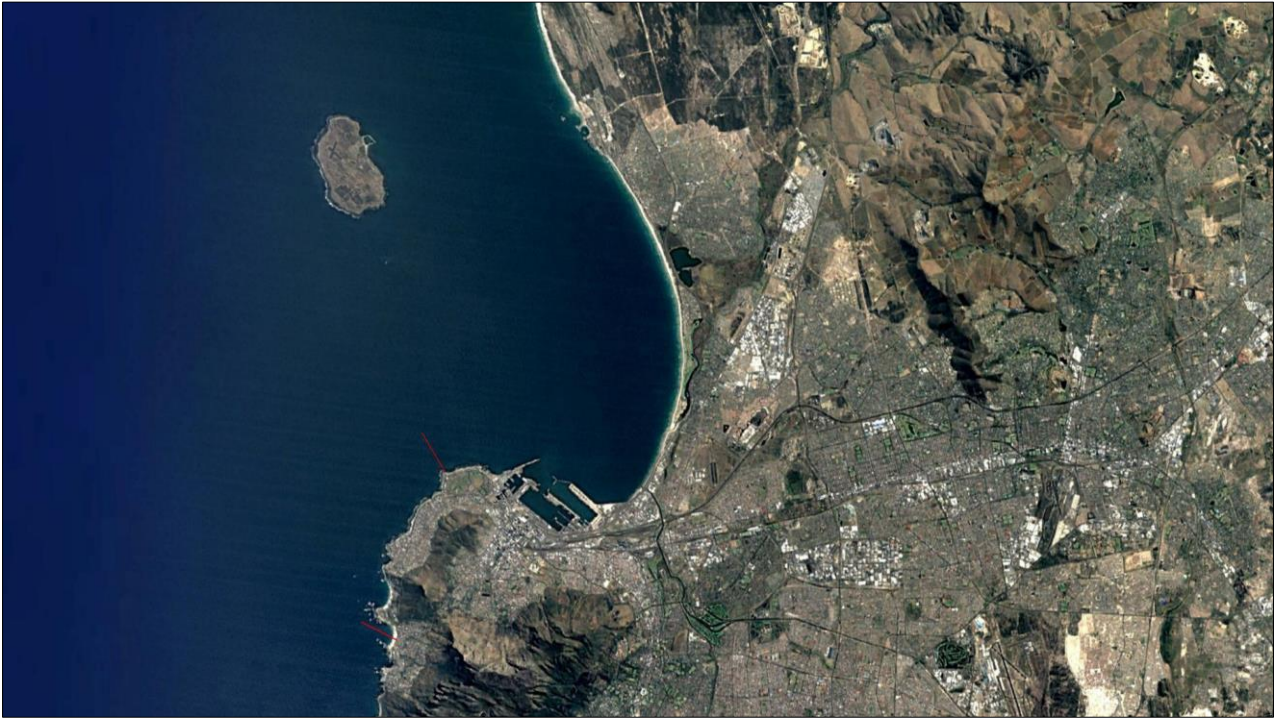


Figure 5.58. Bubble plot representation of chromium Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The Green Point and Camps Bay outfalls are denoted by red lines.



Figure 5.59. Bubble plot representation of manganese Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The largest bubble represents an Enrichment Factor of 1.49. The Green Point and Camps Bay outfalls are denoted by red lines.

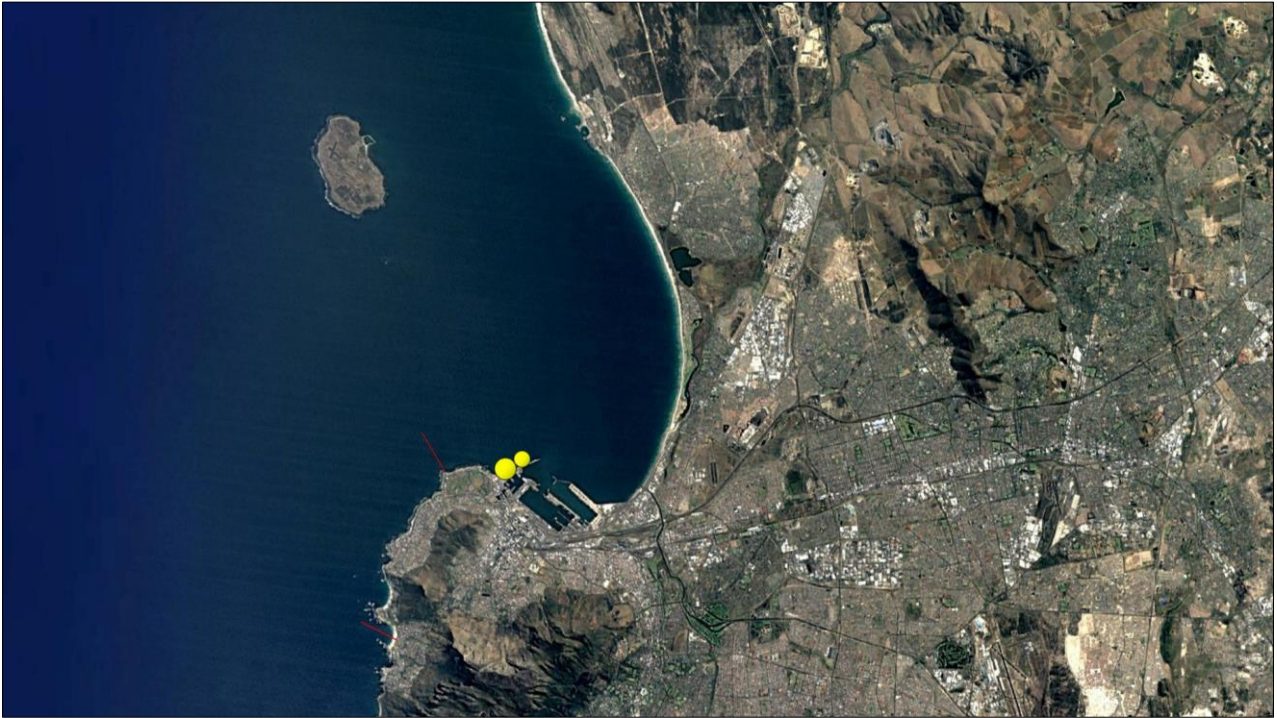


Figure 5.60. Bubble plot representation of nickel Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The largest bubble represents an Enrichment Factor of 1.58. The Green Point and Camps Bay outfalls are denoted by red lines.

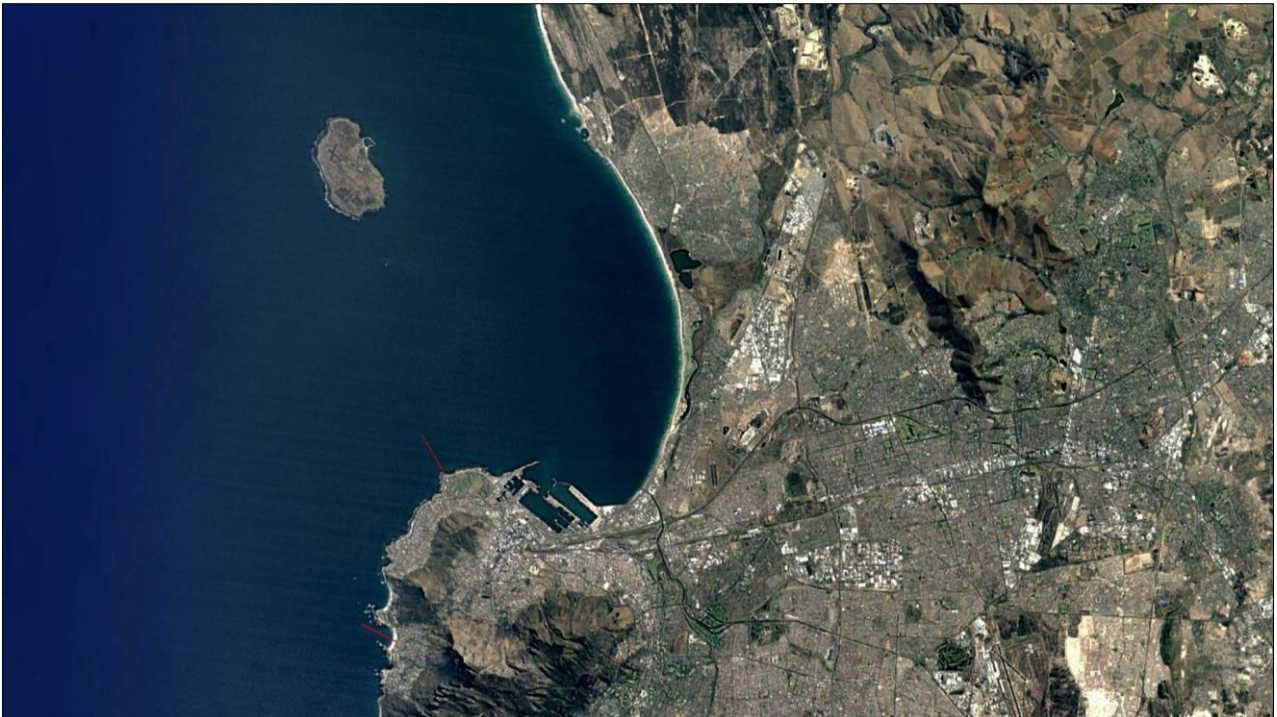


Figure 5.61. Bubble plot representation of lead Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The Green Point and Camps Bay outfalls are denoted by red lines.



Figure 5.62. Bubble plot representation of zinc Enrichment Factors exceeding a value of one for sediment collected in the Table Bay and Camps Bay areas in 2003 (CSIR, 2003). The bottom image provides a close up view of the area between the Green Point outfall and western breakwater for the Port of Cape Town. The largest bubble represents an Enrichment Factor of 4.37. The Green Point and Camps Bay outfalls are denoted by red lines.

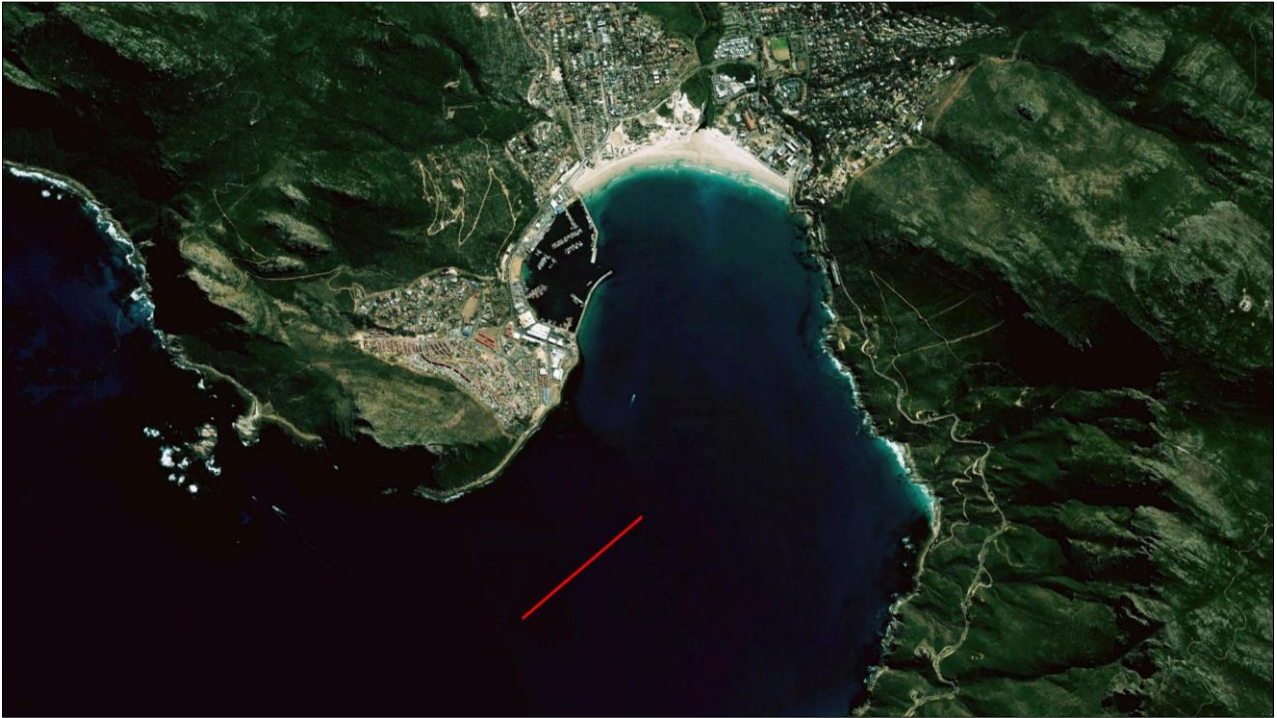


Figure 5.63. Bubble plot representation of iron Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The Hout Bay outfall is denoted by the red line.

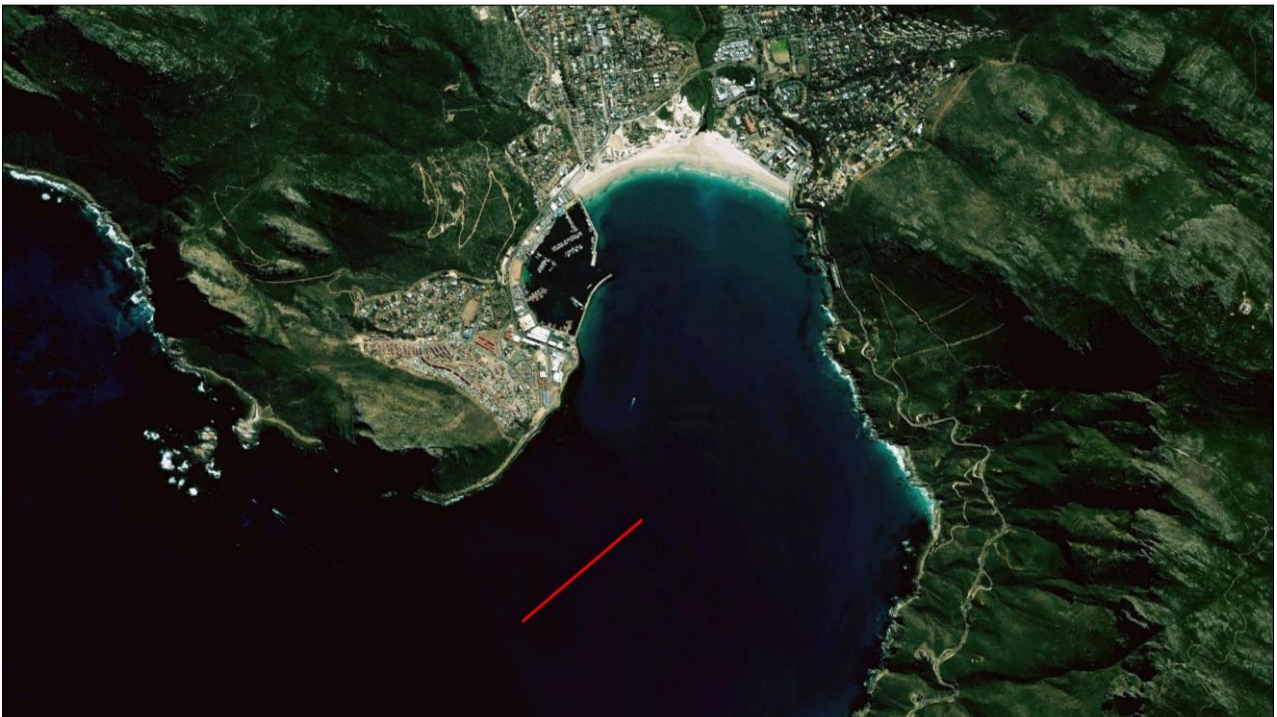


Figure 5.64. Bubble plot representation of arsenic Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The Hout Bay outfall is denoted by the red line.

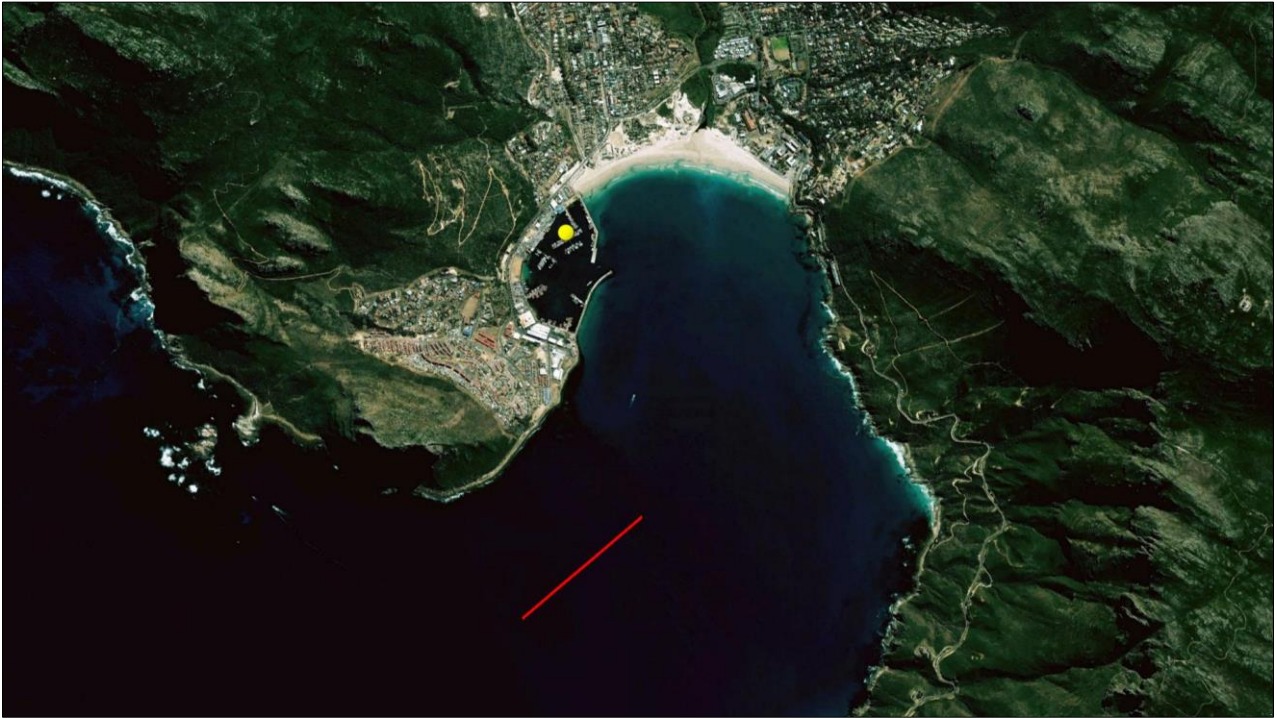


Figure 5.65. Bubble plot representation of cobalt Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The largest bubble represents an Enrichment Factor of 1.12. The Hout Bay outfall is denoted by the red line.

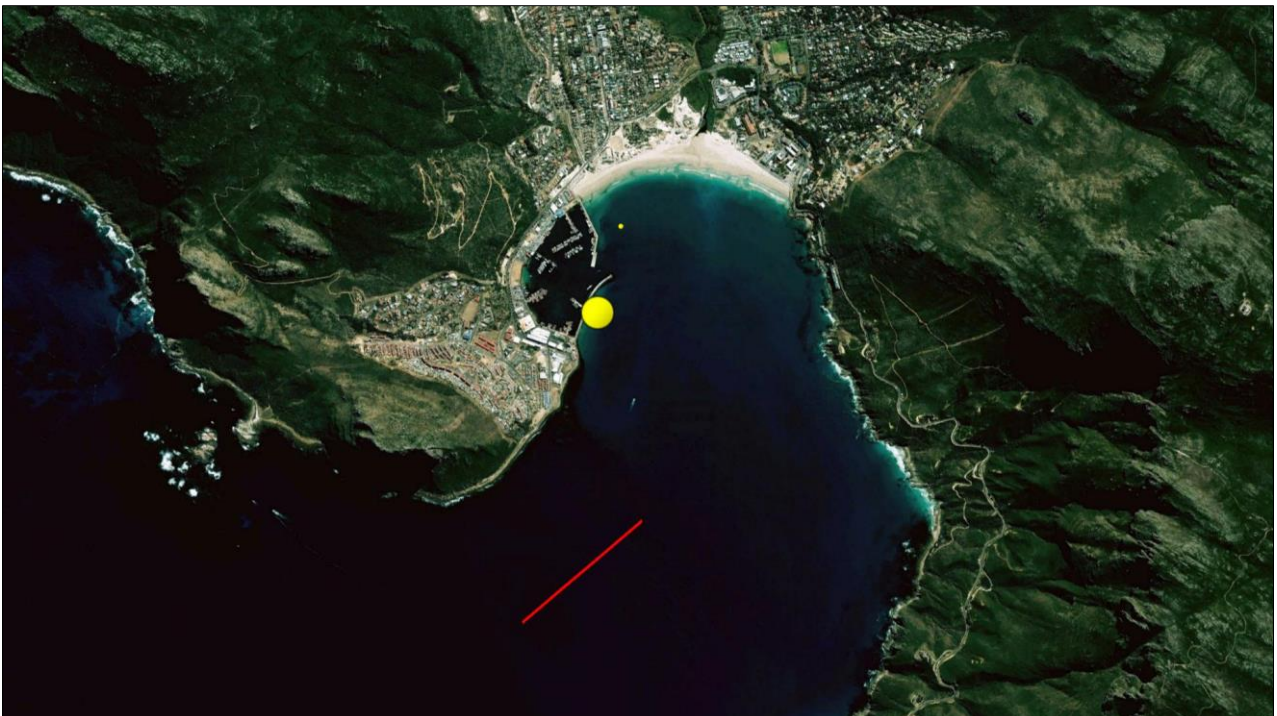


Figure 5.66. Bubble plot representation of copper Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The largest bubble represents an Enrichment Factor of 9.55. The Hout Bay outfall is denoted by the red line.

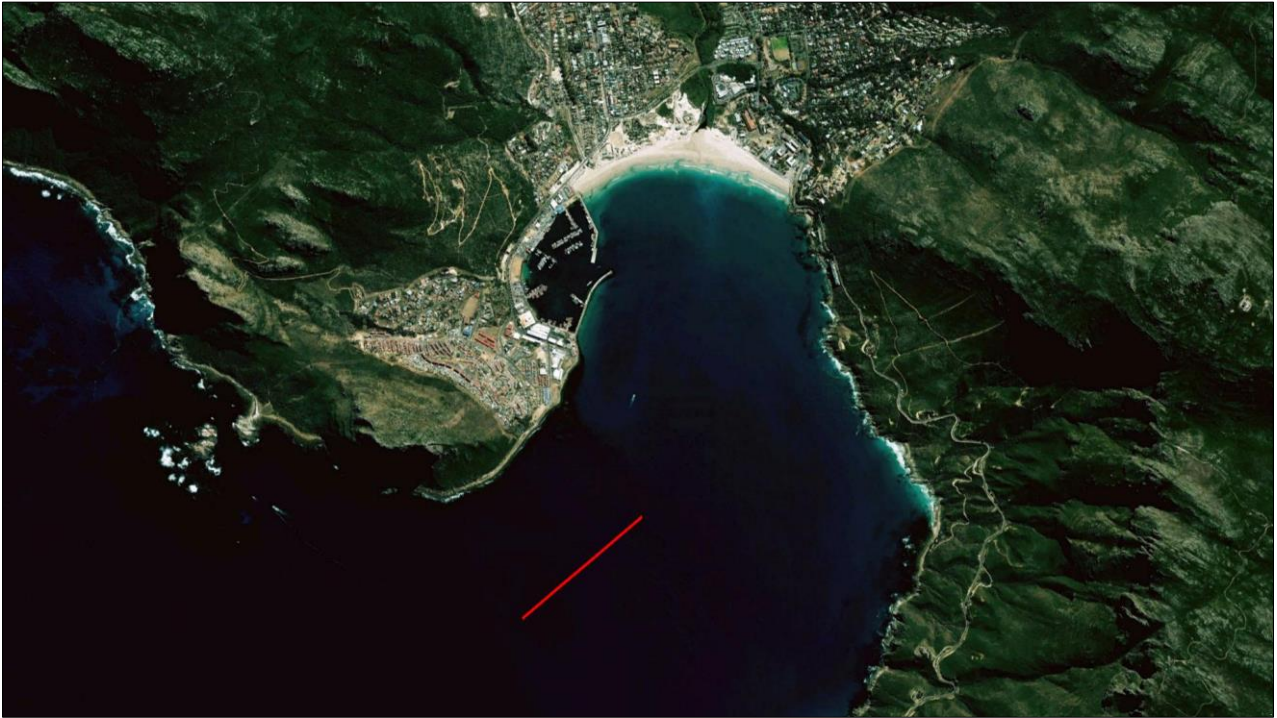


Figure 5.67. Bubble plot representation of chromium Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The Hout Bay outfall is denoted by the red line.

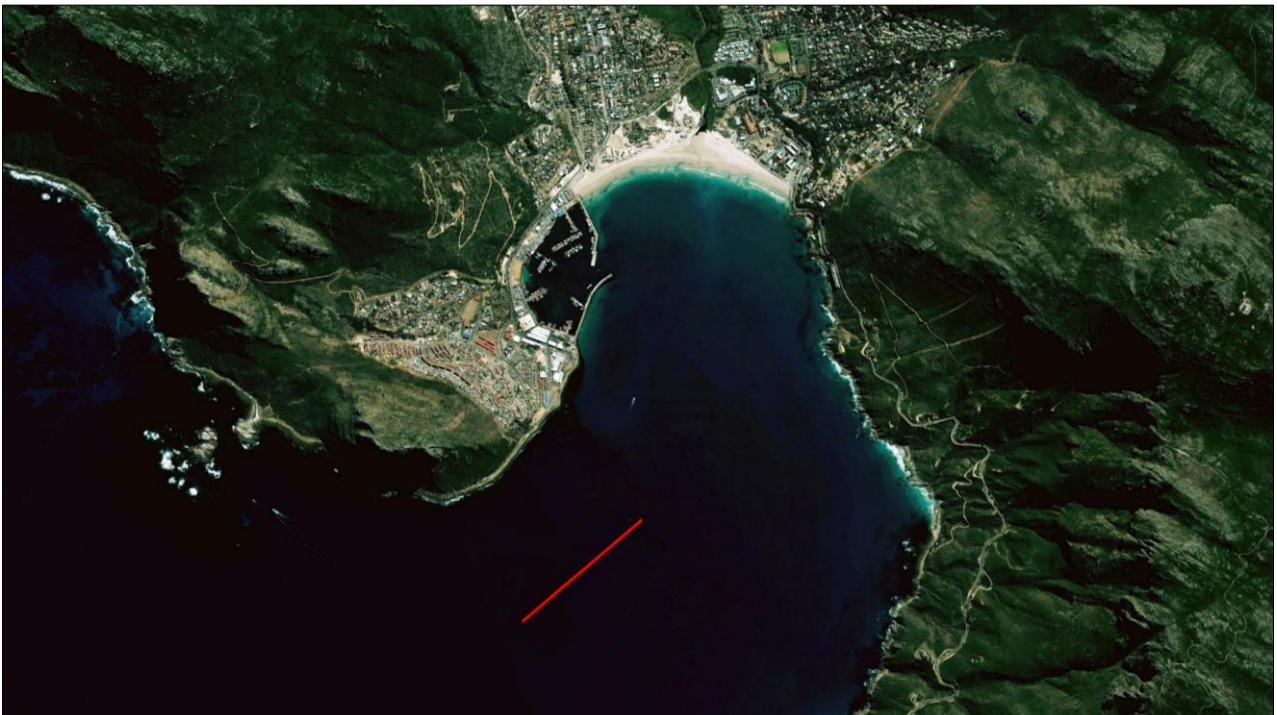


Figure 5.68. Bubble plot representation of manganese Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The Hout Bay outfall is denoted by the red line.

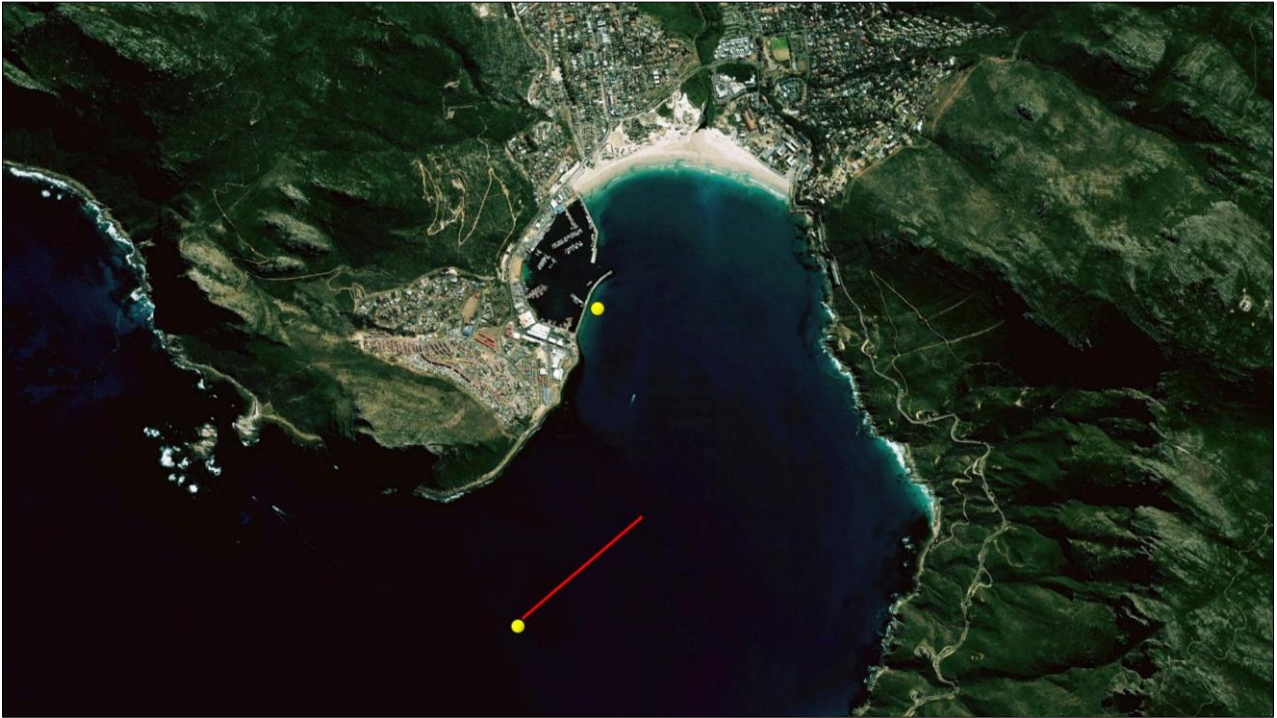


Figure 5.69. Bubble plot representation of nickel Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The largest bubble represents an Enrichment Factor of 1.09. The Hout Bay outfall is denoted by the red line.

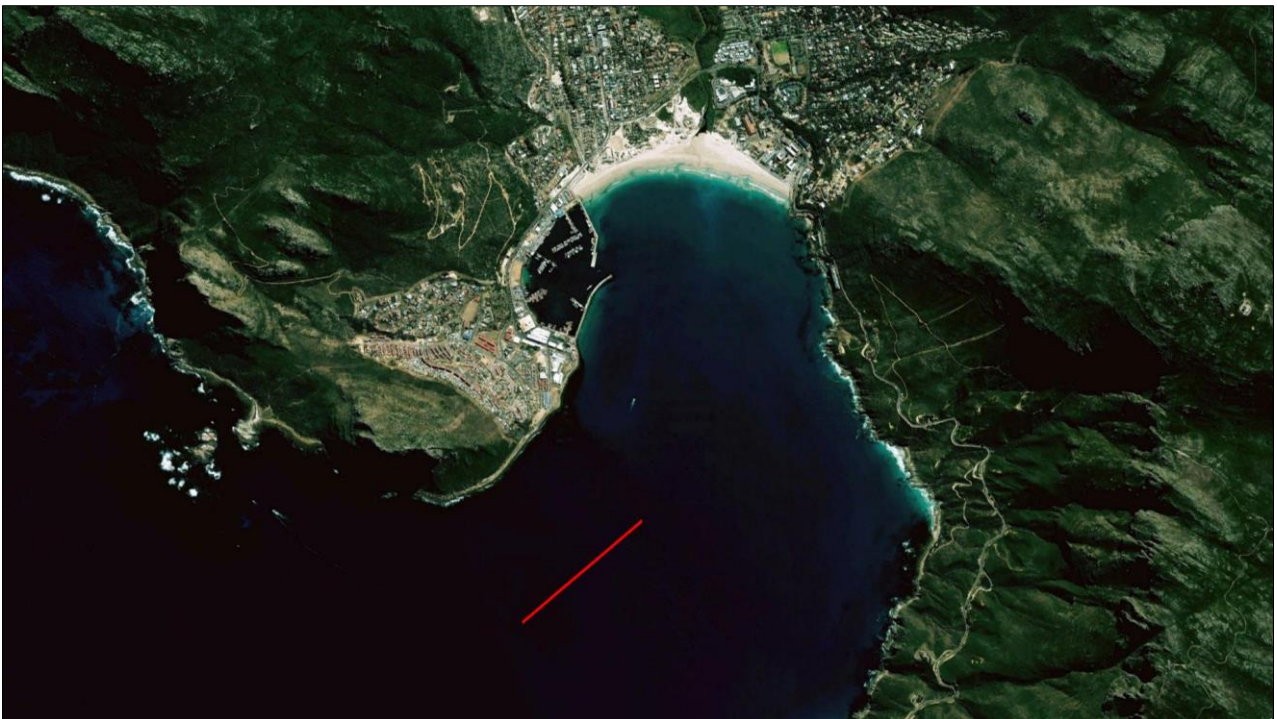


Figure 5.70. Bubble plot representation of lead Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The Hout Bay outfall is denoted by the red line.

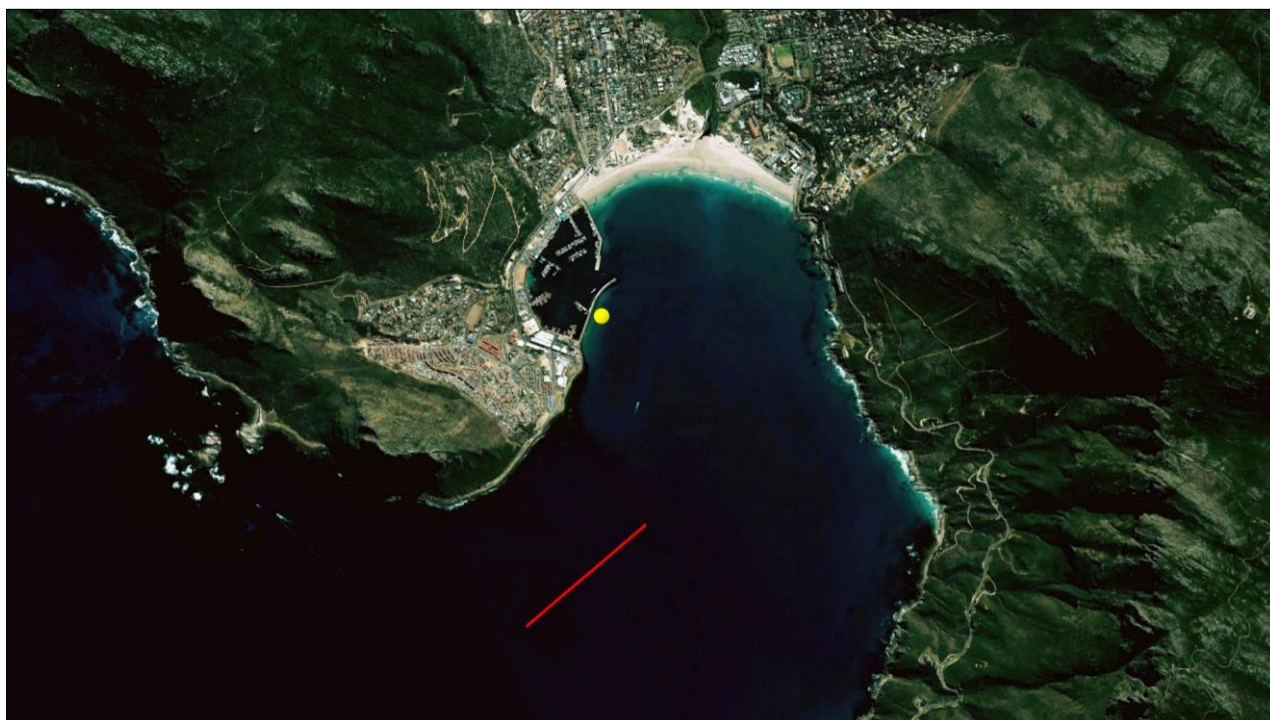


Figure 5.71. Bubble plot representation of zinc Enrichment Factors exceeding a value of one for sediment collected in the Hout Bay area in 2003 (CSIR, 2003). The largest bubble represents an Enrichment Factor of 3.73. The Hout Bay outfall is denoted by the red line.

imposed on the baseline models defined using metal concentrations analysed in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme in Figure 5.74. Numerous concentrations of several metals exceed baseline model upper prediction limits. However, in instances where the concentrations slightly exceed a baseline model upper prediction limit this may reflect a limitation of the baseline model. There was clear evidence for, in some cases significant enrichment of sediment at several sites in the Table Bay area by copper, nickel, lead and zinc. At a site near the Granger Bay Marina (GBay in Figure 5.74) there was significant enrichment by mercury. There was evidence for minor enrichment of sediment at a few sites in Hout Bay by copper, chromium, manganese, nickel and zinc, but significant enrichment at one site (HB7 in Figure 5.72) by mercury.

The analysis of metal concentrations in sediment collected for surveys in 1980, 1993, 1994, 2003, 2005, 2006, 2010 and 2011 reveal several features in common with the 2015/2016 survey. First, sediment in the Camps Bay area was rarely metal enriched, albeit that sediment was only collected in this area in the 2003 and 2015/2016 surveys and

only a few samples were collected for the latter survey. Nevertheless, these and the findings for other chemicals analysed in sediment collected for the 2015/2016 survey (see below) suggests that metals in effluent discharged through the Camps Bay outfall were not historically, and are presently not accumulating to excessive concentrations in sediment in the Camps Bay area. This makes sense when the predominantly coarse-grained nature of sediment at sites in the Camps Bay area is considered (see above), which indirectly reflects strong currents and other forms of turbulence impinging on the seabed.

Second, although sediment near the diffuser section of the Hout Bay outfall, and indeed in the greater Hout Bay area was more frequently metal enriched than sediment in the Camps Bay area the enrichment was infrequent and almost invariably of a low magnitude. This suggests metals in effluent discharged through the Hout Bay outfall were not historically, and are presently not accumulating to excessive concentrations in sediment in the Hout Bay area, at least in the long-term. This also makes sense when the predominantly coarse-grained nature of the sediment in this area is considered. Metal enrichment of sediment in and near Hout

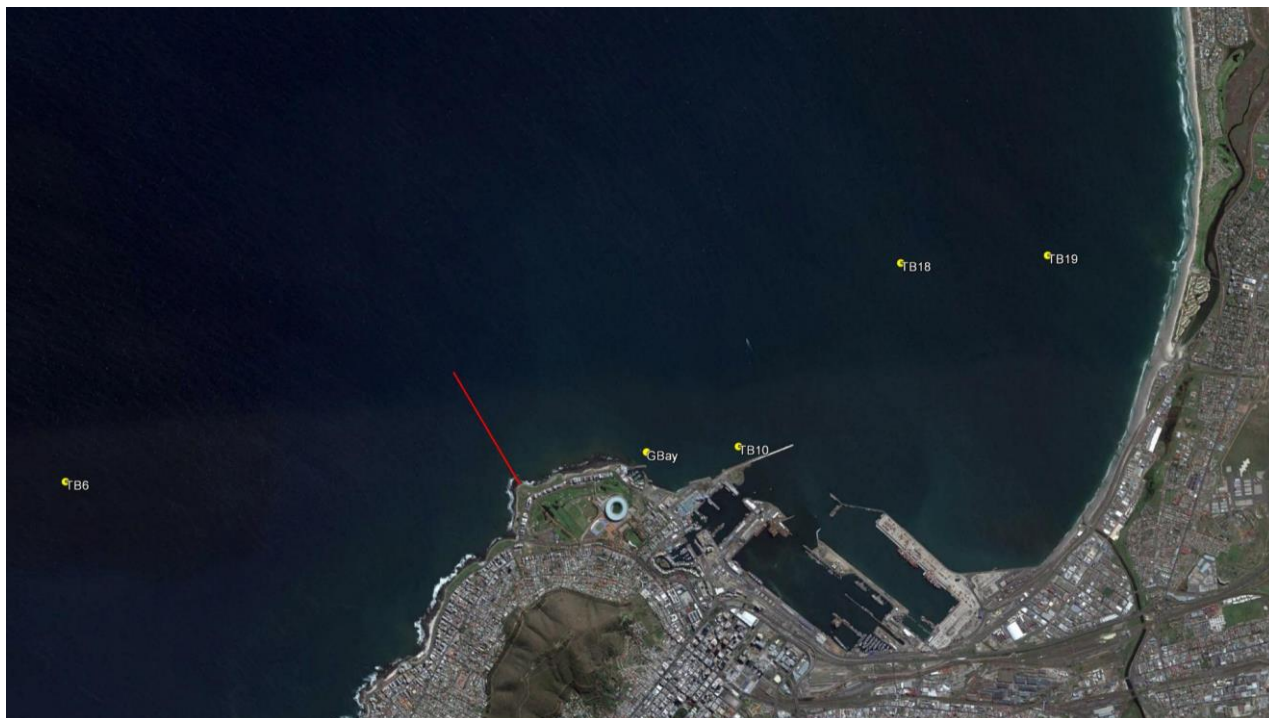


Figure 5.72. Aerial view of the Table Bay area, showing the positions where sediment was collected for physical and chemical analysis for the 2005/2006 and 2010/2011 surveys of the Cape Town outfalls monitoring programme. The Green Point outfall is denoted by the red line.



Figure 5.73. Aerial view of the Hout Bay area, showing the positions where sediment was collected for physical and chemical analysis for the 2005/2006 and 2010/2011 surveys of the Cape Town outfalls monitoring programme. The Hout Bay outfall is denoted by the red line.

Bay Harbour was more pronounced, but this probably reflects metals derived from port-associated activities rather than effluent. The metals enriched to the highest magnitude in sediment collected in and near Hout Bay Harbour in 2003 and 2015/2016 were copper and zinc. These

are perhaps the most common and significant metal contaminants of sediment in ports, primarily due to their use as active agents in antifouling coatings applied to the hulls of vessels (*e.g.* Schiff *et al.*, 2007; Rees *et al.*, 2014).

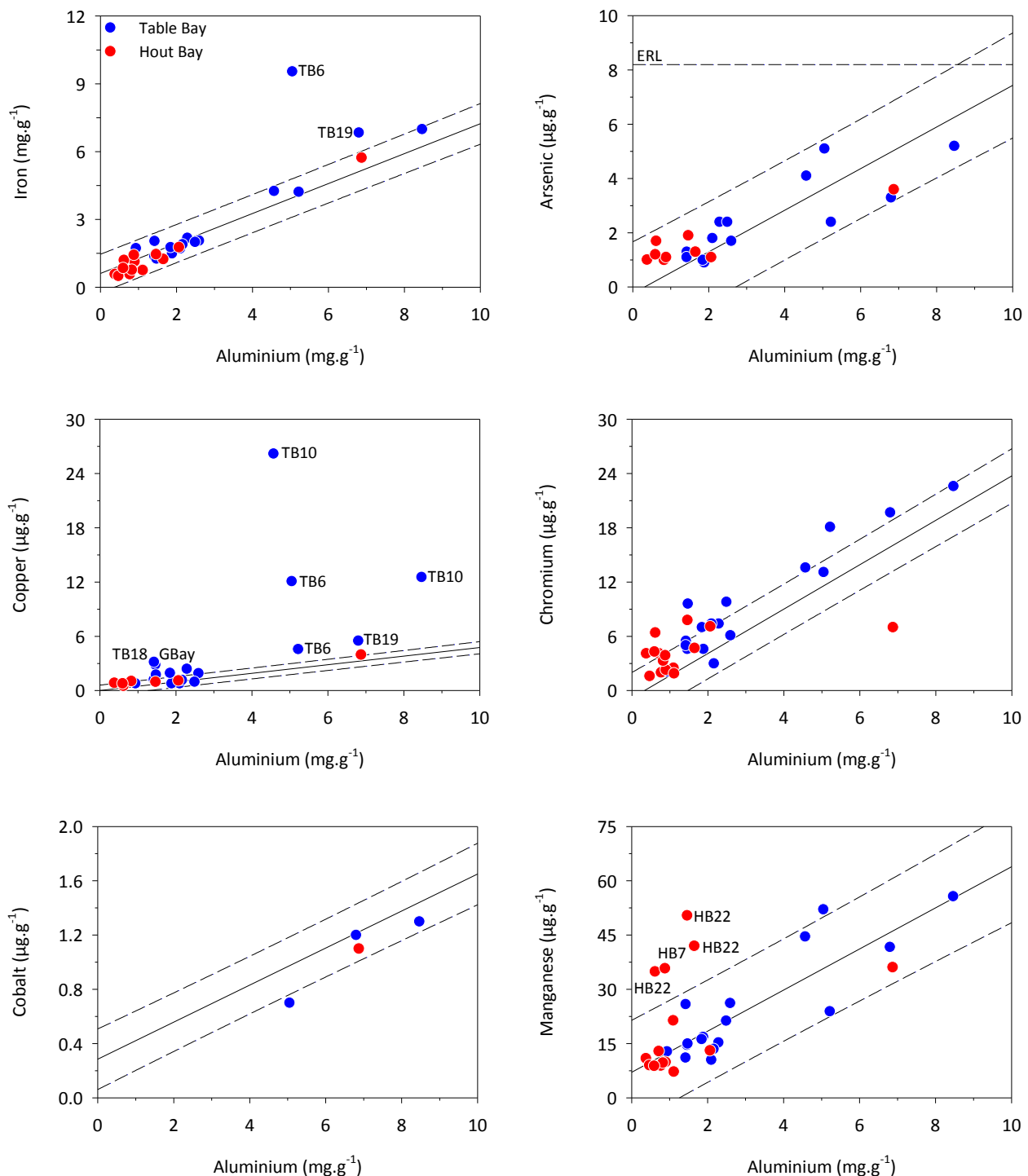


Figure 5.74. Baseline metal concentration models for sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2015/2016, with metal concentrations in sediment samples collected in 2005/2006 (CSIR, 2006) and 2010/2011 (CSIR, 2011) superimposed. Selected data points are highlighted by site identifiers. The horizontal dashed lines represent the Effects Range Low (ERL) and Effects Range Median (ERM) of the sediment quality guidelines defined by Long *et al.* (1995) (only included if the guideline falls within the y-axis range).

Third, metal enrichment of sediment in the Table Bay area was far more frequent and often more pronounced than in the Camps Bay and Hout Bay areas.

Fourth, sediment in the Granger Bay Marina and/or between the marina and the end of the western

breakwater for the Port of Cape Town, and in the southeastern part of Table Bay between the eastern breakwater for the port and the mouth of the Salt River was frequently and often relatively significantly metal enriched. The enrichment was sufficiently pronounced to conclude it reflects contamination. It is impossible to conclude the

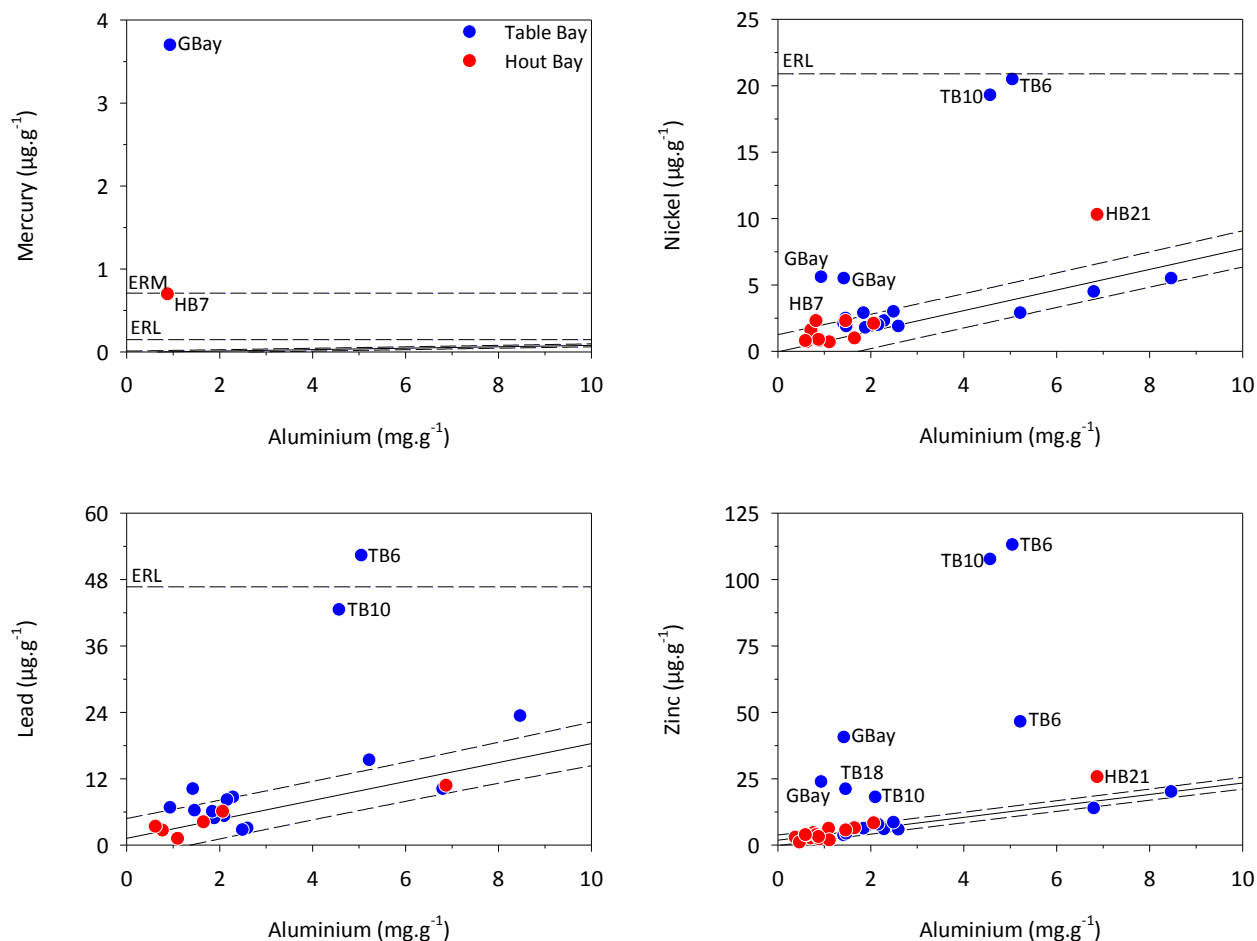


Figure 5.74 continued. Baseline metal concentration models for sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2015/2016, with metal concentrations in sediment samples collected in 2005/2006 (CSIR, 2006) and 2010/2011 (CSIR, 2011) superimposed. Selected data points are highlighted by site identifiers. The horizontal dashed lines represent the Effects Range Low (ERL) and Effects Range Median (ERM) of the sediment quality guidelines defined by Long *et al.* (1995) (only included if the guideline falls within the y-axis range).

enrichment was attributable to the dispersion of effluent from the Green Point outfall or was derived from other land-based sources of metals to the marine environment in Table Bay, or both. Based on the scientific literature there is little doubt metals (particularly copper and zinc) and hydrocarbons amongst other chemicals are introduced to Table Bay via stormwater. Discharges from the Salt and Diep Rivers are also known to be important sources, and the Port of Cape Town a major source of metals (particularly copper) to Table Bay. In fact, the CSIR (1985) estimated that these were more significant sources of most metals than effluent discharged through the Green Point outfall.

Based on the often considerable distance over which the effluent plume emanating from the Green Point outfall is evident at the sea surface in satellite images provided in Google Earth, the

balance of probabilities suggest at least some of the contamination in the greater Table Bay is attributable to effluent discharge (this was also suggested by the CSIR, 2003). This said, there was no evidence sediment in Table Bay was excessively enriched with particulate organic matter in 2003 and 2015/2016, as could conceivably be expected in the case of effluent discharge associated metal contamination of sediment.

5.3.4. Organic Chemicals

Various phenolic compounds were always detected in four effluent samples collected from the Green Point, Camps Bay and Hout Bay wastewater works in 2016 (see Chapter 2). However, no phenols were detected in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme. This probably reflects the fact that most phenolic compounds have a low organic carbon/water partition coefficient (phenol $\log K_{oc}$

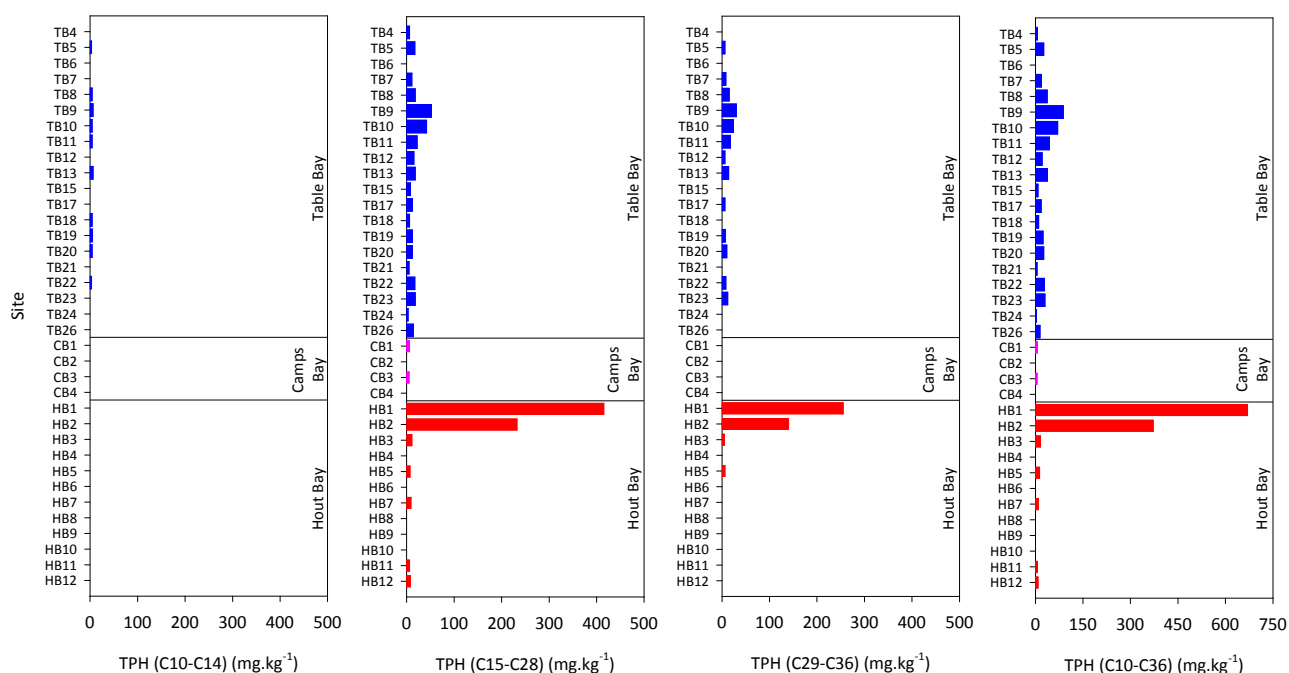


Figure 5.75. Total petroleum hydrocarbon (TPH) concentrations in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

= 1.15 - 3.49) and a low octanol/water partition coefficient (phenol $\log K_{ow} = 1.46$). Phenols are, therefore, not expected to adsorb significantly onto suspended material in the water column and to sediment on the seabed (*e.g.* DMER and AEL, 1996). DMER and AEL (1996) and Shiu *et al.* (1994) provide a short half-life of 550 hrs for phenol in sediment.

Total petroleum and polycyclic aromatic hydrocarbons were also always detected in four effluent samples collected from the Green Point, Camps Bay and Hout Bay wastewater works in 2016. However, only a few polycyclic aromatic hydrocarbon isomers were detected at a low concentration (see Chapter 2). In contrast to phenols, total petroleum, total recoverable and polycyclic aromatic hydrocarbons were detected in sediment collected at most sites at which these chemicals were analysed for the 2015/2016 survey of the Cape Town outfalls monitoring programme. However, not all total petroleum and total recoverable hydrocarbon carbon equivalent ranges or polycyclic aromatic hydrocarbon isomers were detected.

The terms total petroleum and total recoverable hydrocarbons represent a complex mixture of potentially thousands of hydrocarbons. They are referred to as hydrocarbons since almost all are comprised of carbon and hydrogen. Because the composition of identical total petroleum or total

recoverable hydrocarbon concentrations might differ, and because different laboratory methods extract different fractions, total petroleum and total recoverable hydrocarbon concentrations cannot be used to quantitatively assess ecological risk. Rather, they are usually used as indicators of gross hydrocarbon contamination.

Total petroleum hydrocarbons were detected in sediment collected at 28 of the 36 sites at which these chemicals were analysed (Figures 5.75 - 5.77). Carbon range C10-C14 was only at a concentration exceeding the method detection limit in sediment collected in Table Bay, but at low concentrations and with no particular spatial trend between sites (Figure 5.75). Carbon range C15-C28 was detected at all but one site and range C29-C36 at most sites. Only carbon range C15-C28 was detected in sediment collected in the Camps Bay area, and then at a low concentration at two sites (Figure 5.75). In the Hout Bay area only carbon ranges C15-C28 and C29-C36 were detected, the former more often than the latter, but compared to Table Bay the frequency of detection was low. Considering all carbon ranges by far the highest concentrations were in sediment at Sites HB1 and HB2 in Hout Bay Harbour (Figure 5.75). Concentrations at other sites in the Hout Bay area, and as stated above also the Camps Bay area were low. Concentrations in sediment in the Table Bay area were generally



Figure 5.76. Bubble plot representation of total petroleum hydrocarbon (C10-C36) concentrations in sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents a concentration of 88 mg.kg^{-1} . The Green Point and Camps Bay outfalls are denoted by red lines.

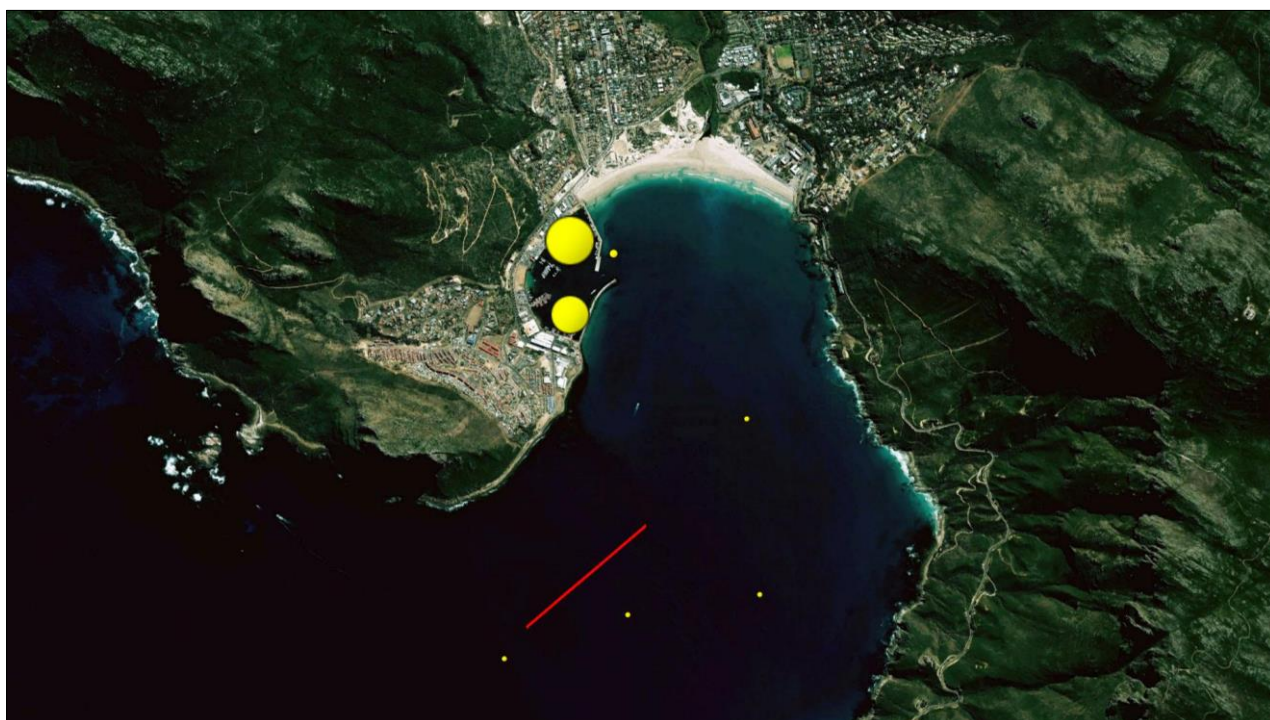


Figure 5.77. Bubble plot representation of total petroleum hydrocarbon (C10-C36) concentrations in sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents a concentration of 670 mg.kg^{-1} . The Hout Bay outfall is denoted by the red line.

slightly higher than in the Hout Bay and Camps Bay areas. The highest concentrations of various carbon ranges in Table Bay were invariably in sediment at Sites TB8, TB9, TB10 and TB11 between the eastern breakwater for the Port of Cape Town and the

mouth of the Salt River, and Site TB13 near the end of the western breakwater for the port (Figures 5.75 - 5.77). Concentrations in sediment near the diffuser sections of the Camps Bay and Hout Bay outfalls were low, and relatively low in sediment

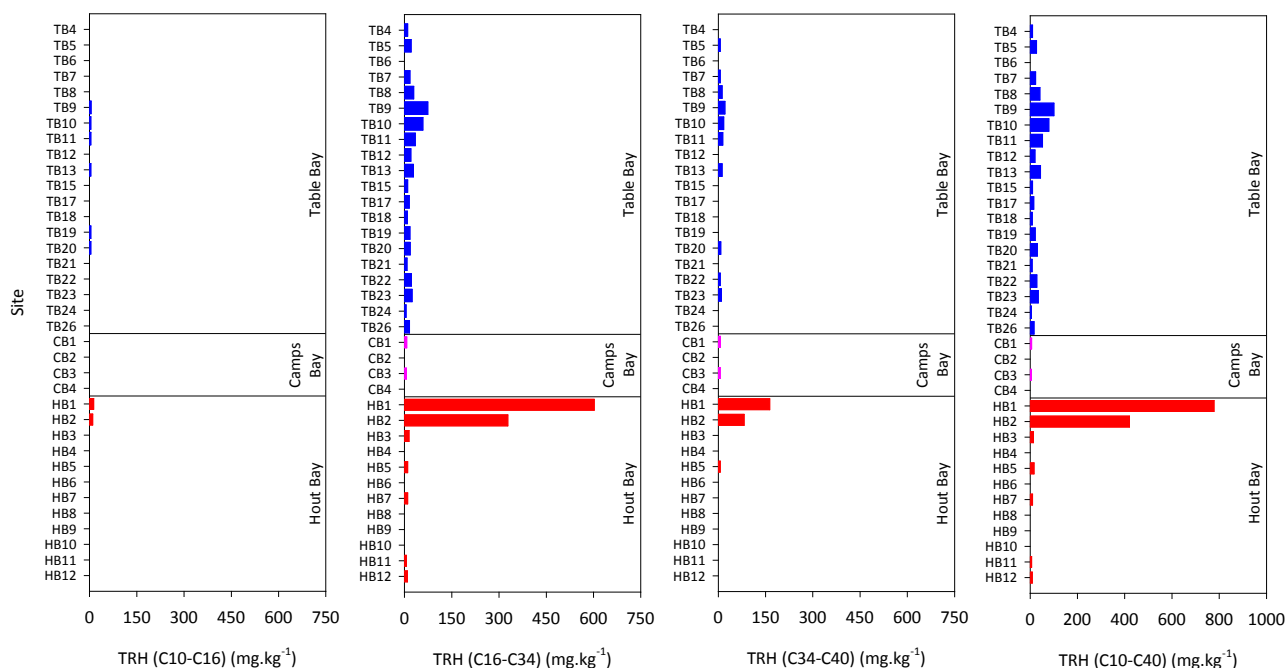


Figure 5.78. Total recoverable hydrocarbon (TRH) concentrations in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

collected near the Green Point outfall diffuser section.

Studies in the Arabian Gulf provided 'background' total petroleum hydrocarbon concentrations of 10 - 15 mg.kg⁻¹ (Massoud *et al.*, 1996; Tehrani *et al.*, 2012). These investigators classified sediment with concentrations of 15 - 50 mg.kg⁻¹ as 'slightly polluted', 50 - 200 mg.kg⁻¹ as 'moderately polluted', and >200 mg.kg⁻¹ as 'heavily polluted'. Using this scheme, total petroleum hydrocarbon concentrations at seven sites in Table Bay would be regarded as background, at 11 sites as slightly polluted, and at two sites (TB9 and TB10) as moderately polluted. Total petroleum hydrocarbon concentrations in sediment at all sites in the Camps Bay and Hout Bay areas would be regarded as background (the concentration of 16 mg.kg⁻¹ at one site is considered to be background) apart from the two sites in Hout Bay Harbour, for which the concentration would be regarded as heavily polluted. These terms/categories are qualitative and, as stated above there are no toxicity thresholds for total petroleum hydrocarbons in sediment.

The extraction procedure for total recoverable hydrocarbons measures the gross quantity of hydrocarbons in sediment in the carbon range C10-C40. The procedure is non-specific and so includes

petrogenic hydrocarbons (*e.g.* paraffins, aromatics), non-petrogenic hydrocarbons of biological origin (*e.g.* vegetable and animal oils), and other organics (*e.g.* chlorinated hydrocarbons, phthalate esters). Total recoverable hydrocarbons were also detected in sediment at 28 of the 36 sites at which these chemicals were analysed (Figures 5.78 - 5.80). The spatial trend was virtually identical to that for total petroleum hydrocarbons, as reflected in the strong positive correlation between carbon range C10-C36 for total petroleum hydrocarbons and C10-C40 concentrations for total recoverable hydrocarbons ($r = 0.999$, $p < 0.001$). Total recoverable hydrocarbon concentrations were, however, slightly higher than total petroleum hydrocarbon concentrations.

Polycyclic aromatic hydrocarbons were detected in sediment at 18 of the 36 sites at which these chemicals were analysed (Figures 5.81 - 5.83). The highest total concentration was in sediment at Site HB1 in Hout Bay Harbour followed by sediment at Sites TB10 between the eastern breakwater for the Port of Cape Town and mouth of the Salt River, Site TB13 near the end of the western breakwater for the port, TB11 near the eastern breakwater for the port, and Site HB2 in Hout Bay Harbour. Concentrations in sediment near the diffuser section of each outfall were low, and for most sites near the Camps Bay and Hout Bay outfall diffuser



Figure 5.79. Bubble plot representation of total recoverable hydrocarbon (C10-C40) concentrations in sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents a concentration of 100 mg.kg^{-1} . The Green Point and Camps Bay outfalls are denoted by red lines.

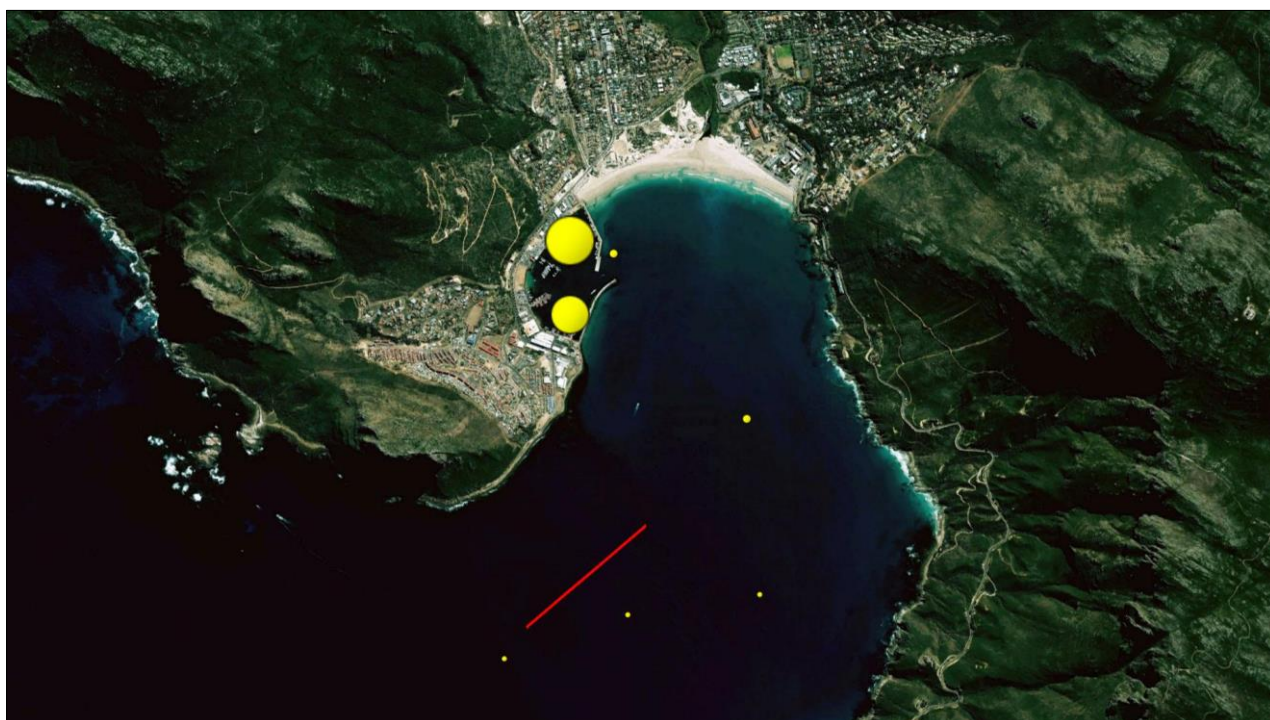


Figure 5.80. Bubble plot representation of total recoverable hydrocarbon (C10-C40) concentrations in sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents a concentration of 778 mg.kg^{-1} . The Hout Bay outfall is denoted by the red line.

sections were usually below the method detection limit. The correlation between carbon ranges C10-C36 for total petroleum hydrocarbons and C10-C40 for total recoverable hydrocarbons, and the total polycyclic aromatic hydrocarbon concentration was

strong ($r = 0.984$ and 0.985 respectively, $p < 0.001$ in both cases) provided the concentrations for Sites TB10, TB11 and TB13 are considered outliers. This suggests localised sources of polycyclic aromatic hydrocarbons to these sites.

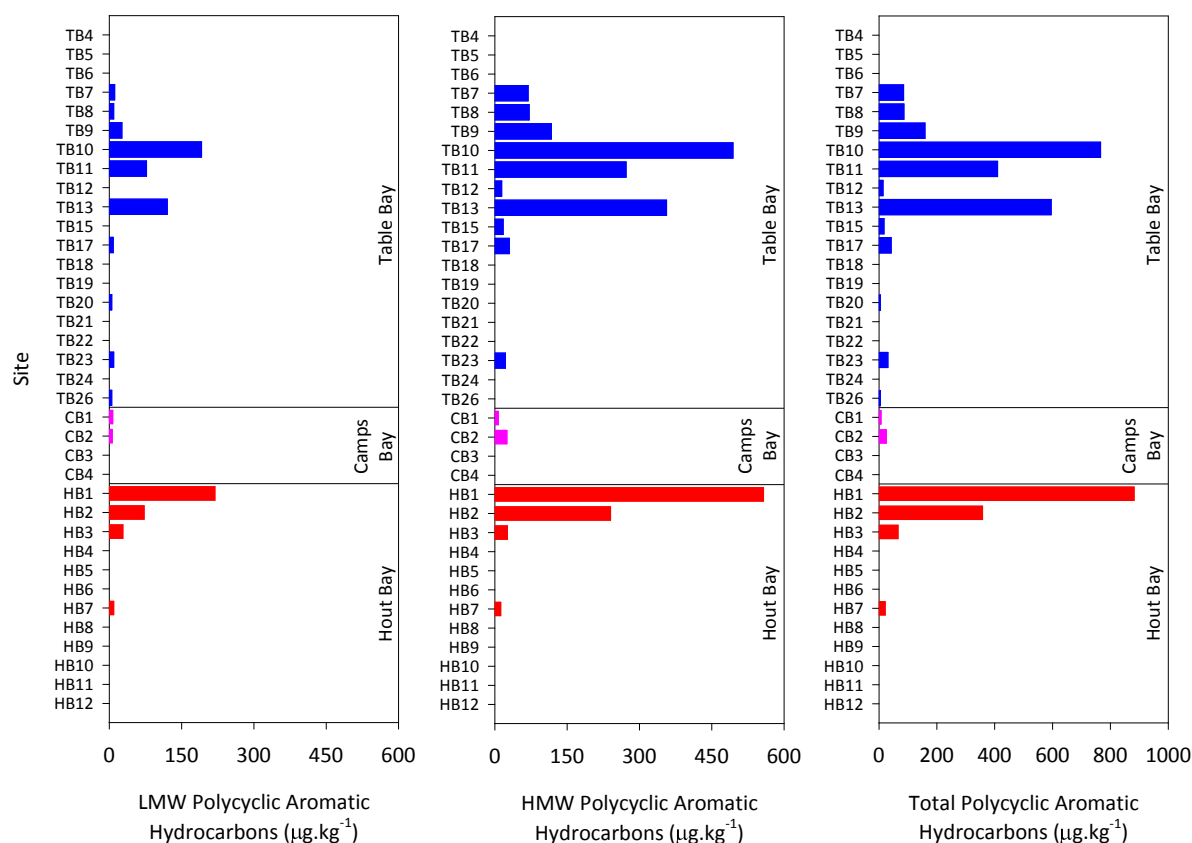


Figure 5.81. Sum low molecular weight (LMW), sum high molecular weight (HMW) and total polycyclic aromatic hydrocarbon concentrations in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

To place these findings into context, the CSIR (2015) analysed an identical suite of polycyclic aromatic hydrocarbon isomers in sediment collected at 30 sites in rivers, wetlands and estuaries in the Cape Town area in 2013. Polycyclic aromatic hydrocarbons were detected in sediment at all but two sites. The total concentration varied widely, from below the method detection limit ($<4 \mu\text{g.kg}^{-1}$) in sediment at sites in Rietvlei and Kuils River to $3687 \mu\text{g.kg}^{-1}$ in sediment at a site in the Liesbeek River. The total concentration in sediment at 12 of the 30 sites was $\leq 83 \mu\text{g.kg}^{-1}$, and $\geq 693 \mu\text{g.kg}^{-1}$ in sediment at eight sites. With relevance to this study the total polycyclic aromatic hydrocarbon concentration in sediment at two sites in the Diep River was <4 and $459 \mu\text{g.kg}^{-1}$, at a site in Zoarvlei was $1724 \mu\text{g.kg}^{-1}$, and at five sites in the catchment of the Salt River (in Kuils, Liesbeek, Black and Vygekraal Rivers) was 134, 475, 1519 and $3687 \mu\text{g.kg}^{-1}$. These discharge directly or indirectly into Table Bay and represent potential sources of hydrocarbons to the bay. The total concentration in sediment at a single site sampled in the Disa (Hout Bay) River was $274 \mu\text{g.kg}^{-1}$. Although this is relatively low, river flow may nevertheless be a

vector for the introduction of polycyclic aromatic hydrocarbons to Hout Bay. There are clearly significant anthropogenic sources of polycyclic aromatic hydrocarbons in Hout Bay Harbour.

Total polycyclic aromatic hydrocarbon concentrations in sediment in rivers, wetlands and estuaries in the Cape Town area in 2013 were generally higher than in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme. If the data are combined the total polycyclic aromatic hydrocarbon concentration in sediment collected at Sites HB1, TB10, TB13, TB11, HB2 and TB9 is ranked 9th, 10th, 12th, 15th, 17th and 19th respectively for the 66 sites. Thus, polycyclic aromatic hydrocarbon concentrations are generally higher in river and estuarine sediment than in sediment offshore.

As a further point for comparison the CSIR (unpublished data) analysed an identical suite of polycyclic aromatic hydrocarbon isomers as those analysed for the 2015/2016 survey of the Cape Town outfalls monitoring programme in sediment collected at 16 sites in the Port of Cape Town in

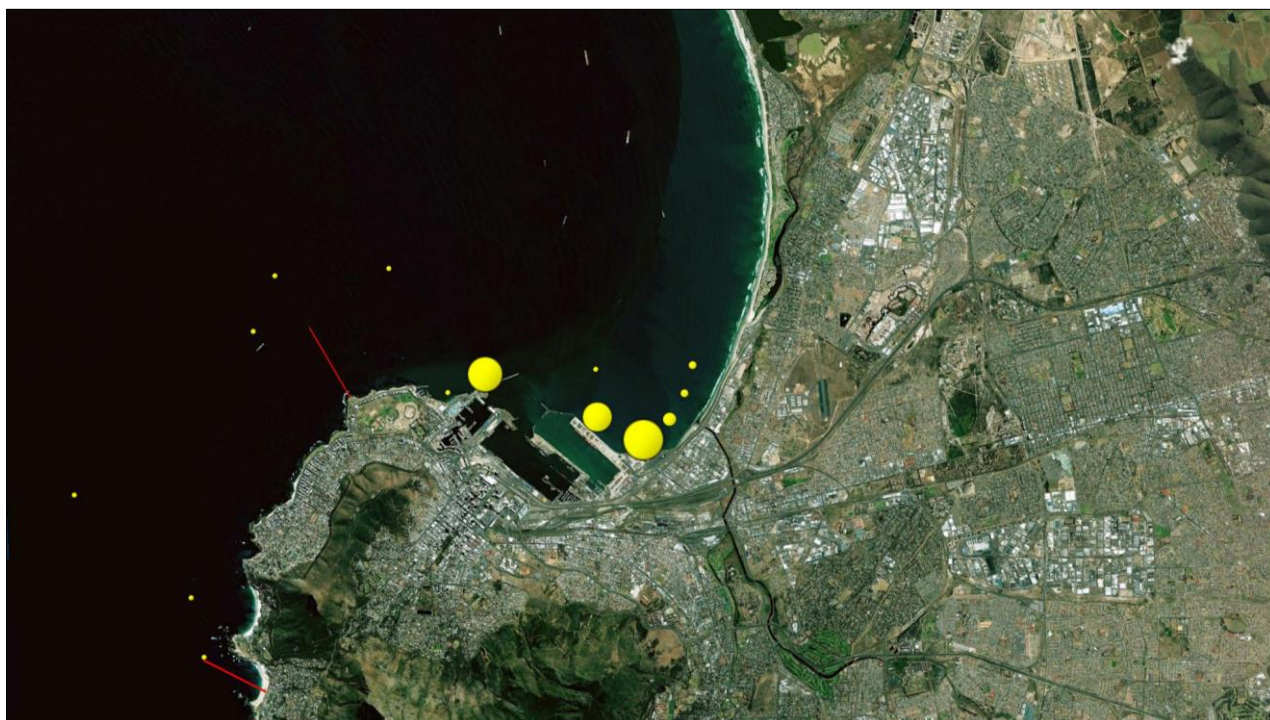


Figure 5.82. Bubble plot representation of total polycyclic aromatic hydrocarbon concentrations in sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents a concentration of $766 \mu\text{g.kg}^{-1}$. The Green Point and Camps Bay outfalls are denoted by red lines.

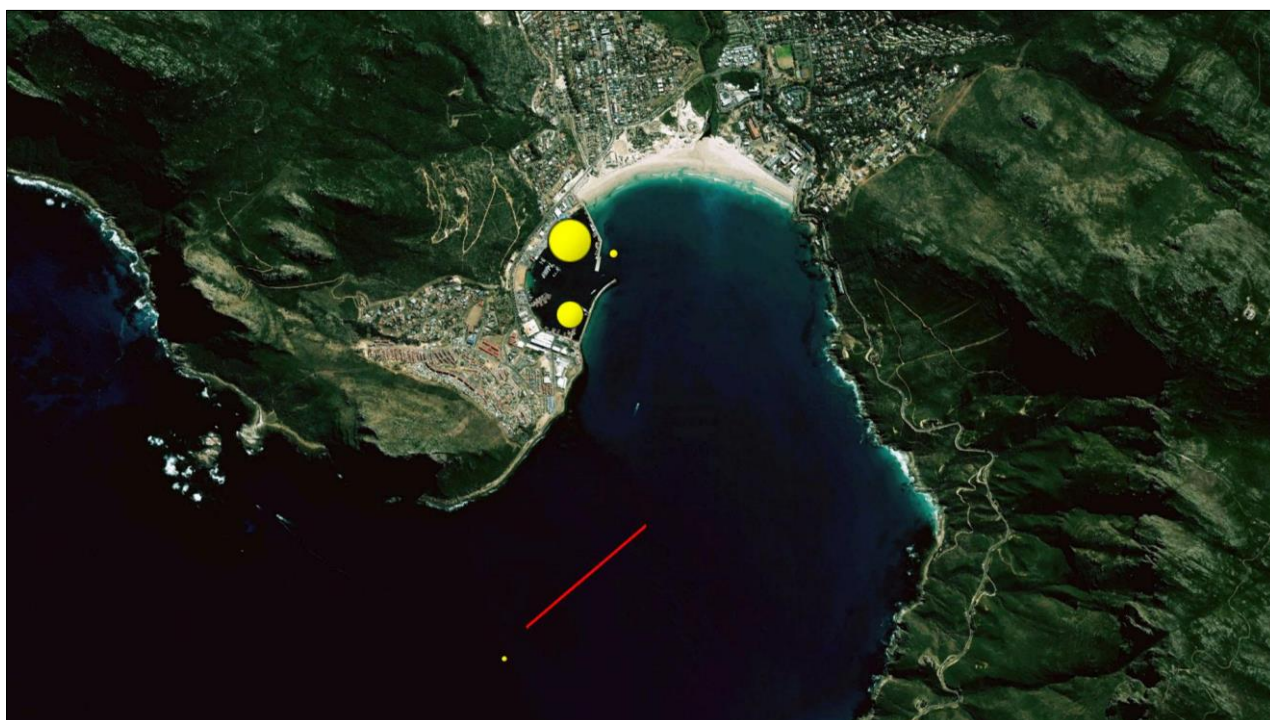


Figure 5.83. Bubble plot representation of total polycyclic aromatic hydrocarbon concentrations in sediment collected in the Hout Bay area for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents a concentration of 882 mg.kg^{-1} . The Hout Bay outfall is denoted by the red line.

2016. The total polycyclic aromatic hydrocarbon concentration in sediment at these sites ranged from $576 - 20\,249 \mu\text{g.kg}^{-1}$ (median concentration = $2698 \mu\text{g.kg}^{-1}$). The concentrations in sediment at most sites in the port were considerably higher

than concentrations in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The port may be a source of hydrocarbons to Table Bay through tidal exchange. There are, however, other potential

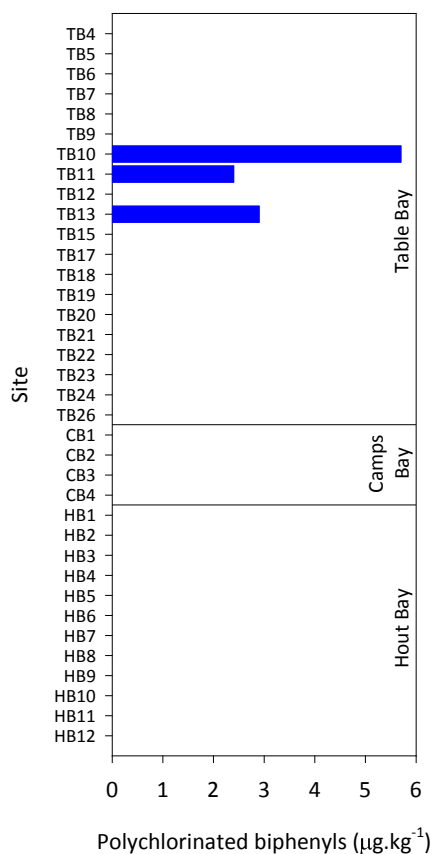


Figure 5.84. Total polychlorinated biphenyl concentrations in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

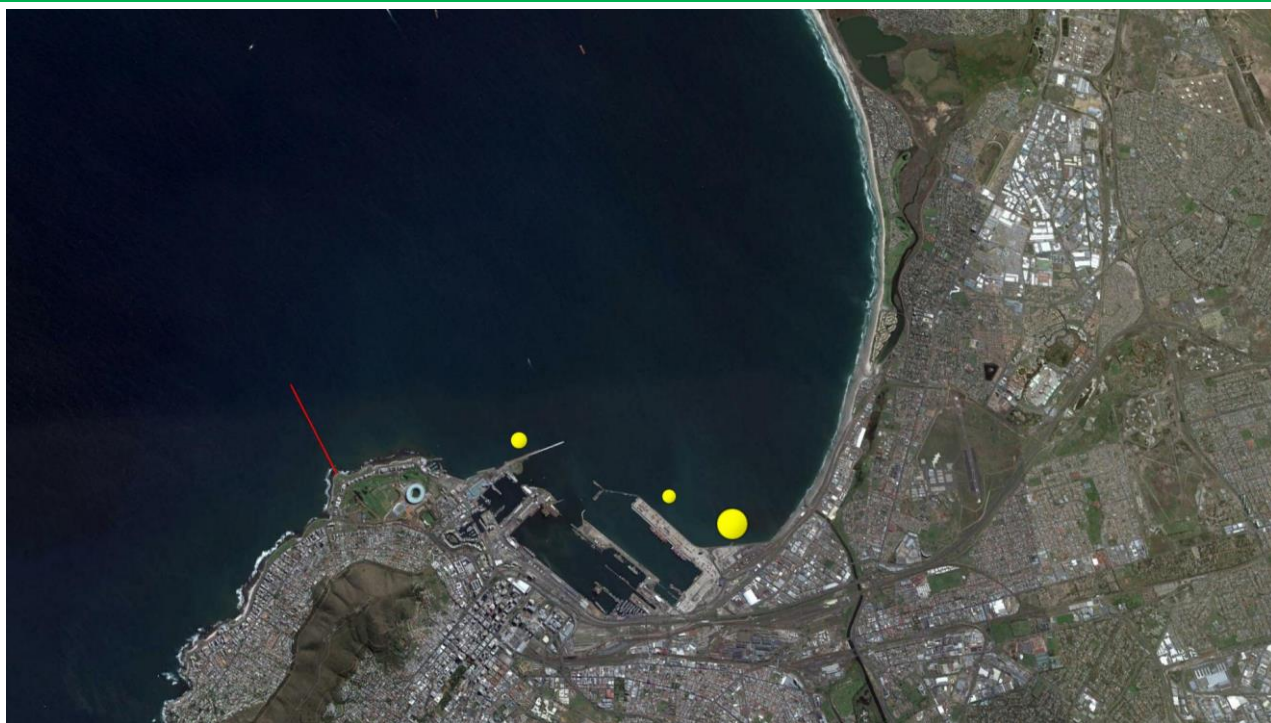


Figure 5.85. Bubble plot representation of polychlorinated biphenyl concentrations in sediment collected in the Table Bay and Camps Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The largest bubble represents a concentration of $5.7 \mu\text{g.kg}^{-1}$. The Green Point and Camps Bay outfalls are denoted by red lines.

sources of polycyclic aromatic hydrocarbons to Table Bay. Stormwater from urban areas has, for example, been identified as a significant source of these chemicals to aquatic ecosystems (e.g. MoT,

2003; Ma *et al.*, 2017).

Total petroleum and total recoverable hydrocarbon concentrations were strongly positively correlated

to the mud fraction of sediment if concentrations for Sites HB1 and HB2 in Hout Bay Harbour are considered outliers ($r = 0.839$ and 0.847 respectively, $p < 0.001$ in both cases), but weakly and not statistically significantly correlated to the total organic content of the sediment. Total polycyclic aromatic hydrocarbon concentrations were also strongly positively correlated to the mud fraction of the sediment ($r = 0.920$, $p < 0.001$) if concentrations for Sites TB10, TB11, TB13 in Table Bay and HB1 and HB2 in Hout Bay Harbour are considered outliers. As was the case for total petroleum and total recoverable hydrocarbon concentrations, polycyclic aromatic hydrocarbon concentrations were weakly and not statistically significantly correlated to the total organic content of the sediment. The strong linear relationships for most sites suggest current mediated dilution, dispersion and settlement of hydrocarbons on sediment in the marine receiving environments. The outliers, in contrast, suggest more significant localised sources to these sites.

Based on the spatial trend for total petroleum, total recoverable and polycyclic aromatic hydrocarbon concentrations in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme there is no clear evidence that effluent was a significant source of these chemicals in sediment in the marine receiving environments provided areas in Table Bay where the highest concentrations were detected are taken as having land-based sources other than effluent. The different contribution of various carbon ranges to the total petroleum and total recoverable hydrocarbon concentration between the Table Bay area on the one hand and the Camps Bay and Hout Bay areas on the other implies different sources of hydrocarbons to and/or factors that differentially influence their accumulation in sediment in these areas. As was the case for metals there is no means for discriminating between hydrocarbons derived from effluent and other land-based sources with the data at hand. It is unlikely the entire hydrocarbon concentrations were effluent-derived considering the numerous sources of hydrocarbons to the marine environment off urban areas. In the Cape Town outfalls study area these are likely to include stormwater runoff and flows from the Salt and Diep Rivers, and tidal export from the Port of

Cape Town.

Polychlorinated biphenyls were never detected in four effluent samples collected from the Green Point, Camps Bay and Hout Bay wastewater works in 2016 (see Chapter 2). Polychlorinated biphenyls were detected at a very low concentration in sediment collected at three of the 36 sites at which these chemicals were analysed for the 2015/2016 survey of the Cape Town outfalls monitoring programme, namely Sites TB10 and TB11 near the eastern breakwater for the Port of Cape Town and Site TB13 near the western breakwater for the port (Figures 5.84 and 5.85). Only one or two (of the 21) congeners analysed were detected. The absence of polychlorinated biphenyls in effluent but their (albeit very infrequent detection) in sediment at sites TB10, TB11 and TB13, where the sediment was the, or amongst the most significantly contaminated by metals and hydrocarbons suggests the contamination was either not, or at least not entirely attributable to effluent discharge. The source/s of the polychlorinated biphenyls is uncertain but could include tidal export from the Port of Cape Town and via contaminated river flow. This conclusion is based on the fact that polychlorinated biphenyls were detected in sediment collected in some parts of the Port of Cape Town in 2016 at high concentrations (CSIR, unpublished data) and at moderate concentrations in sediment collected in some rivers, wetlands and estuaries (e.g. Liesbeeck River) that discharge into Table Bay in 2013 (CSIR, 2015).

5.3.5. Estimate of the Toxicological Significance of Chemical Concentrations in Sediment

A critical end-point of any outfall monitoring programme is to determine if effluent discharge is significantly adversely impacting on the ecology of the receiving environment. It is not possible to determine if chemical pollution has occurred and the extent and significance of the pollution, either alone or relative to other stressors inducing ecosystem alteration, by measuring concentrations of chemicals in the environment (Ludwig and Iannuzzi, 2005). These measurements provide information on contamination, that is, chemicals present where they would not normally occur or at concentrations above the natural background, but

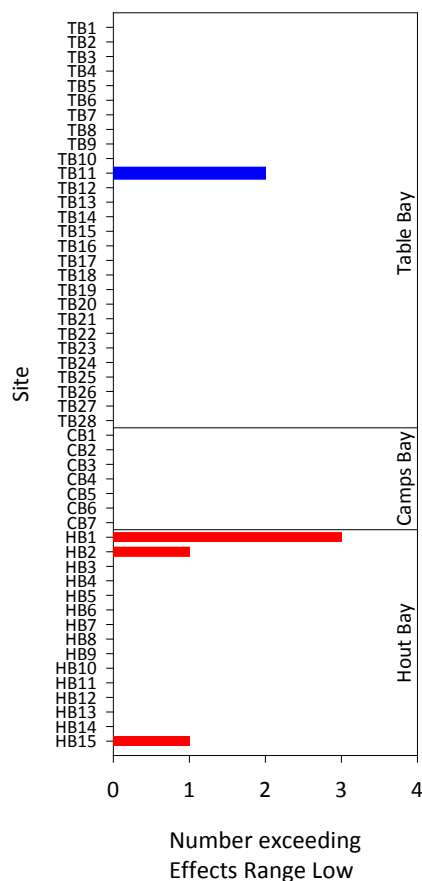


Figure 5.86. Number of metals at a concentration that exceeded the Effects Range Low in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

do not provide information on pollution, that is, contamination that causes adverse biological effects. All pollutants are contaminants, but not all contaminants are pollutants since chemicals introduced into the environment may be more or less bioavailable to organisms depending on their form, modifying factors in the environment, the environmental compartment they occupy, and the reactions (behavioural and physiological) of exposed biota (Chapman *et al.*, 2003).

To determine if metals, hydrocarbons and polychlorinated biphenyls in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme were at concentrations presenting a toxic risk to sediment-dwelling organisms requires some form of biological analysis. The most common approach in marine effluent discharge monitoring programmes is to compare the structure and composition of benthic macrofaunal communities between putatively effluent impacted and non-impacted (reference)

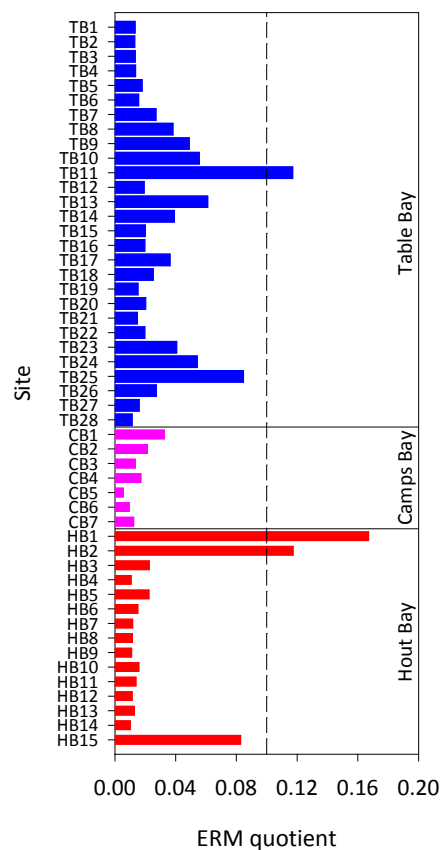


Figure 5.87. Effects Range Median (ERM) quotient for chemicals in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

sites. Aberrations in the type (species) and abundance of organisms that characterise the community at sites near the point of effluent discharge relative to communities at non-impacted sites are taken as indicative of an impact provided there are no other factors confounding such interpretation. Certain benthic macrofauna thrive in sediment significantly impacted by effluent discharge (*e.g.* capitellid polychaetes) and are widely recommended as indicators of such impact (*e.g.* Pearson and Rosenberg, 1978; Diaz-Castaneda and Harris, 2004; CSIR, 2016). The analysis of benthic macrofaunal communities was identified as a potential indicator of ecological impacts for the 2015/2016 survey of the Cape Town outfalls monitoring programme. However, as discussed above the presence of exposed reef near the Green Point and Camps Bay outfalls made it difficult or impossible to collect sediment for benthic macrofaunal community analysis in areas putatively most impacted by effluent discharge. Furthermore, even if benthic macrofauna could be collected the highly variable nature of the sediment grain size would probably make it difficult to separate effects

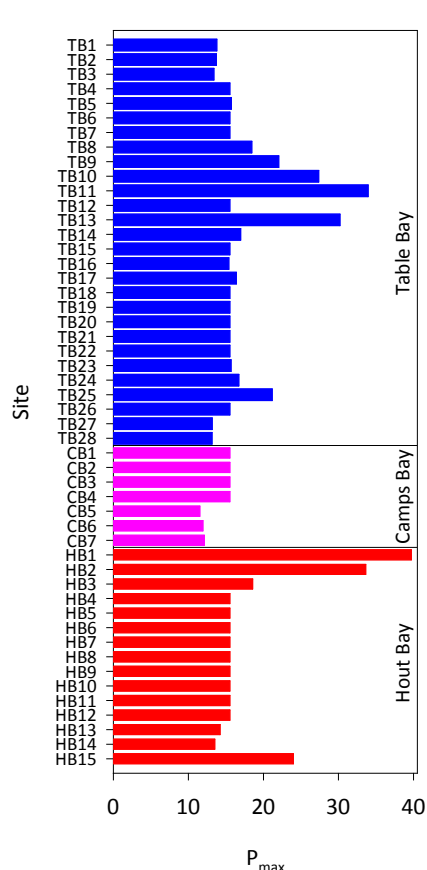


Figure 5.88. Maximum probability (P_{max}) for observing toxicity to amphipods for chemicals in sediment collected in the Table Bay, Camps Bay and Hout Bay areas for the 2015/2016 survey of the Cape Town outfalls monitoring programme.

on community structure and composition due to exposure to contaminants in sediment and those caused by other environmental factors, such as the variation in sediment grain size. This is because many benthic macrofauna respond to sediment grain size, water column depth and so on. The difficulty collecting sediment also poses challenges for an alternate or complimentary approach to biological assessment, namely the toxicity testing of whole sediment.

In circumstances where the use of benthic macrofauna and whole sediment toxicity testing is difficult most investigators use sediment quality guidelines to estimate the risk posed by chemicals in sediment to sediment-dwelling organisms. This is in spite of limitations of sediment quality guidelines (e.g. Pettigrove and Hoffman, 2005; Wetherington *et al.*, 2005). These include that sediment quality guidelines have been defined for only a small proportion of chemicals that may be contaminants in sediment. Sediment quality guidelines also do

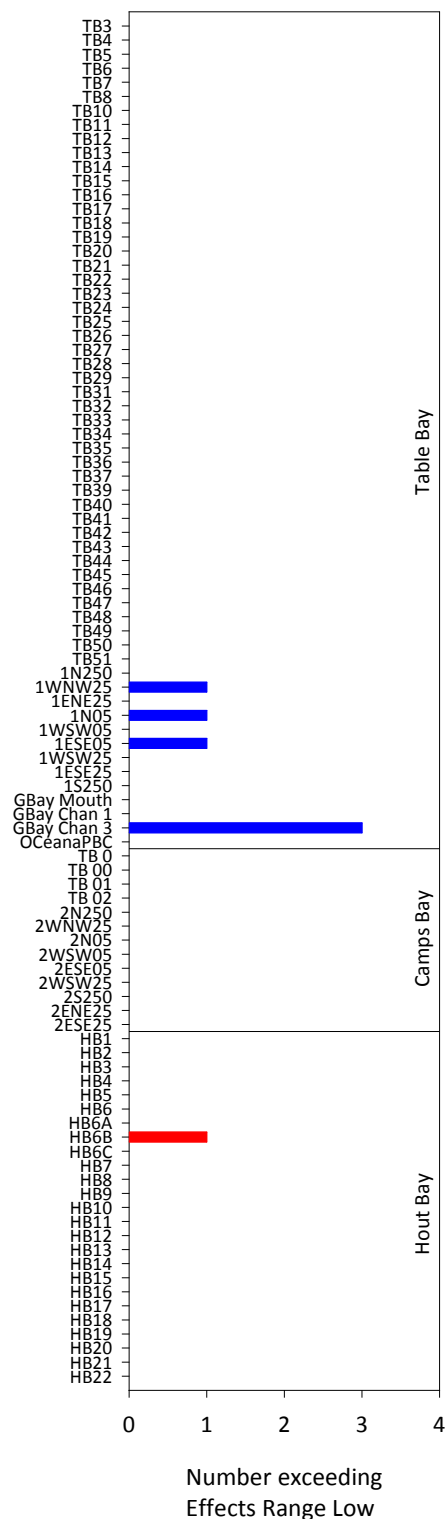


Figure 5.89. Number of metals at a concentration in sediment collected in the Table Bay, Camps Bay and Hout Bay areas in 2003 (CSIR, 2003).

not unequivocally discriminate between concentrations of chemicals in sediment that cause adverse biological effects and those that do not. Thus, no sediment quality guidelines have been shown to consistently predict toxicity, although they are generally reliable for predicting the absence of toxicity. Sediment quality guidelines are thus best

viewed and used as a screening tool, to identify sediment that requires further analysis through biological assessment.

The Department of Environmental Affairs has defined sediment quality guidelines for deciding if sediment identified for dredging in South African ports is of a suitable quality for openwater disposal. However, only guidelines for metals were defined and they are only intended for use in ports. There was also uncertainty on baseline concentrations of metals in sediment in Western Cape coastal ecosystems at the time the guidelines were defined (this has to some extent been resolved). As a result, sediment quality guidelines defined for use in North American coastal ecosystems by Long *et al.* (1995) were used to estimate the toxicological significance of metal concentrations in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme. The guidelines defined by Long *et al.* (1995) are more conservative (lower) than the Department of Environmental Affairs guidelines, although the Long *et al.* (1995) guidelines were the basis for some Department of Environmental Affairs guidelines. Long *et al.* (1995) derived two guidelines, the Effects Range Low and Effects Range Median. The Effects Range Low represents the concentration below which toxic effects to sediment-dwelling organisms are unlikely to be observed (<10% incidence for metals and <25% incidence for most organic chemicals), while the Effects Range Median represents the concentration above which toxic effects are likely to be frequently observed (>60% incidence for most metals and >80% incidence for most organic chemicals). Concentrations between the Effects Range Low and Effects Range Median pose a potential toxic risk to sediment-dwelling organisms, with the risk theoretically increasing as the concentration approaches the Effects Range Median. The incidence of toxic effects for concentrations falling between the Effects Range Low and Effects Range Median ranged between 20 - 30% for most metals and 40 - 60% for most organic chemicals. It is important to note the guidelines were intended as screening tools to identify sediment that requires further assessment, and not as a tool for predicting toxicity. There is thus no certainty the guidelines will consistently predict toxicity for chemicals at a concentration exceeding the Effects Range Median,

or the lack of toxicity for chemicals at a concentration below the Effects Range Low. Furthermore, Long *et al.* (1995) provided a low confidence in the ability of mercury and nickel guidelines to predict toxicity. Thus, only 42% of mercury concentrations and 11% of nickel concentrations that exceeded the Effects Range Median were associated with a toxic effect.

There are no South African sediment quality guidelines for polycyclic aromatic hydrocarbons and polychlorinated biphenyls. The sediment quality guidelines defined by Long *et al.* (1995) were thus also used to estimate the toxicological significance of these chemicals in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme. Long *et al.* (1995) derived guidelines for individual polycyclic aromatic hydrocarbon isomers, for the sum of low and high molecular weight isomers separately, and the total polycyclic aromatic hydrocarbon concentration (*i.e.* sum of all isomers). Only the sum of low and high molecular weight isomer and total polycyclic aromatic hydrocarbon guidelines were used for this survey. Long *et al.* (1995) did not derive guidelines for total petroleum and total recoverable hydrocarbons.

The copper concentration in sediment at Site TB11 near the eastern breakwater for the Port of Cape Town and Sites HB1 and HB2 in Hout Bay Harbour, the zinc concentration in sediment at Site HB1 in Hout Bay Harbour, and the nickel concentration in sediment at Site HB15 in the Disa (Hout Bay) River exceeded the Effects Range Low (Figures 5.9 and 5.86; note that the Long *et al.* (1995) guidelines were not derived for application to freshwater ecosystems but are used here to interpret metal concentrations at Site HB15 for comparative purposes). The nickel and zinc concentration in sediment at these sites slightly exceeded the Effects Range Low, but the copper concentration substantially exceeded the guideline (Figure 5.9). Metal concentrations in sediment at all sites were well below the Effects Range Median. The arsenic concentration in sediment at Site HB1 in Hout Bay Harbour slightly exceeded the Effects Range Low. However, this is spurious as the concentration falls within the baseline model prediction limits and is thus not identified as enriched/contaminated

(Figure 5.9). In other words, the Long *et al.* (1995) guideline for arsenic is too low for sediment in the Cape Town outfalls study area. Similar problems are evident when the Long *et al.* (1995) sediment quality guidelines are used to interpret metal concentrations in sediment in other coastal parts of South Africa (CSIR, personal observation). The virtual absence of metal concentration exceedance of the Effects Range Low, the low magnitude exceedance in instances where the guideline was exceeded, and the lack of exceedance of the Effects Range Median suggest there was little likelihood that metals in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme were at concentrations that were acutely toxic to sediment-dwelling organisms. The highest possibility for acute toxicity was associated with the copper concentration in sediment at Site TB11 near the eastern breakwater for the Port of Cape Town and Sites HB1 and HB2 in Hout Bay Harbour.

The sum of low ($<4 - 219 \mu\text{g.kg}^{-1}$) and high molecular weight ($<4 - 557 \mu\text{g.kg}^{-1}$) isomer concentrations, and total polycyclic aromatic hydrocarbon concentration ($<4 - 882 \mu\text{g.kg}^{-1}$) in sediment at all sites for the 2015/2016 survey of the Cape Town outfalls monitoring programme were well below the Effects Range Low (552, 1 700 and 4 022 $\mu\text{g.kg}^{-1}$ respectively) and Effects Range Median (3 160, 9 600 and 44 792 $\mu\text{g.kg}^{-1}$ respectively). There was thus little likelihood that polycyclic aromatic hydrocarbons in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme were at concentrations acutely toxic to sediment-dwelling organisms.

The total polychlorinated biphenyl concentration (2.4, 2.9 and 5.7 $\mu\text{g.kg}^{-1}$) at the three sites in Table Bay where these chemicals were detected in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme were well below the Effects Range Low (22.7 $\mu\text{g.kg}^{-1}$) and Effects Range Median (180 $\mu\text{g.kg}^{-1}$). There was thus little likelihood that polychlorinated biphenyls in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme were at concentrations acutely toxic to sediment-dwelling organisms.

To account for the fact sediment quality guidelines cater for individual chemicals but sediment is often contaminated by a mixture of chemicals, Long *et al.* (1998) advocated use of a mean sediment quality guideline quotient to estimate the combined effect of chemicals. In this approach each chemical is divided by its Effects Range Median to define a quotient. The quotients are summed and then divided by the number of chemicals for which quotients were calculated. Higher mean sediment quality guideline quotients have been shown to generally be associated with a greater probability for toxicity to sediment-dwelling organisms. Long *et al.* (2012) defined four ranges of sediment-dwelling organism exposure to chemicals based on mean Effects Range Median quotients, namely Minimum (<0.1), Low ($0.1 - <0.3$), Moderate ($0.3 - <0.5$) and Maximum (≥ 0.5). Across these ranges the incidence and magnitude of toxicity generally increased, and abundance of most stress-sensitive and stress-tolerant benthic invertebrate taxa in field collected sediment samples decreased and increased respectively. Based on the mean sediment quality guideline quotients for chemicals in sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme the highest risk posed by metals, and at sites where polycyclic aromatic hydrocarbons and polychlorinated biphenyls were analysed were (in order) Sites HB1 and HB2 in Hout Bay Harbour and Site TB11 near the eastern breakwater for the Port of Cape Town (Figure 5.86). The mean sediment quality guideline quotient for these sites was 0.17, 0.12 and 0.12 respectively, which fall into the lower range of the Low category defined by Long *et al.* (2012). The mean sediment quality guideline quotient for other sites fell into the Minimum category.

Long *et al.* (2006) observed a benthic invertebrate species richness decline from 91 to six species for sediment with a quotient <0.03 compared to $>0.2 - 2$. The quotient for 36 of the 50 sites sampled in the 2015/2016 survey of the Cape Town outfalls monitoring programme was <0.03 , while that for all but three of the remaining sites was <0.1 . This again suggests there was little likelihood that chemicals in sediment were acutely toxic to sediment-dwelling organisms.

Field *et al.* (2002) provide an alternate approach to

the use of distinct thresholds defined by sediment quality guidelines for estimating the toxicological significance of chemicals in sediment. Field *et al.* (2002) compiled a large database of sediment samples collected in estuarine and marine ecosystems in the United States of America with matching chemistry and toxicity testing data based on the use of marine and estuarine amphipods. Data for individual sediment samples were sorted by ascending concentration for each chemical. The data was screened to reduce the influence of samples that did not contribute to toxic effects associated with the particular chemical of interest. The relationship between the concentration of a chemical and incidence of toxicity (survival) to amphipods was then described through logistic regression analysis. The models describe, on a continuous scale, the relationship between sediment chemistry and probability for an acutely toxic response in amphipods. Field *et al.* (2002) derived models for individual chemicals and mixtures of (multiple) chemicals. The multiple chemical model, which provides a so-called $P_{\max}$ value, was calculated for sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme. For this purpose chemicals at concentrations below the method detection limit were replaced by a concentration equivalent to the detection limit. This was considered a conservative approach since it will result in a higher estimate of toxicity compared to the conventional approach of replacing non-detects by a concentration of one-half the detection limit.

The use of logistic regression models derived by Field *et al.* (2002) assumes benthic amphipods in the Cape Town outfalls study area are similarly sensitive to contaminants as amphipods used for whole sediment toxicity testing in the United States of America. The $P_{\max}$ varied between 11.5 for Site CB5 on the Camps Bay shoreline to 39.7 for Site HB1 in Hout Bay Harbour (Figure 5.85). The probability for a toxic response in amphipods exceeded 20% at eight sites, five in the Table Bay area and three in the Hout Bay area (including the Disa [Hout Bay] River). This suggests there was a very low possibility that amphipods at some sites could have experienced acute toxicity as a result of exposure to chemicals in the sediment. At sites where metals and organic chemicals were analysed,

a metal was always the most important contributor to the probability for toxicity (53 - 100% contribution, median = 91%).

The toxicological significance of metal concentrations in sediment collected in the Green Point, Camps Bay and Hout Bay areas in previous surveys was also estimated by comparison to the Long *et al.* (1995) sediment quality guidelines. The copper concentration in two sediment samples extracted from a core collected in 1980 (CSIR, 1982) at Site 14 near the end of the western breakwater for the Port of Cape Town slightly exceeded the Effects Range Low (Figure 5.43). The lead concentration in one sediment sample extracted from the core collected at this site and in sediment at Site 42 off the entrance to the Port of Cape Town also slightly exceeded the Effects Range Low. In all cases the metal concentrations were well below the Effects Range Median. There was thus little likelihood that metals in sediment collected in Table Bay in 1980 were acutely toxic to sediment-dwelling organisms.

The mercury and nickel concentration in sediment collected at two sites near the Hout Bay outfall diffuser section in 1994 (CSIR, 1994) considerably and slightly exceed the Effects Range Low, but no metal concentrations in sediment collected in 1993 exceed the Effects Range Low (Figure 5.46). There was thus little likelihood that metals in sediment collected in Hout Bay in 1993 and 1994 were at concentrations acutely toxic to sediment-dwelling organisms apart possibly for the mercury concentration in sediment collected at one site in 1994. However, this concentration was highly anomalous in that it was far higher than the concentration at other sites (when detected) and suggests that toxic effects, if evident, would have been restricted to sediment-dwelling organisms in a very small area.

The arsenic and copper concentrations in sediment collected in the Granger Bay Marina, and the copper concentration in sediment collected at Sites 1N05 and 1ESE05 near the Green Point outfall diffuser section and Site HB6B near the Hout Bay Harbour in 2003 (CSIR, 2003) exceed the Effects Range Low (Figures 5.49 and 5.88). In all instances, the magnitude of exceedance was relatively small and the concentrations were well below the Effects

Range Median. There was thus little likelihood that metals in sediment collected in the Cape Town outfalls study area in 2003 were acutely toxic to sediment-dwelling organisms.

The mercury concentration in sediment collected at Site GBay near Granger Bay and Site HB7 inshore of the Hout Bay outfall in 2011 (CSIR, 2011) exceed the Effects Range Median (Figure 5.72). The lead concentration in sediment collected in 2011 at Site TB6, about 4 800 m to the west of the Green Point outfall terminus, exceeds the Effects Range Low. The lead concentration in sediment at Site TB10 near the western breakwater for the Port of Cape Town and the nickel concentration in sediment at Sites TB6 and TB10 in the same survey are slightly lower than the Effects Range Low. The low magnitude exceedance of Effects Range Low suggests there was little likelihood that metals in the sediment were at concentrations acutely toxic to sediment-dwelling organisms with the exception of mercury in sediment collected at Sites GBay and HB7 in 2011. However, these concentrations were highly anomalous in that they were not only very high but were the only mercury concentrations that exceeded the method detection limit. This suggests that toxic effects, if evident, would have been restricted to sediment-dwelling organisms in a very small area.

In conclusion, comparison of metal, hydrocarbon and polychlorinated biphenyl concentrations in sediment collected in the Cape Town outfalls study area in 1980, 1993, 1994, 2003, 2005, 2006, 2010, 2011 and 2015 to sediment quality guidelines, and the use of mean sediment quality guideline quotients and logistic regression modelling to estimate their toxicological significance suggests that for virtually all sites where sediment was collected there was little likelihood these chemicals were at a concentration presenting an acute toxic risk to sediment-dwelling organisms. Apart from Hout Bay Harbour the greatest risk was posed by contaminants in sediment near the Port of Cape Town and mouth of the Salt River.

5.4. Conclusions

Results of the physical and chemical analysis of sediment collected for the 2015/2016 survey of the Cape Town outfalls monitoring programme reveal

that sediment in parts of the Table Bay, Camps Bay and Hout Bay marine receiving environments was slightly enriched by particulate organic matter and was contaminated by metals, hydrocarbons and/or polychlorinated biphenyls. There was, however, no relationship between contaminant concentrations in sediment and distance from the outfall diffuser sections. The most contaminated sediment was in fact usually situated a considerable distance from the outfall diffuser sections, and usually fairly near the shoreline at or near potential sources of contaminants to the marine environment off Cape Town. These include the Salt River, stormwater discharge points, the Port of Cape Town, and Hout Bay Harbour. This makes it difficult to determine if contaminants in the sediment were derived from effluent at all but a few sites near the outfall diffuser sections, and even at these sites the link to effluent is usually not certain.

Although sediment was contaminated by metals, hydrocarbons and polychlorinated biphenyls, the concentrations of these chemicals in the sediment were usually low. In other words the contamination was not severe. This implies that metals, polycyclic aromatic hydrocarbons, and by inference other chemicals in effluent discharged through the Green Point, Camps Bay and Hout Bay outfalls that have a propensity for adsorbing onto sediment are not accumulating excessively in sediment in most parts of the Cape Town outfalls study area, at least not in the long-term. This conclusion is consistent with the findings of previous surveys in the Cape Town outfalls study area. Thus, despite the long history of effluent discharge into the marine environment off Cape Town (over 115 years) there is no evidence for the severe chemical contamination of sediment in the Table Bay, Camps Bay and Hout Bay areas.

Two sediment quality guidelines were used to estimate the toxicological significance of chemical concentrations in sediment collected in the marine receiving environments, a lower guideline that indicates the onset of possible acutely toxic effects and an upper guideline that indicates a high possibility for such effects. Although concentrations of some metals in sediment at a small proportion of sites exceeded the lower guideline the magnitude of exceedance was not only usually small but almost entirely restricted to chemicals in sediment

collected in Hout Bay Harbour and the Disa (Hout Bay) River. All metal concentrations were well below the upper guideline. Polycyclic aromatic hydrocarbon and polychlorinated biphenyl concentrations in all sediment samples were well below the lower guideline. The same applies to metal concentrations in sediment collected in the Cape Town outfalls study area between 1980 and 2011, even though the mercury concentration in two samples exceeded the highest sediment quality guideline. This suggests that chemicals in the sediment were at concentrations unlikely to have presented an acutely toxic risk to sediment-dwelling organisms. Two other approaches used to estimate the toxicological significance of chemical concentrations in sediment also showed there was a low likelihood that chemicals in the sediment were at concentrations presenting an acutely toxic risk to sediment-dwelling organisms. Regardless of the actual sources of metals, hydrocarbons and polychlorinated biphenyls in sediment in the Cape Town outfalls study area, and even if all contamination of sediment is attributed to effluent discharge following the precautionary principle, it is thus apparent that currents and other forms of turbulence limit the accumulation of contaminants in sediment in most parts of the Cape Town outfalls study area to concentrations that present an acutely toxic risk to sediment-dwelling organisms. It is possible contaminants derived from effluent and/or other land-based sources in sediment in the Cape Town outfalls study area may be impacting sediment/bottom-dwelling organisms through chronic toxicity, but cannot easily be estimated.

The fact that contaminants are not accumulating to acutely toxic concentrations in sediment in the Cape Town outfalls study area might seem counterintuitive considering the outfalls discharge effluent into or near (semi-enclosed) bays and, importantly, because comment in the media from numerous sources seems to have created an impression that contaminant concentrations in these environments must intuitively be high. Although sheltered marine environments are more susceptible to contaminant inputs than exposed environments, it is clear Table Bay, Camps Bay and Hout Bay are not as sheltered as it outwardly might seem. Thus, currents and other forms of turbulence appear to be consistently strong enough to limit the

significant accumulation of contaminants in sediment in these areas in the long-term.

It is recommended that chemicals identified in effluent that are known, based on their properties, to accumulate in sediment and to pose an ecological risk at elevated concentrations, and chemicals that provide a highly specific tracer of effluent be analysed concurrently in sediment in future surveys for the Cape Town outfalls monitoring programme. The positions where sediment quality should be monitored should ideally be informed by simulations of the fate of effluent in the near- and farfield through numerical modelling. Sediment monitoring should continue to have a 'regional' focus, that is, on identifying areas in the near- and farfield where contaminants may be accumulating in sediment and sources of the contaminants. The analysis of a chemical, or chemicals that provide a highly specific tracer of effluent should be concurrently analysed along with chemicals conventionally analysed in sediment to aid in identifying the fate and impact of effluent discharged through the outfalls on the seabed.

While contaminants in effluent discharged through the outfalls do not appear to be accumulating to acutely toxic concentrations in the Green Point, Camps Bay and Hout Bay areas, they could be accumulating in low bed sheer stress areas in deeper waters in the far-farfield (*e.g.* on the Benguela Shelf). The CSIR (2003) provided evidence for the settling of effluent-derived particulate organic matter on the seabed at the outer boundaries of Table Bay and Hout Bay. Even if sediment in the far-farfield (*e.g.* Benguela Shelf) is found to be contaminated it will be impossible to determine if the contaminants were derived from effluent unless highly specific chemical tracers of effluent are concurrently analysed and detected in the sediment. Although such monitoring is not recommended as part of the Cape Town outfalls monitoring programme, determining if contaminants are accumulating in sediment in the far-farfield should be investigated if the opportunity arises (*e.g.* by 'piggy backing' on other studies). This should address concerns of the public, the regulator and scientists on the potential wider-scale impact of effluent discharge into the marine environment off Cape Town.