Ocean Sediment Program

2020 assessment year report

Sydney WATER

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1 Executive summary

Extended time-series monitoring to understand anthropogenic impacts and potential longer-term change in benthic marine communities has been advocated for deepwater ocean outfalls in other parts of the globe (Currie and Parry, 1999; Rees et al., 2006). The EPA (1998) '*Study Design for Long-term Monitoring of Benthic Ecosystems Near Sydney's Deepwater Ocean Outfalls'* enables periodic assessment of the longer-term performance of the Sydney deepwater ocean outfalls and provides a mechanism to alert for development of possible long-term accumulative effects. Sydney Water has implemented that program design under the Ocean Sediment Program, which monitors both sediment chemistry and benthic infauna. The two overarching objectives were: to assess if there is a chronic impact occurring; and to evaluate if any potential existing impact is spreading around the Malabar outfall. Outcomes from statistical and graphical analyses under the 13 sub-objectives raised from the above two objectives have formed lines of evidence to allow a weight-of-evidence assessment.

Low organic concentrations and a lack of anoxia have persisted across the Sydney Deepwater Outfall study region over the 2001 to 2020 period due to ocean currents and internal ocean waves being sufficiently large at times to re-suspend bottom sediments. The apparent lack of hypoxia was also due to low initial dilution values of at least 100:1 being exceeded about 94%, 98% and 87% of the time for North Head, Bondi and Malabar outfalls, respectively. This 100:1 dilution criterion is based on Puente and Diaz (2015) who considered it is difficult for hypoxia to develop at or above that dilution level in the open sea where intense mixing from wave and currents enable a large surface area for re-aeration. Assessment of outfall community structure indicated organic input from discharges has not resulted in sediment anoxia. Temporal fluctuation in community structure detected at the three outfall and three reference locations in the current study was also noted in the pre-commissioning study at these locations (including the future outfall locations).

The potential for build-up in sedimentary metal concentrations was suggested to be unlikely as no long-term trend in grain size was apparent at the three outfall locations over the 21 years of granulometry study. Moreover, a sediment-granulometry gradient was observed with increased fining to the south across the nine study locations. The best modelled relationship was recorded between benthic infauna and sedimentary fines and not to metal contaminants.

The current post-commissioning investigation detected a gradual change in community structure from north to south in the study area, which was also displayed in taxonomic turnover south of the Malabar outfall. The pre-existing sediment metal enrichment in offshore sediment detected before commissioning of the deepwater ocean outfalls in the areas of the present-day outfalls may have posed a long-term, low risk of adverse biologic effects that has influenced benthic community structure together with sediment granularity at all nine locations of the study.

The Ocean Sediment Program has provided over 20 years of data to examine possible long-term accumulative effects in this 2020 assessment report. The weight-of-evidence provided by this study suggests accumulation of contaminants in offshore ambient sediments has not increased and that the risk of adverse biological effects have not increased beyond pre-commissioning concentrations. Evidence from analyses of companion infauna data suggest that the three Sydney deepwater ocean outfalls have not caused significant ecological impact.

2 Introduction

In the 1970s planning was undertaken to replace three cliff face ocean outfalls (North Head, Bondi and Malabar) discharging approximately 940 ML/day, or 80% of sewage generated by the City of Sydney with deepwater ocean outfall disposal (Besley and Birch 2019a). The stated objective at that time was to treat and dispose of sewage in a safe, aesthetically acceptable manner, while simultaneously protecting the receiving waters for present and future beneficial uses (Philip and Pritchard, 1996). The deepwater ocean outfall disposal option was designed to meet receiving water quality criteria, which in summary were: maintenance of ocean waters visually free of oil and grease and other floatable material; protection of beaches for public health and aesthetic satisfaction; and protection of ocean waters to retain a natural and diverse, but not unnecessarily unchanged, variety of marine life (Philip and Pritchard, 1996).

The three deepwater ocean outfalls commissioned in the early 1990s were assessed for the first two years (1990 and 1991) of operation under a five-year study (the Environmental Monitoring Program, EMP) (Philip and Pritchard, 1996). Generally, the EMP established that the deepwater outfalls performed well and mitigated most of the environmental problems previously experienced when shoreline outfalls were in operation (e.g. Krogh and Scanes, 1997; Underwood and Chapman, 1997) without creating any major new problems in the ocean waters in the short term (Pritchard et al., 1996). Nevertheless, the EMP raised concerns about long-term accumulation of sewage particulates and associated contaminants in offshore sediments and associated effects on biological communities (Scanes and Philip, 1995; Philip and Pritchard, 1996).

These concerns helped shape conditions set out in NSW EPA Environment Protection Licences (North Head EPL number 378, Bondi EPL number 1688, and Malabar EPL number 372) for the three deepwater ocean outfalls, which require: ongoing monitoring of wastewater concentrations and volumes discharged; oceanographic modelling to understand plume movement and settling of sewage contaminants from data collected by a permanent oceanographic monitoring station; and periodic assessment of ocean sediments for accumulation of contaminants and changes in infauna communities (under the Ocean Sediment Program) based on the recommendations detailed in the '*Study Design For Long-term Monitoring of Benthic Ecosystems Near Sydney's Deepwater Ocean Outfalls'* (EPA, 1998). Beach monitoring was also conducted (OEH, 2011). Together this monitoring enables assessment of the longer-term performance of the deepwater ocean outfalls and provided a mechanism to alert for development of possible long-term accumulative effects. Similar extended time-series monitoring to understand anthropogenic impacts and potential longer-term change in benthic marine communities has been advocated for deepwater ocean outfalls in other parts of the globe (Currie and Parry, 1999; Rees et al., 2006).

2.1 Ocean Sediment Program objectives

The long-term objective of the Ocean Sediment Program [as specified in the original licence conditions derived from EPA (1998)] were to address the following questions:

1) Is there a chronic impact of effluent from Sydney's deepwater ocean outfalls?
2) Is there any spreading of a potential existing impact from effluent discharge around the Malabar outfall?

These long-term objectives are based on issues outlined by the EPA (1998). The respective null hypotheses that the sampling design addresses are:

1) there is no chronic impact occurring
2) any potential existing impact is not spreading

EPA (1998) notes that the two hypotheses above require different sampling strategies. Under their design the first question uses near outfall sampling points at all three outfalls, while the second question looks at a gradient study south of the Malabar outfall only (EPA, 1998, page 6, Table 1).

It is recognised that achieving the long-term objectives will require a dataset that covers a substantial temporal scale. The existing dataset spans the period from 2000 to 2020. The objective of this report is to present the data in a format that describes observed conditions and any changes through time, and to investigate a range of statistical approaches to analysing the data that can ultimately be used to satisfy the program objectives.

The sampling design is detailed in EPA (1998). A summary is outlined below.

- The major strategy for this monitoring program is to compare conditions at sites near the outfalls (impact sites) with those at sites removed from the outfalls (reference or control sites). Statistically significant differences between the two types of sites would be construed as 'impacts from the deepwater outfalls'. Ultimately, the program is required to provide Sydney Water with 'an early warning system … that can effectively signal the need for responding to environmental degradation'. (Sites in this context are referred to as locations within the current report)
- To balance costs with the need for timely response to environmental degradation, a nested approach has been adopted with detailed analyses undertaken on the sediment chemistry and biology ('assessment indicators') every third year and has recently been transitioned to every fourth year to align with IPART funding cycle. These analyses include the identification and enumeration of benthic organisms, nutrients, trace metals and organic contaminants. During the intervening years, samples are analysed for total organic carbon and the percentage of fines in the samples ('surveillance indicators').

Sampling for the Ocean Sediment Program is conducted annually during February. Sampling for 'assessment' years has been conducted in 2002, 2005, 2008, 2011, 2014, 2016 and 2020. The other intervening years since 2000 were surveillance years. Data collected in 1999 have been discounted as invalid, as some of this was collected from incorrect geographic coordinates.

A number of different statistical and graphical analyses were conducted on the sediment chemistry and benthic community datasets. If test outcomes (lines of evidence) point in the same direction, they then provide a weight-of-evidence to assess if differences are real or not, and this in turn provides confidence in the overall analysis outcome.

To provide these lines of evidence, the following sub-objectives have been raised from the above two overall study objectives.

To assess question 1 objective (if there is a chronic impact occurring) there are ten sub-objectives:

- to examine long-term total organic carbon (TOC) concentrations and sediment granulometric composition at outfall locations through time and against reference locations
- to assess the potential risk of adverse biological effects of sediment metal concentrations at outfall locations and at reference locations
- to assess the potential risk of adverse biological effects of sediment organochlorine compounds (OC) and polycyclic aromatic hydrocarbons (PAH) concentrations at North Head and Malabar outfall locations
- to assess total sedimentary concentration to percentage fines with ANCOVA
- to assess temporal change at reference locations and spatial differences in benthic macrofauna communities between reference locations
- to assess differences in benthic macrofaunal communities between outfall locations and reference locations
- to examine the structure of benthic macrofaunal communities across the nine study locations and to assess temporal change in these communities
- to examine the relationship between change in sediment metal concentrations and benthic community structure across the nine locations of the study
- to examine the relationship between change in fine sediment and benthic community structure across the nine locations of the study
- to examine benthic macrofaunal community structure of the nine study locations to granulometry

To evaluate question 2 objective (if any potential existing impact is spreading around the Malabar outfall) there are three sub-objectives:

- to examine the relationship between sediment metal concentrations and benthic community structure at five spatially distant locations situated to the south of the Malabar outfall
- to examine taxonomic turnover of the benthic macrofaunal community at five spatially distant locations situated to the south of the Malabar outfall
- to assess if macrofaunal community structure of the Malabar outfall location is related to temporal fluctuations in granulometry

2.2 Definition of disturbance and impact

For the purpose of this report Sydney Water has adopted two specific definitions from the scientific literature. This relates to the use of the words ‘disturbance’ and ‘impact’, with the definitions derived from Underwood and Chapman (1995), Downes et al. (2002) and Morris and Therival (2009).

In relation to Sydney Water’s activities, a water quality disturbance occurs from discharge into receiving waters such as a creek, river, estuary and ocean. Disturbance can be shown by a recorded change in the chemistry of the receiving waters, such as an increased concentration of a nutrient.

A water quality disturbance does not always cause a change in the structure of an ecological community; the concentration of a contaminant may be below the threshold concentration required to trigger ecological change. In the ANZECC (2000) guidelines this is described under the wording threshold concentrations. Thus, a water quality disturbance can occur without a measurable ecological impact.

Where concentration of a chemical in the water quality disturbance exceeds a threshold concentration, an impact in a nearby ecological community structure may become measurable when compared to (a number of) ecological communities at more distant (or upstream) reference locations.

2.3 Previous studies

A summary of the more pertinent sediment studies conducted in the Sydney region are presented below.

2.3.1 Physical processes affecting sediment movement

The settlement and resuspension of particulate matter from a buoyant jet (such as from the deepwater outfall plumes) is complex. It may be possible that such particulate matter finally settles some distance from the outfall, depending on patterns or ocean currents and waves. Consequently, high concentrations of contaminants (attached to particulate matter) may reside at distance from, rather than close to, the ocean outfalls.

Internal waves were identified as a major physical process in the Sydney region (Middleton et al., 1997). Internal waves may interact with the sea floor, shoal and break in much the same way as surface waves on the beach. The dissipation of energy due to breaking internal waves may result in disturbance of the sediments and significant sediment movement. Quantification of sediment movement due to internal waves in the Sydney region has not been undertaken. However, sediment movement will be proportional to the power of the internal wave (a product of the wave amplitude and its period).

In waters east of Bondi Beach (water depth of 65 m), high-frequency internal waves of amplitude 10 m and period 10-30 minutes have been observed (Middleton et al., 1997). The amplitude of

internal waves at tidal periods (12 hours) has been observed at 20-30 m. Such internal waves are not unique to the Sydney region.

2.3.2 Sediment chemistry

To help satisfy the operational needs of Sydney Water, Schneider et al. (1994) reported the results of a baseline survey of the contaminants in marine sediments off Sydney (survey conducted in 1990 prior to the commissioning of the deepwater outfalls). A grid-based design was used covering an area bounded by Curl Curl Beach in the north, Cape Banks in the south and seawards to approximately 7 km. The water depths from which the samples were taken ranged from 10 m to 100 m. The grid spacing in the southern part of the study area (surrounding the Malabar deepwater outfall site), was 0.5 km resulting in approximately 150 samples. Sampling was conducted on a 1 km grid in the northern part of the region (surrounding the Bondi and North Head deepwater outfall sites), resulting in approximately 80 samples. Extensive reef systems in the northern part of the system prevented a finer sampling grid. Sediment samples were collected between August 1990 and April 1991 using a modified Rossfelder vibrocorer.

As part of this study, Schneider and Wyllie (1991) tested a range of sediment samplers to assess their ability to retrieve undisturbed sediments. The retention of fine particles was used to compare a variety of grab samplers and corers. The results indicated that samples from the Van Veen grab sampler retained the lowest percentage and greatest variability of fines, while samples from the box corer and Smith-McIntyre grab retained an intermediate percentage of fines and the piston corer and vibrocorer retained the highest percentage of fines. Samples from the vibrocorer also exhibited the least variability.

Sediment cores were logged, split and stored in Teflon bags at –25^{o}C for later analysis. Samples were analysed for physico-chemical properties (including grain size, total organic carbon and carbonates), a suite of metals (arsenic, cadmium, copper, chromium, iron, lead, nickel, manganese, mercury, selenium and zinc) and a suite of organochlorines (PCBs, HCBs, Lindane, Aldrin, Dieldrin, heptachlor, heptachlor epoxide, chlordane, DDT, DDD, and DDE). No samples were collected for analysis of the benthic community.

A comparison of seven laboratories was carried out to assess the precision and accuracy of each facility. The results indicated that none were capable of undertaking all of the analyses to the required level of precision or accuracy. All laboratories were within a factor of two in their analysis of metals, while some did not detect organochlorines samples spiked at ‘exceptionally high environmental levels’.

The main findings from this survey are summarised below.

- Elevated concentrations of metals were generally observed in a band 2-4 km offshore. In the nearshore zone, the contaminants in the sediments are in transit, being resuspended as a result of storm events. The particulate material further offshore is deposited, resulting in an accumulation of contaminants in the sediments. Beyond 4 km offshore, there is little reworking of sediments and the contaminants in sediments in this region have generally low concentrations.

- Sydney Harbour appears to be the major source of contaminants in sediments for the following substances: copper, lead, mercury, zinc, chlordane, heptachlor epoxide, Aldrin and DDD. It also appears to be a main source of PCB, Lindane and nickel contamination.
- Botany Bay appears to be the primary source of HCBs, Dieldrin and Lindane. It is noted that the sampling grid terminated near Cape Banks on the northern side of Botany Bay. The use of these data to link Botany Bay with offshore contamination may not be clearly defined.
- While the shoreline ocean outfalls were often associated with the highest concentrations of contaminants, their spatial extent was generally small (within 1 km of the outfall). Concentrations of cadmium, copper, lead, mercury, zinc, chlordane, DDT, DDD, DDE and Lindane were observed near the North Head shoreline outfall. However, this site may be confounded by dumped material. Contaminants in the sediments did not appear to be associated with the Bondi shoreline outfall. Sediments near the Malabar shoreline outfall contained elevated concentrations of chromium, chlordane, DDT, DDE, Aldrin and heptachlor epoxide.
- Groundwater was implicated as the source of contaminants (chromium, chlordane, DDT, Dieldrin, HCB and PCBs) near Maroubra Beach and as a source of selenium near Coogee Beach. However, it was recognised that confirmation studies would need to be undertaken to confirm the groundwater as a significant source of contaminants of the sediments in these regions.
- Sediment movement appears to be associated with several mechanisms. Under the dominant East Australian Current, finer particles move generally towards the south. Conversely, under storm conditions, there is likely to be increased riverine input of sediments, resuspension of previously deposited sediments and a net movement of (both fine and coarse) sediments towards the north (the predominate direction of major storms).
- In water depths of less than 30 m, sediment reworking to a depth of at least 1 m is likely. Much of this sediment movement was estimated to have occurred in the last 10 years. There is unlikely to be any sediment reworking in water depths exceeding 120 m. This is in contrast to studies by Field and Roy (1984) and Roy (1985), who suggested that the sediments in this region have remained largely undisturbed for the last 7,000 years.
- The distribution of metals was generally correlated with iron content, total organic carbon and water depth, while the distribution of organics was principally related to terrigenous gravel content of the sediment, porosity and sand particle size. Neither organic nor inorganic contaminants were strongly associated with the fine sized particles. This is in contrast to the findings of many reported studies.
- While concentrations of the contaminants were generally low, reviews of sediment toxicity data suggested that concentrations of lead, mercury, zinc, PCBs and DDT (and possibly DDD and HCBs) were capable of producing observable toxic effects in biota.

Based on the work described in Schneider et al. (1994), Schneider and Davey (1995) developed a regression model for the distribution of contaminants in the sediments off the coast of Sydney. The independent variables in the model are: iron, total organic carbon, water depth, grain size and

carbonate content. For concentrations of copper and chromium, more than 60% of the variability could be explained. The conclusions reached in Schneider et al. (1994) were reiterated in this paper.

In 2000, Matthai and Birch (2000) published an article on the effects of coastal cities on surficial sediments along the central NSW coast, from the inner shelf (water depth <60 m) to the outer shelf (water depth around 200 m). The definitions of inner, middle and outer shelf were based on the sediment texture as a reflection of ambient conditions on the seafloor. The samples collected from the middle shelf, defined as a low-energy depositional environment were the most relevant to the current Sydney Water study.

Samples were collected from 309 locations, between Jervis Bay in the south and Port Stephens in the north, using a Smith-McIntyre grab sampler similar to that used in the current study. Vibrocorer samples were also collected from some locations to assess sediment quality prior to anthropogenic influences.

The Matthai and Birch (2000) study identified areas of relative enrichment of trace metals in the surficial sediments adjacent to the three major coastal cities of Wollongong, Sydney and Newcastle. The middle shelf zone, defined as the low energy depositional zone, appeared to contain the highest levels of trace metals. The levels of enrichment relative to pre-anthropogenic or minimal anthropogenic influence varied from city to city and parameter to parameter, with samples collected offshore from Newcastle generally having the highest level of enrichment. Relative to other coastal shelf environments, the levels measured on the central NSW coast were low.

Other findings and observations of the Matthai and Birch (2000) study that are relevant to the current Sydney Water study included:

- For the majority of metals, the enrichment on background levels was minimal (<1.2 times). Only copper, lead and zinc had enrichment values exceeding 1.5 times background levels
- Adjacent to Sydney, enrichment of copper, lead and zinc in the fine fractions of sediments results mainly from the disposal of large volumes of sewage effluent. They also suggest lead in the fine fraction of these sediments may be derived from a source other than sewage alone.
- A rapid decline in the concentrations of trace metals with increasing distance from the major cities. This is directly related to the efficient dispersion of particulates along the inner shelf in the high-energy environment.

2.3.3 Sediment biology

Monitoring of the marine sediments offshore of Sydney has been conducted on a regular basis since prior to the commissioning of Sydney's deepwater ocean outfalls between 1990 and 1991. The potential impacts of the deepwater ocean outfalls included the accumulation of contaminants in the sediments and their impact on benthic faunal communities (Gibbs, 1988).

Initial sediment studies constituted part of the Sydney Deepwater Ocean Outfalls Environmental Monitoring Program (EMP). The forerunner of this program was the Pilot Study for the EMP

(Gibbs, 1988). The primary objective of the pilot study was the identification of resource requirements and sampling techniques to carry out a cost effective and statistically robust sampling program.

The results of a review of sediment sampling methods (grab sampler, corers and dredges) were presented in Gibbs (1988). Based on this review, a Smith-McIntyre grab covering an area of 0.1 m^2 was used to obtain the sediment samples during the Pilot Study for the EMP. Murray and Murray (1987) described a sediment 'scoop' system that does not disturb the surface sediments and, by sealing the scoop after collection, does not lose fine materials in the retrieval process. The effectiveness of the bite profiles from different types of grab samplers, including the Smith-McIntyre, can be found in Riddle (1989). A subsequent review of different sampling techniques (Schneider and Wyllie, 1991) determined that vibro-coring was an efficient method of retrieving undisturbed sediment samples that retain the fine fractions of the sediments.

Three replicate sediment samples were obtained from a total of 27 sites located in nine across-shelf transects, along the 30 m, 60 m and 100 m isobaths. Inshore, three of the sites were located near the old cliff-face outfalls and the remaining six were reference sites. Similarly, along the 60 m isobath, three of the sites represented each of the deepwater ocean outfalls, the remaining six were reference sites. The nine offshore sites were reference sites. At each site, two samples were washed and preserved for infauna identification, and a third sample was frozen and retained for chemical analysis (Gibbs 1988).

The results from this pilot study indicated (Gibbs 1988):

- reliable samples were not obtained from the North Head site
- the species composition at the three depths were different
- four samples provided between 70% and 75% of species
- at least three samples should be collected from each site
- sampling should be conducted at the Bondi and Malabar deepwater outfall sites (as well as at four reference locations: two to the north of Bondi, one between Bondi and Malabar and one to the south of Malabar)
- no recommendations were made regarding the analysis of contaminants in the sediments.

2.3.4 Integrated sediment chemistry and biology

The sampling design to help assess impacts on the marine sediments of wastewater discharges from the deepwater ocean outfalls is described in EPA (1992a, 1992b). As for the pilot study, a Smith-McIntyre grab with a 0.1 m^2 surface area was used for sampling sediments.

Sampling was conducted at three reference sites and three treatment sites along the 60 m isobath. Two locations were identified at each site and three replicate grab samples were obtained from each location. Sampling was undertaken on three occasions (Winter 1989, Summer 1990 and Autumn 1990), with the first of these used to further refine the sampling techniques. The data from this survey was not used in the subsequent statistical analyses.

The results of this study indicated:

- substantial variability in the abundance of macroinvertebrates in the sediments off Sydney
- little difference observed between the outfall and control sites. However, there was substantial spatial and temporal variability among sites
- polychaetes generally dominated fauna
- due to a concern regarding statistical power, the study recommended that sampling be conducted at three locations within each site

Based on the results of the pre-commissioning studies, EPA (1992c) indicated that there would need to be a substantial change in abundance (100% or more depending on the species) to achieve power of 0.8 using three replicates.

The sampling design for examining contaminants in the sediments (EPA, 1992b) varied considerably from that for the soft sediment communities. Samples were collected using a modified Van Veen grab. Sampling was originally planned using gravity cores, but a poor retrieval rate of sediments led to abandonment of this technique. This resulted in only one complete sampling event prior to commissioning of the deepwater outfalls.

Six locations were identified, one at each of the three deepwater outfalls, near Terrigal and Turimetta Head in the north and offshore from Marley Beach in the south. Four zones were identified at each location. At the three outfall sites, one zone was located close to the diffusers, while the remaining three zones were located to the north, south and east of the outfall. Three replicate samples were obtained from each zone. Surface sediment samples were analysed for a range of physico-chemical parameters, metals and organics. Analyses were undertaken using the raw data and using data normalised according to particle size.

The results from the EPA (1992b) study indicated:

- uncertainties in the results from the Terrigal site (data from this site was not used in subsequent analyses)
- particle size has a low correlative power to metal content, with the exception of zinc and copper (there was no strong basis for normalising the data with particle size)
- concentrations of metals in the sediments of the Sydney region were comparable with background concentrations found in other regions worldwide (sediments in the Sydney coastal region are not contaminated with organochlorine compounds, but it was noted that the sensitivity of the analytical methods was relatively low)
- a high degree of within-location variability, comparable to the variability between locations
- power analyses indicated generally high power (greater than 0.8) for the metals and slightly less for the organics
- power estimates increased when the data were normalised against particle size.

As part of the post commissioning program for the EMP, sediment samples were collected (nominally) every three months using a 0.1 m^2 Smith-McIntyre grab sampler from the above six sites (three control and three outfall sites). Six replicate samples were obtained from each site and

the animals contained in each sample identified to (generally) family level. Statistical analyses of these data were undertaken to determine whether 'observed changes in the abundances of soft-bottom organisms around the outfalls were the result of spatial and temporal variations or attributable to the deepwater outfalls.'

In the Sydney Deepwater Outfalls EMP, Final Report Series, Volume 5, *Impacts on Marine Ecosystems* (EPA 1996) there appear to be contradictory conclusions. On page 40 the authors conclude: 'The univariate statistical analysis (asymmetrical analysis of variance) detected significant sustained impacts on the soft-bottom communities surrounding the Malabar, North Head and Bondi deepwater outfalls. Increases and decreases in the abundance of soft-bottom organisms occurred at the same outfall and also varied among outfalls.' However, on page 41 the author contradicts this finding by saying; 'The asymmetrical design, as with many symmetrical designs, is not without particular problems and these were summarised in Otway et al. (1994). Specifically, the design does not permit tests for sustained impacts…' The authors go on to discuss various observations of divergence which may or may not represent impacts but follow this with; 'As no appropriate test for sustained impact is possible, the statistical significance of this result could not be examined.' Results of multivariate analysis echoed the spatial and temporal fluctuations detected by univariate analysis, but were unable to detect impacts at the community level.

Additional results of the EMP report are best summarised as:

- differences in 23 (North Head), 9 (Bondi) and 11 (Malabar) groups of soft-bottom organisms were detected after commissioning
- no short term impacts were detected
- the direction of change at Malabar and North Head varied among taxa (abundance of some taxa increased, others decreased), while abundance of taxa increased at the Bondi deepwater outfall
- the mud fraction of the sediments showed a significant increase at the Malabar deepwater outfall and a significant decrease at the North Head deepwater outfall (a non-significant result was returned for the Bondi deepwater outfall)

Due to the limited time frame over which the EMP study was conducted, the natural temporal variation could not be separated from putative potential impacts. Out of this work, Otway et al. (1996) noted that as the dataset grows temporally the power improves to separate, if present, a measurable impact due to a water quality press disturbance (represented by discharges from the deep ocean outfalls in the offshore ocean environment) from natural variation of the turbulent ocean environment.

The model of Pearson and Rosenberg (1978) for soft bottom sediment communities suggests that, as abundance declines close to the outfalls, we would expect the difference in mean abundance to exceed 75%. If this occurs, a-priori power analysis would indicate that there is the power to detect 'significant' changes of this magnitude with the current sampling design of the Ocean Sediment Program. Unfortunately, the time scale over which these changes may occur is not known.

EPA (1996) noted that '… the substantial variability in the structure of the soft-bottom communities has the potential to mask the effects of pollution'. Both physical and biological processes were identified as potential disrupters of the successional sequence of the integrity of the sediments.

Contaminants in the sediments were measured at six locations (three reference and three outfalls) at six-monthly intervals between July 1990 and July 1993. To help increase the statistical power of the sampling design (identified in the pre-commissioning studies as a potential problem), a fourth reference site (Jervis Bay) was added to the sampling program in January 1992. Sediment samples were collected using a Van Veen grab sampler from four zones within each site. Three replicate samples were obtained from each zone on each sampling occasion. Samples were analysed for a range of trace metals and organochlorine compounds, as well as for total organic carbon and the percentage of fines in each sample. The data were analysed using both univariate and multivariate techniques.

The results from these analyses are summarised below (EPA 1996):

- the concentrations of trace metals were generally found to be below levels that may potentially cause biological effects. However, it is noted that the overseas guidelines against which these conclusions were assessed may not necessarily be 'applicable to Australian environmental conditions.'
- significant correlations were found between the percentage fines and chromium, manganese, selenium and zinc
- no significant correlation was found between total organic carbon and any trace metal
- no significant spatial-temporal interactions were found between outfall and control sites for cadmium, manganese, nickel, silver or zinc. However, significant interactions were found for arsenic, cobalt, copper, lead, mercury and selenium. Concentrations of arsenic, cobalt, copper and lead were generally elevated at the outfall sites compared with the control sites
- non-metric multi-dimensional scaling of the data failed to identify any discernible patterns or associations in the data
- for organochlorine analyses more than 80% of samples recorded 'below detection limits'. Only HCBs were consistently detected throughout the study. While not discounting the possibility for biological effects to occur due to organochlorine contamination, the study did not indicate 'an increase in HCB concentrations associated with the deepwater outfall locations.'
- pre-commissioning sampling was undertaken on only one occasion, therefore it was not possible to confidently determine the effects of the outfalls on the sediments.

An intensive sediment sampling program was conducted in 1995/96 (EPA, 1997). Sediment samples were collected using a 0.08 m^2 Smith-McIntyre grab sampler. Three sampling programs were adopted:

- small scale spatial study. Conducted in February 1995, 25 samples were obtained from each of three sites located to the south, north and east of the Malabar outfall

- small scale temporal study. Conducted monthly between July 1995 and August 1996, a total of 25 samples were collected from the southern side of the Malabar outfall on each occasion
- gradient study. Conducted in June 1996, five samples were collected from each of nine sites, increasing in distance from the Malabar outfall. The most southerly site was located 20 km south of the outfall.

Although no inter-laboratory comparisons were undertaken (as in Schneider et al. 1994), quality assurance was conducted using both blank and duplicate samples. This procedure identified a number of issues, which were resolved by using a different laboratory.

A large number of statistical analyses were undertaken. These included: bootstrapping to construct confidence intervals, maximum likelihood techniques to develop theoretical distributions of the data, univariate analyses to assess spatial and temporal differences and multivariate analyses to examine relationships among groups of samples.

Results from these analyses are summarised below (EPA 1997):

Small scale spatial study

- biological data were generally highly skewed and non-normal
- spatial differences between sites 200 m apart are statistically significant
- correlations between sediment and biological community data are statistically significant
- there is a high correlation between the percentage of fine sediments and both metals and nutrients
- grab samples obtained from sites more than 50 m apart are essentially independent.

Small scale temporal study

- although relatively small, there are temporal differences within a site
- spatial correlations between the physical and biological data were observed from month-to-month
- again, there is a high correlation between the percentage of fine sediments and both metals and nutrients
- correlations between environmental and biological variables were higher within a month than between months.

Gradient study

- the proportion of fine sediments between 2 and 4 km south of the Malabar outfall was relatively high. It was unclear whether this was due to the outfall or to natural sediment sorting
- spatial differences between sites at increasing distances from the Malabar outfall appears to be related to the proportion of fines in the sediments.

While no obvious change was observed in the benthic community examined in this study, the 'potential for unobserved species replacement' was noted as the benthic community was only identified to the family level.

There was no obvious accumulation of metals or nutrients in the sediments near the Malabar outfall. However, as noted above, the proportion of fines between 2 and 4 km from the Malabar outfall did increase compared to other locations. In this study (and in many other studies), an increase in the percentage of fines was linked to increased concentrations of metals and nutrients. This is in contrast to the findings of Schneider, Davey and Lock (1994) and Schneider and Davey (1995). However, this study did recognise that the proportion of fines in the sediments only accounted for a relatively small fraction of the overall variability in the benthic community.

The role of sediment transport in changing the distribution of chemicals in the sediments was noted. Understanding of the processes for sediment movement at water depths near those of the deepwater outfalls was identified as an area needing further investigation.

2.3.5 Publication of 2016 and 2019

Tate and Marvell (2016) revisited 25 years after commissioning of the first of Sydney's deepwater ocean outfalls (the Malabar outfall in September 1990), the process leading to construction of the deepwater ocean outfalls, and the respective design criteria of the outfalls. They provided an outline of monitoring undertaken since commissioning, and also commented on sustainability for ongoing disposal of wastewater from the majority of Sydney's population. Tate and Marvell (2016) stated 'At least in the short to medium term, and from an environmental impact perspective, the deepwater outfalls are a sustainable viable option for the disposal of wastewater. However, from a purely water resource perspective, and because wastewater comprises mainly drinking water, Koop and Hutchings argued in 1996 that disposal to oceans is probably not a sustainable option. They asserted that reuse and recycling of the wastewater must form part of any better use of the water resource, while conceding that community support, cost, environmental benefit, priorities, timeframes and different engineering options all need to be considered. It should be noted that reuse was considered as part of the original disposal concept, but this option was not taken up due to the cost and energy required and the large volumes of water and lack of suitable and viable customers. This summation remained true in 2015. We acknowledge that water is an increasingly critical resource and that wastewater nutrient recovery is emerging as a viable option. Coupled with the uncertainty of a rapidly changing climate means Sydney Water will need to carefully plan for the ongoing availability of the water resource and wastewater treatment options.'

The Tate and Marvell (2016) paper provided the impetus to analyse trends of three relatively long-term datasets collected post-commissioning of the deepwater ocean outfalls. The first dataset enabled oceanographic modelling to understand plume movement and settling of sewage contaminants from data collected by a permanent oceanographic monitoring station (between 2006 and 2017) as required under NSW EPA Environment Protection Licences (for the three deepwater ocean outfalls). The second dataset comprised the Ocean Sediment Program monitoring data that provided periodic assessment of ocean sediments (2002, 2005, 2008, 2011, 2014, 2016) for accumulation of contaminants and changes in infauna communities based on the recommendations detailed in the '*Study Design for Long-term Monitoring of Benthic Ecosystems Near Sydney's Deepwater Ocean Outfalls'* (EPA, 1998). While the third dataset explored

Beachwatch monitoring data (1993 to 2017). A series of five articles were published in the Marine Pollution Bulletin Volume 145 in August 2019 with these articles revisiting aspects of the series of articles published over two decades ago titled ‘Disposal of sewage to the ocean-a sustainable solution?’ by Koop and Hutchings (1996) and associated authors in Volume 33 Issues 7-12 of the Marine Pollution Bulletin (1996). Associate Professor G.F. Birch of The University of Sydney provided advice to develop the 2019 articles to a suitable publication standard and also guided analysis of the sediment chemistry article (Besley and Birch 2019b).

For this assessment report, the recent data has been added to form a combined dataset of 2002, 2005, 2008, 2011, 2014, 2016 and 2020 assessment year sample collections. Analysis techniques employed in the sediment chemistry article (Besley and Birch 2019b) and infauna article (Besley and Birch 2019c) have been run on this combined dataset together with analysis of covariance employed in past OSP reports. Further details of analysis methods used in the current report can be seen in section 5.

3 Sampling methods

3.1 Study area

The study area covers the mid-shelf zone from Long Reef to Marley (Figure 3-1). The three northern most study locations of Long Reef, North Head and Bondi, are in waters approximately 60 m deep. The remaining six study locations, at Malabar (0 km to 7 km), Port Hacking, and Marley are located in waters approximately 80 m deep (Figure 3-1).

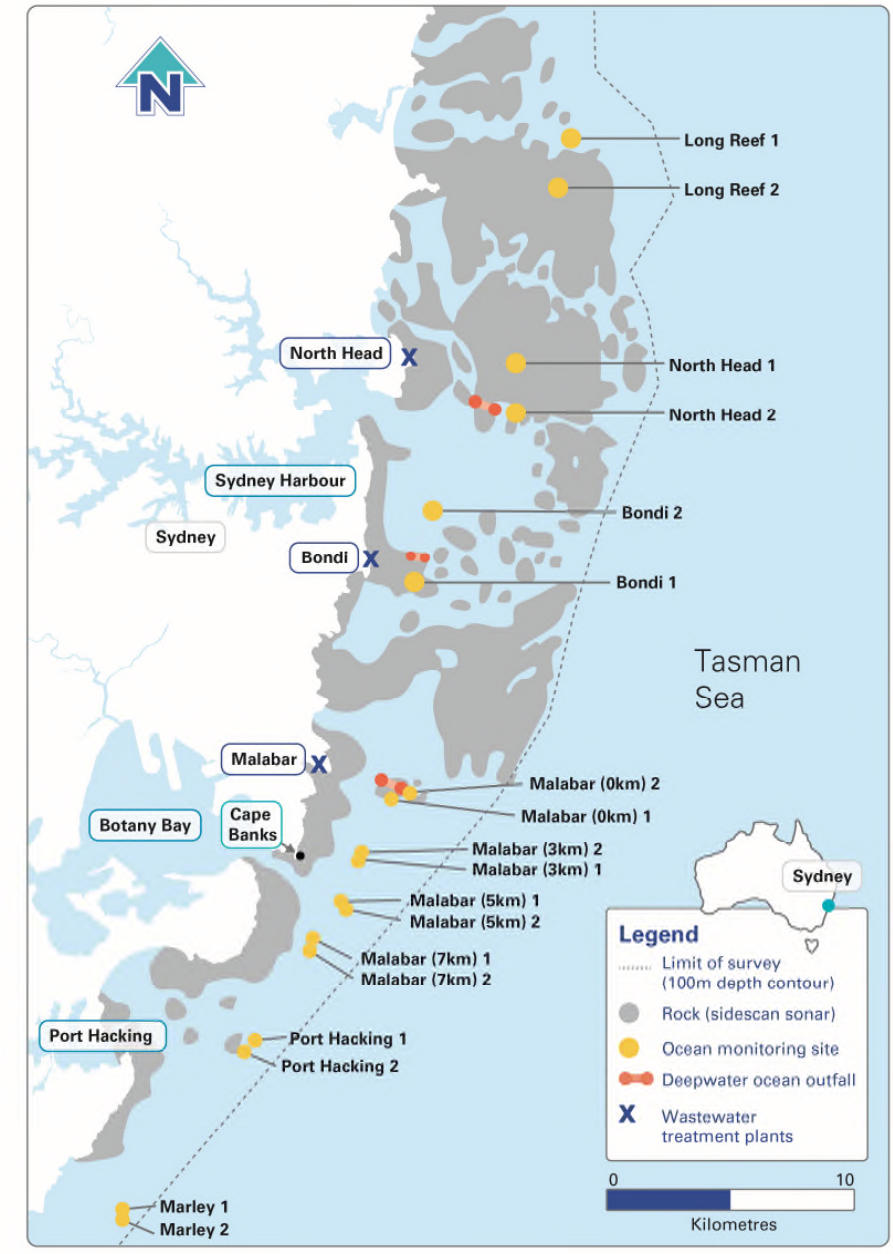


Figure 3-1 Map of the Ocean Sediment Program showing sample sites of the nine locations and the relative position of the deepwater outfall diffuser arrays that disperse wastewater

3.2 Field methods

3.2.1 Site selection within a study location

The sampling design adopted for this study is detailed in EPA (1998) and Sydney Water (2002). This section outlines the positions of the sampling sites and the method used to determine the positions of the five (5) random sub-sites at each sampling location. The method of sub-site selection is consistent with the method outlined in EPA (1998).

In order to select 5 random sub-sites, a 250 m x 250 m spatial grid was constructed and centred on the sampling site referred to in EPA (1998). The grid is subdivided into 50 m lengths along each axis, 50 m being equivalent to one length unit. Therefore, the grid consists of 50 m x 50 m cells and each point in the grid is allocated (x,y) co-ordinates ranging from zero to five as illustrated in Figure 3-2. To establish the grid position of (0,0), the sample positions were converted from latitude and longitude to easting and northing in Australian Map Grid (AGD 66, AMG zone 56). Prior to this, 125 m was subtracted from both the easting and northing of the original reference positions. This allowed the grid to be centred on these positions (Figure 3-2 and Appendix A).

The co-ordinates for the 5 sub-sites were produced by randomly generating two sets of numbers (each representing either the x or y co-ordinates) ranging from 0 to 5. An example is shown in Figure 3-2 with the co-ordinates (3,1). These co-ordinates were converted to easting and northing by adding the appropriate lengths that corresponded to the (x,y) co-ordinates. Since each cell is 50 m x 50 m, each co-ordinate 'unit' corresponds to a length of 50 m. For example, for the position depicted in Figure 3-2, with the co-ordinates (3,1), 150 m (or 3 x 50 m) was added to the easting and 50 m (or 1 x 50 m) was added to the northing of the (0,0) position previously calculated. The actual co-ordinates for each of the random sub-sites used during sampling are provided in Appendix A.

Since each sub-site provides one sediment sample, 5 randomly selected samples were collected from each of two sites within a study location. This yields 10 replicate samples from each study location on each sampling occasion.

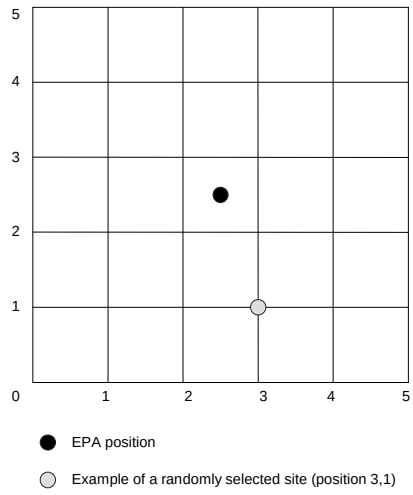


Figure 3-2 Grid used to randomly select 5 sub-sites at each of the original EPA (1998) sites

3.2.2 Sediment collection

The following section outlines the method used to collect sediment samples from the predetermined sampling positions.

The Motor Vessel Oceanographer and crew were contracted as a stable platform, from which a "Smith McIntyre" grab (capacity approximately 5 L, Figure 3-3) was deployed at the randomly located sub-sites. This was achieved by manoeuvring the vessel to within approximately ±5 m of the sub-site position (this is the estimated accuracy of the Differential Global Positioning System – DGPS) before immediately deploying the grab.

Figure 3-3 Smith McIntyre grab

The motor vessel was held in position until the grab reached the seafloor and a sediment sample was taken. In order to ensure samples were as representative as possible, the angle and speed at which the grab was lowered to the seafloor was controlled and maintained for all the sub-sites. The grab was lowered to approximately 3 m above the seafloor and then released to collect the sample. In setting the angle and speed at which the grab was lowered, consideration was given to two things: maximising the volume of the sediment sample retrieved and minimising the bow wave generated from the grab moving through the water column. This method of controlling the grab fall rate has been shown elsewhere to reduce the loss of the fine surface material (Blomquist 1992).

3.2.3 Sediment sub-sampling and storage

The following section outlines the sediment sampling and sub-sampling methods and procedures followed for the immediate storage of the collected sediment samples. Flow diagrams of the offshore sediment program sampling overview Figure 3-4 and sediment sampling/sub-sampling procedures Figure 3-5 show a breakdown of the steps involved.

A retrieval of the grab was deemed successful if it collected a minimum sediment volume of one litre for benthic macrofauna analysis and 500 mL for chemical analyses (in 2 x 250 mL or 1 x 500 mL glass containers). 1 mL of sample volume is considered to be the approximate equivalent of 1 g wet weight for convenience. The minimum weights for sample analysis are subsequently achieved with sample to spare by assuming this weight equivalence to volume.

Separate samples were taken for physico–chemical analysis/benthic macrofauna analysis. This was done by collecting five separate samples from each site, for analysis at the conclusion of the sampling period.

Samples submitted for analysis on completion of the sampling run, had sub-samples taken for physico-chemical parameters by randomly taking single sediment sub-samples with a volume of approximately 250 mL. This was carried out twice for two separate containers, one for organic compound analyses and one for the remaining physical and chemical parameters. This was done by carefully syphoning off the overlying seawater and removing approximately 500 mL of sediment in total, using a stainless-steel scoop into the 2 sample bottles.

Poor weather conditions were encountered consistently during the 2005 sampling period, and as a result, it was deemed that the use of a glass cylinder for sediment sub-sampling was deemed an unacceptable Health and Safety risk. An alternative approach has been used since 2008, whereby the grab sample was carefully placed in a large porcelain tray and a sub-sample was removed using a pre-washed (with acetone) stainless steel trowel. Analysis of results must be undertaken with this change of procedure in mind.

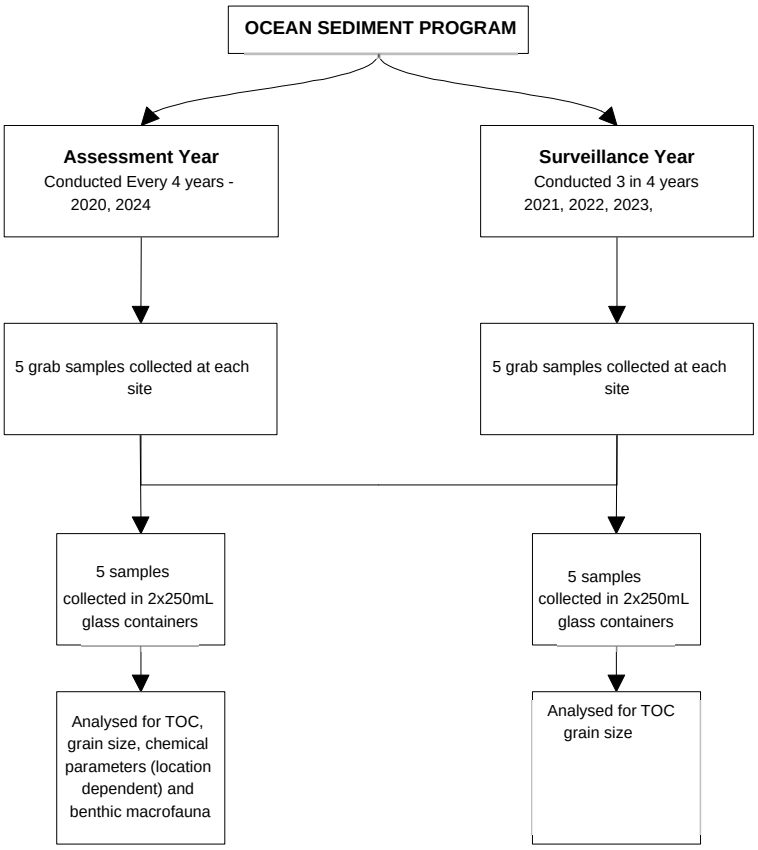


Figure 3-4 Overview of the Ocean Sediment Program sampling process

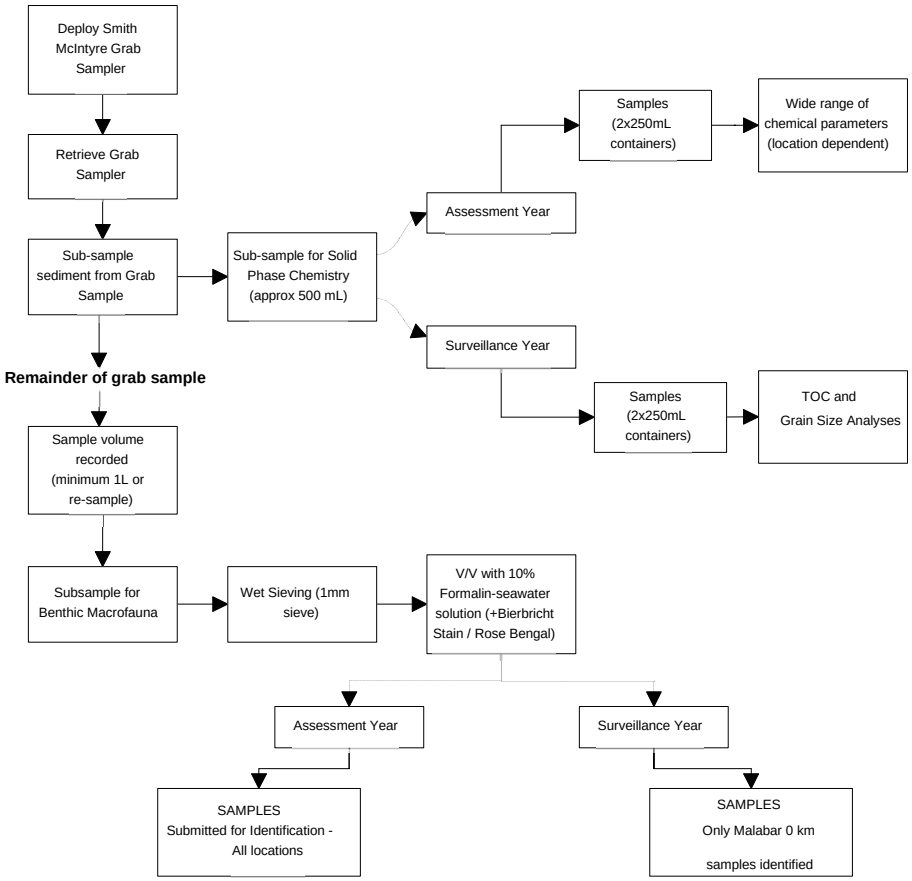


Figure 3-5 Schematic diagram of the sediment sampling procedure

Samples were placed in an appropriately labelled, pre–washed glass storage container with a Teflon-lined lid. Each sample jar was put in a zip-locked plastic bag and placed immediately in a freezer (freezer temperature approximately –20^{o}C). The samples were stored this way until analysis.

The sediment sub–sampling tools were rinsed with deionised water between sub-sites at each location, and new pre–washed sampling tools were used at each sample location.

The remaining sample was used for benthic macrofauna analysis. Remaining sediment was deposited into a container from the grab sample. The volume of the sample material in the container was recorded and then the sediment was gently rinsed through a 1 mm aperture box sieve using low pressure seawater. Care was taken not to scrape or force material through the sieve by the use of any of the tools or the hose used for rinsing. All materials ≥ 1 mm retained by the sieve were transferred to an appropriately labelled, detergent-washed glass container, and preserved in a 10% formalin and seawater solution. This mixture, which consists of 5 mL Rose Bengal in 2.5 L formalin mixed with 22.5 L seawater, was to aid in the preservation of the sample and identification of benthic invertebrates. Each of the infauna sample containers was placed in a plastic zip-lock bag and stored in a cool dry area until they were transported back to the laboratory for analysis. Benthic macrofaunal numbers were not large enough in 2005, 2008 or 2020 to warrant subsampling. As such, the whole infauna sample containers sample was processed.

Nine out of 270 samples from 2011, 2014 and 2016, had sample volumes exceeding 1 L resulting in subsampling. The sub-sampling method used in 2011, 2014 and 2016 processed 50% of the sample using a ‘Modified Marchant Sample Box’ with random selection of compartments within the box. Random selection avoided bias toward obvious larger taxa. Sample volumes in these nine samples were multiplied by two to provide comparable count estimates.

In 2002, benthic macrofauna samples whose volume exceeded 1 L (after rinsing and sieving) were partially sub-sampled in the laboratory due to high numbers of benthic invertebrates collected at some locations this year. This was done by first removing all animals from the sediment and placing all worm tubes into a separate jar. The non-tube fraction of the sample was sorted and identified, separating each taxa into a separate vial. The tubeworms were then sub-sampled by weight. The tubeworm fraction was drained of alcohol until dripping stopped and was then weighed. One-eighth of the total weight was determined. Two one-eighth sub-samples of the tubeworm fraction were then removed to separate jars and labelled. One one-eighth sub-sample was sorted, identified and counted. Any animals not in the following tubeworm families were added back into the main sample, and the data sheet adjusted accordingly. The tubeworm families sub-sampled were: Maldanidae (bamboo worms); Oweniidae (polychaete worms); and Ampharetidae (polychaete worms). To identify each tubeworm, the head of the worm was located and uncovered in the tube. The worm was counted only if a head was present for consistency with all other counts and identifications. If tubeworms were sub-sampled, quality control checks for the sample included checks on the ‘remains’ of the tubeworm sub-sample (empty tubes, tubes with fragments), as is routinely done for the ‘remains’ of the main sample. If the total number of individuals in the first one-eighth tubeworm sub-sample was less than 100, the second one-eighth sub-sample was sorted and identified as above. If one one-eighth sub-sample was sorted, the counts for each of the three tubeworm families listed above were multiplied by eight to provide an estimate of those families comparable to other taxa present. If two one-eighth sub-samples were sorted, the number of worms in each of the three families was summed and multiplied by four to provide an estimate comparable to other families present in the sample. All data sheets were corrected for tubeworm sub-sampling.

4 Analytical methods

4.1 Overview

A summary of the sub-sampling requirements for the analyses conducted is presented in Figure 4-1. Method detection limits for all parameters are presented in Table 4-1.

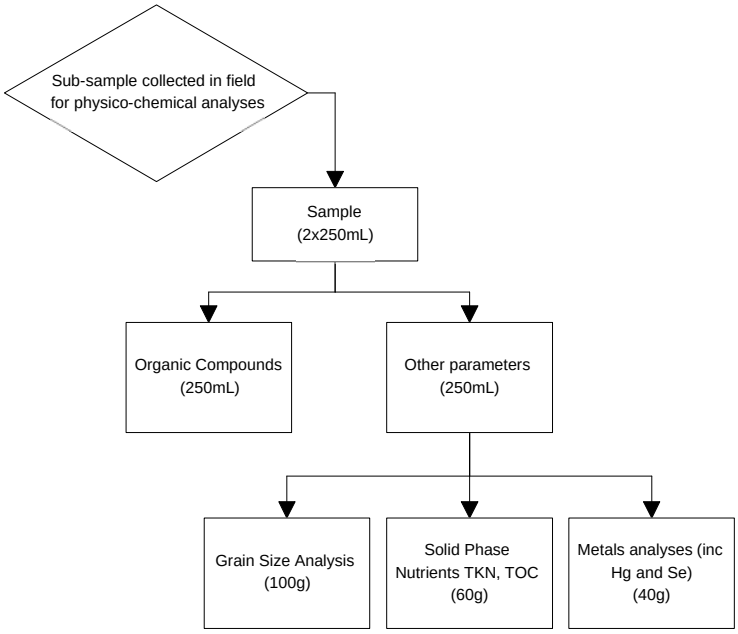


Figure 4-1 Flow chart of analytical sub-sampling requirements

4.2 Trace metals by ICP-AES, ICP-MS, CV-AAS

About 2 g of dried (at 35^{o}C) and ground sample was weighed and transferred to a Teflon vessel, to which HNO_3 and $H2O_2$ were added. The vessel was placed in a microwave for digestion, after which the contents were diluted to 250 mL and analysed by ICP-AES, ICP-MS or Hydride generation AAS for arsenic and selenium or cold vapour AAS for mercury. Moisture content is determined on a separate sample portion if required.

For mercury analysis, some of the HNO_3 / $H2O_2$ digest is analysed by cold vapour AAS (FIMS) analysis. Mercury in solution is reduced to mercury metal with SnCl2, stripped by argon and transported to the cell where absorbance is measured.

Table 4-1 List of analytes, practical quantitation limits (PQL) and methods

Analyte	PQL mg/kg	Analytical method reference
Aluminium	0.3	USEPA (2014) 6020B
Arsenic	0.01	USEPA (2014) 6020A
Cadmium	0.01	USEPA (2014) 6020B
Chromium	0.03	USEPA (2014) 6020B
Chlorophenols		APHA (2012) 6420
Copper	0.02	USEPA (2014) 6020B
Cresols	0.01*	In house method – TC034
Iron	0.1	USEPA (2014) 6020B
Lead	0.02	USEPA (2014) 6020B
Mercury	0.01	APHA (2012) 3112B
Nickel	0.01	USEPA (2014) 6020B
Nitrogen (TKN)	20	APHA (2012) 4500- Norg/NO3 – I/J
Organochlorine pesticides	0.0005*	APHA (2012) 6630 (modified)
PAH's	0.01*	APHA (2012) 6640 (modified)
Particle size		In house method derived from AS1289.C6.1 - 1997
PCB's	0.01*	APHA (2012) 6630 (modified)
Phosphorus (total)	0.5	APHA (2012) 4500-P – H/J
Selenium	0.01	USEPA (2014) 6020A
Silver	0.01	USEPA (2014) 6020B
TOC (total organic carbon)	0.01%	APHA (2012) 5310C

*Detection limit may not be achieved if there is high level matrix interference. From previous experience with this project, high levels of matrix interference are expected to occur infrequently.

4.3 Particle size analysis (wet sieve)

Approximately 50 g of wet sample was used initially. The wet sample was passed through the various sieve sizes in descending size order, with each sieve rinsed with water to ensure all possible material passed through. The material that remained in each sieve (corresponding to a particular size fraction) and the material that passed through the smallest sieve were transferred to separate pre-weighed beakers and dried at 105ºC. The total weight was calculated by adding the weights of the various fractions and the weight of each fraction then used to calculate the size fraction as a percentage of the total.

4.4 Total Kjeldahl Nitrogen (TKN)

Samples were digested with potassium sulphate, sulphuric acid and mercuric oxide as a catalyst to convert ammonium compounds to ammonium sulphate. The resulting ammonia nitrogen was determined using the salicylate modification of the automated phenate method.

4.5 Total Organic Carbon (TOC)

For the TOC analysis, the sample was dried at 40^{o}C, and homogenised using a mortar and pestle. 1 g of dried sample was digested with HCl and homogenised again. Approximately 5 mg of sample was weighed for analysis. The analysis method was then based on converting all organic and inorganic substances by flash combustion. All of the resulting gases were reduced and separated by gas chromatography (GC) and detected by TCM. The sample was digested with 1N hydrochloric acid in a ratio of 1:5 sample/acid. All results were reported as % dry weight.

4.6 Organochlorine Pesticides, HCB, and Polychlorinated Biphenyls (PCB's)

A known amount of sample was dried using sodium sulphate and extracted by ultrasonication with dichloromethane (DCM). The samples were concentrated and a clean-up procedure using alumina was employed to enable separation of polychlorinated biphenyls (PCBs) and organochlorines (OCs). The samples were analysed by GC.

4.7 Polyaromatic Hydrocarbons (PAH's)

A known amount of sample was dried using sodium sulphate and extracted by ultrasonication with DCM. The samples were concentrated and a clean-up procedure using silica gel employed and analysed by gas chromatography/mass spectrometry (GC/MS).

4.8 Cresols

A known amount of sample was extracted with an acetonitrile/water mixture using sonication. The samples are then analysed by HPLC using a fluorescence detector.

4.9 Chlorophenols

A known amount of sample was acidified with concentrated sulphuric acid then dried using sodium sulphate before being extracted by ultrasonication with DCM. The samples were concentrated and derivatised with acetic anhydride then analysed by GC/MS.

5 Data analysis methods

Assessing control and outfall locations

To assess whether the deep ocean outfalls were resulting in any measurable disturbance in sediment quality, analyses were made comparing control or reference locations (not expected to be influenced by the outfalls) with each outfall location (proximate to and potentially disturbed by the outfalls) (Figure 3-1).

Malabar gradient study

Data collected adjacent to Malabar outfall and locations 3 km, 5 km and 7 km south of the outfall along with the two southern control locations (Figure 3-1) were investigated to determine if a spatial gradient, in terms of level of sediment contamination relative to the outfall location, could be found in the area to the south. This was conducted under the premise that the wastewater plume from the outfall dispersed predominantly in a generally southerly direction, as indicated by oceanographic modelling of the plume distribution (Appendix F and Tate et al., 2019).

Significance level, testing software, abbreviations for location codes

Unless stated otherwise, a level of significance of 0.05 was used in this report.

Statistical analysis routines of nMDS, mMDS, PCA, PCO, ordered-ANOSIM, CLUSTER, BVSTEP, Shade plot, PERMANOVA, CAP, DISTLM and ANCOVA were run with the PRIMER version 7.0.13 (Clarke et al., 2014a) and add on PERMANOVA+ module (Anderson et al., 2008).

To enhance readability of some graphics and tables the following location abbreviations are used: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference.

5.1 Sediment characterisation

5.1.1 Available data

Available sediment data varied between surveillance and assessment years. During surveillance years, sediment analyses were of grain size and TOC determinations. The data available from assessment years was more extensive and available from all nine locations, which comprised results from laboratory analysis of sediment samples for 12 sedimentary metals [aluminium (Al), silver (Ag), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn)], two organic chemicals M-cresol and naphthalene along with grain size and TOC measurements. Also collected during assessment years was a more expansive list of 41 organic chemicals, analysed from the sediment samples collected at the outfall locations of North Head and Malabar 0 km. Results of these sediment chemistry parameters were tabulated by range of concentrations detected for each assessment year.

5.1.2 Analysis of long-term trends in total organic carbon

Monitoring of total organic carbon (TOC) was measured to identify signs of excessive organic matter accumulation that when combined with a high fines content may result in lower oxygen permeation, increased microbial oxygen uptake/demand and a subsequent accumulation of toxic by-products (Florek and Rowe, 1983; Fenchel et al., 1998). These conditions may become harmful to benthic communities and lead to an impoverished benthic community (Diaz and Rosenberg, 1995; Como et al., 2007). The NSW EPA specified criterion value of 1.2% (99th percentile) for the Malabar 0 km outfall location was used to characterise TOC results from the nine study locations across surveillance and assessment years. TOC results were also plotted by location and year.

5.1.3 Analysis of long-term trends in sediment granulometry

Sediment granulometry was also measured to detect build-up of fines (< 0.063 mm), which may indicate potential for increased metal concentrations. Mean particle size percentage composition was cumulatively plotted for the three size classes by location and year where data were available from the various surveillance and assessment years.

A metric multidimensional scaling (mMDS) ordination was conducted on the three grain size classes (gravel, sand and fines) based on the Manhattan distance resemblance measure raised on location-year averaged percentage composition. This mMDS ordination plot was overlaid with a multi-segmented bubble plot displaying the three size classes for each averaged sample.

5.1.4 Assessing potential risk of adverse biological effects using SQGs

Monitoring of sedimentary metals (Ag, As, Cd, Cr, Cu, Hg, Pb, Zn) and organic chemicals that included OCs (chlordane, dieldrin, endrin, lindane, p.p'-DDD, p.p'-DDE, DDT, total PCBs) and PAHs (acenaphthene, anthracene, benzo(a)anthracene, benzo(a)pyrene, chrysene, dibenzo(a,h)anthracene, fluoranthene, fluorene, naphthalene, phenanthrene, pyrene) allowed assessment of the potential risk of adverse biological effects as these metal and organic chemicals had assigned sediment quality guideline (SQG) values of ANZECC (2000) and revision of Simpson and Batley (2016). The ANZECC (2000) SQG value and high SQG value correspond to the effects range low (ERL) and effects range median (ERM) of Long et al., (1995). The ERL is the value below which adverse biological effects are seldom observed and ERM represents the value above which adverse biological effects are expected to occur frequently (Long et al., 1995). Concentrations between the two guidelines indicate intermediate risk where effects would occur occasionally.

Since contaminants do not occur as single chemicals within ocean sediments, a number of schemes have been developed to assess the effects of chemical mixtures for aquatic sediments (Long et al., 1998, 2000, 2006; Long and MacDonald, 2010; Fairey et al., 2001). The mean ERM quotient (MERMQ) scheme was used to assess eight metals (outlined above) sampled from all nine locations by assessment year. The MERMQ scheme requires normalising the concentration of each chemical with respect to its ERM value, summing the quotients for each substance and dividing by the number of chemicals with available SQG values.

5.1.5 Analysis considerations of 2005

Prior to data analyses for the 2005 data assessment report, investigations of the data structure were carried out to determine the need for normalisation and transformation of the data. An initial assessment of the homogeneity of variance was conducted using Bartlett's Test. The test was made on the following data groupings and manipulations (Table 5-1).

In general terms, data groupings greater than those for a single site failed the test of homogeneity of variance; and none of the transformations or normalisations tested improved this situation across the range of parameters assessed. In discussions with the then, Office of Environment and Heritage (OEH) (now DPIE) it was decided that, while this assumption for conducting Analysis of Variance (ANOVA) was not met, ANOVA is sufficiently robust to be an appropriate test for use as required despite the outcomes of the Bartlett's tests. Given the assessment was conducted on data collected from a period of 7 years, it was determined that the outcomes of further assessment using data collected since 2005 was unlikely to change the outcomes. Subsequently, Bartlett's test was not conducted on data collected from 2008 onwards. An advantage of performing ANOVA with PERMANOVA+ software is that it potentially overcomes the limitation of lack of homogeneity, as 'p values' are calculated by permutation.

Table 5-1 Data groups prepared for Bartlett's tests for homogeneity of variance

Data manipulations	Data groupings												
	All locations all years	All years 60 m locations	All years 80 m locations	All locations 1999 only	All locations 2002 only	All locations 2005 only	60 m locations 1999 only	60 m locations 2002 only	60 m locations 2005 only	80 m locations 1999 only	80 m locations 2002 only	80 m locations 2005 only	Each location (12) all years
Raw data													
Normalised against mud													
Normalised against TOC													
Raw data square root transform													
Raw data log10 transformed													
Raw data reciprocal transformed													
Mud normalised data square root transformed													
Mud normalised data log10 transformed													
Mud normalised data reciprocal transformed													
TOC normalised data square root transformed													
TOC normalised data log10 transformed													
TOC normalised data reciprocal transformed													

Similarly, correlations were produced for data reported in the 2005 data assessment report to assess relationships between parameters measured, particularly between fines, TOC and metals. It was found that there was no consistent relationship between either TOC or particle size and the chemical parameters measured, and that relationships between the chemical parameters and TOC or particle size were generally no stronger than between many of the chemical parameters. As with the Bartlett's test, it was determined that further correlations would not add value to the previous work and would therefore not be conducted from 2008 onwards.

The correlation findings presented in the 2005 data assessment report are in agreement with Schneider et al. (1994), who found that 'neither metals or organochlorines had a strong association with the fine sized particles (mud) in the sediment.

From these initial data assessments, there was little to indicate that a particular normalisation or transformation should be conducted prior to data analysis. It was decided in 2005 that ANOVA would be conducted on the raw data and Analysis of Covariance (ANCOVA) would be trialled using fine grain size as a covariate where appropriate. This was repeated in 2008, 2011, 2014, 2016 and again in 2020 with checks of both fine grain size and TOC as covariates.

5.1.6 Description of analysis of covariance conducted from 2008

ANCOVA is a statistical technique that allows the analyst to control one variable in a data set that correlates with the variable of interest. For example, it has been widely reported that metal contamination in sediments will be predominantly associated with the amount of fine sediment. Thus, if a sample contains a large amount of mud it may also contain elevated concentrations of metals. However, if the samples were looked at as metals per gram of fine sediment they may have the same concentration. Similarly, this potential relationship with fine sediments will add to the variability of the sample and may confound differences between sites.

Consider the following hypothetical example. Using ANOVA on samples with variable fine sediment content to which metals are attached provides data that contains the natural variability of the metal, as well as the natural variability of the sediment. This produces larger variance than for each variable alone and may result in a graph such as Figure 5-1. ANOVA would not detect a difference between these locations.

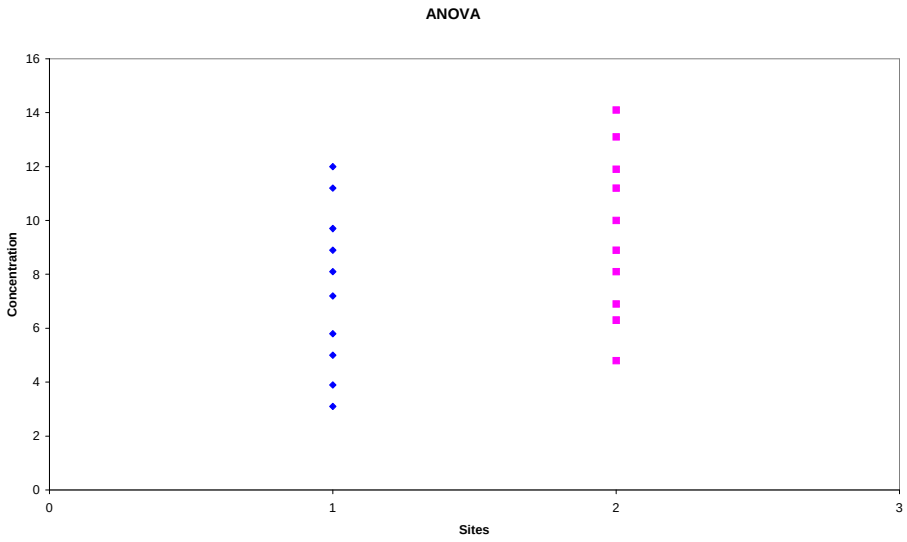


Figure 5-1 Spread of data comparing locations using ANOVA

However, the picture could be substantially different if the sediments are also plotted so that the variance associated with them can be controlled (Figure 5-2).

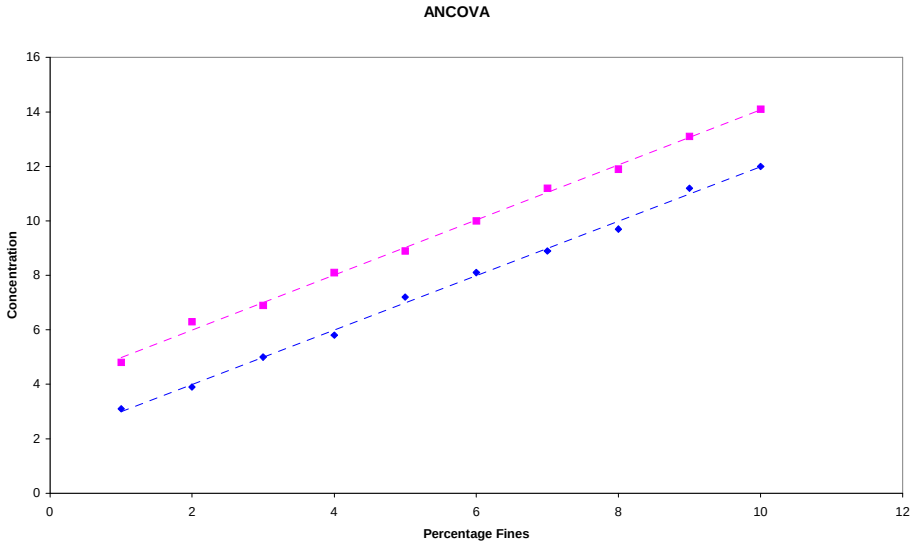


Figure 5-2 Spread of data comparing locations while controlling for the variation associated with fine sediments, as would be done for ANCOVA

ANCOVA allows the experimenter to address the question of whether the difference between the lines (locations) is significant. The underlying assumption, however, is that the slope of the lines are similar.

Prior to running ANCOVA, this assumption regarding the slope of the lines must be tested. If the slopes are similar, as in Figure 5-2, the Null Hypothesis that there is no difference between the slopes will be supported and the ANCOVA can proceed. If the slopes of the lines are not the same (example provided in Figure 5-3), the Null Hypothesis will be rejected and ANCOVA would not be used.

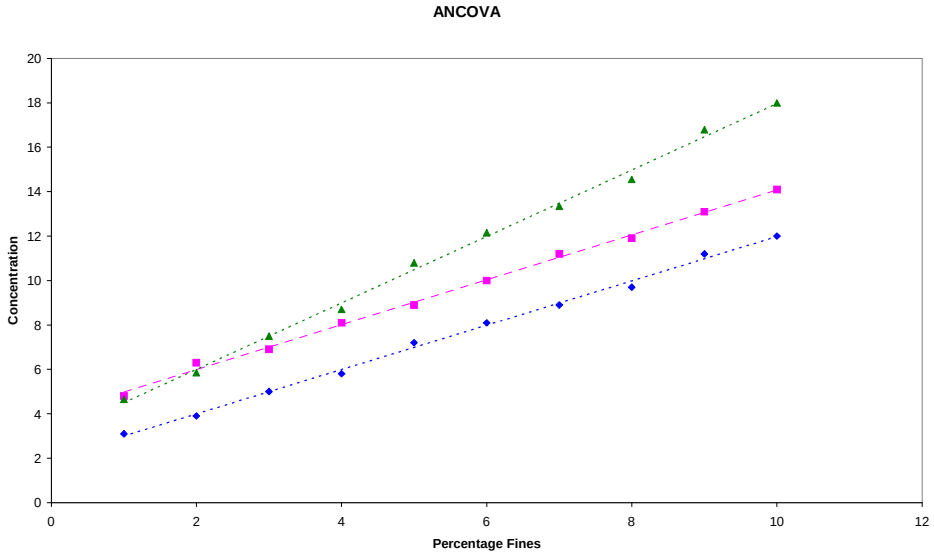


Figure 5-3 The slope of these lines would be significantly different and thus the assumptions of ANCOVA would not be met

5.1.7 Application of analysis of covariance and analysis of variance

Initially, ANCOVA was run using the fine sediment fraction (percentage fines <0.063 mm in ambient sediment) as the covariate. If the assumption of this ANCOVA was met (that is the interaction term was not significant) and the Locations factor was significant, a pair-wise comparison was run between all combinations of sites. If the assumption was not met an ANCOVA using TOC as the covariate would be run. As previously this was followed by a pair-wise comparison if it was valid to do so.

If both ANCOVA's did not meet the assumption, then ANOVA would be run on unadjusted data followed by pair-wise comparisons provided the 'Location' factor was significant.

ANCOVA and ANOVA were run using the PERMANOVA+ for Primer package. Under this package, the regression line comparison (to see if they have the same slope) is made via the interaction term of a two-way ANOVA. This is followed by a pair-wise comparison of Euclidian distance, where the variate and co-variate are both taken into account.

This testing provided a view of the 2020 assessment year data for sedimentary metals.

5.2 Benthic infauna statistical analyses

Analysis techniques of benthic infauna employed in Besley and Birch (2019b; 2019c) have been applied to combined 2002, 2005, 2008, 2011, 2014, 2016 and 2020 assessment year sample collection datasets.

In the below statistical methods, pre-processing comprised dispersion weighting followed by transformation to address statistical and then biological considerations (Clarke et al., 2014a). Dispersion weighting addressed the problem of undue emphasis being given to high-abundance high-variance taxa, with square root transformation helping to balance the depth of view of less-abundant and more-abundant taxa (Clarke et al., 2014a). The Bray-Curtis association measure was used to raise the dissimilarity matrix for ecological data prior to running multivariate techniques listed below. All ordinations listed below were run with 1000 random starts.

5.2.1 Analysis of temporal and spatial differences in community structure at reference locations

To test for temporal and spatial differences in community structure across the three reference locations permutational analysis of variance (PERMANOVA) (Anderson, 2001) was run with fixed factors of 'Location' and 'Year' together with interaction term of 'Location x Year'. 'Location' had three levels: Long Reef, Port Hacking and Marley. 'Year' had seven levels: 2002, 2005, 2008, 2011. 2014, 2016 and 2020.

A non-metric multidimensional scaling (nMDS) ordination plot based on location-year centroids with a split trajectory overlay was constructed on the above dissimilarity matrix. The trajectory numeric factor was 'Year' and split trajectory factor was 'Location' to visually examine the 'Location x Year' interaction of the above PERMANOVA model.

5.2.2 Analysis of differences in community structure at each outfall to the three reference locations

Three nMDS ordination plots based on Location-Year centroids were raised to allow visual inspection of community structure of the three reference locations to each outfall location. Each of the three benthic community datasets were initially dispersion weighted by site-year groupings.

A dendrogram was raised for each of these three datasets using the group average classification technique. Dendrograms were visually inspected to see if an early division separated the outfall location Location-Year centroids from all three reference locations Location-Year centroids.

Rank dissimilarities of an nMDS ordination may not reveal all dimensionality of a multivariate data cloud. As a check for hidden dimensionality Principal Coordinates analysis (PCO) (Gower, 1966) ordination plots were inspected. PCO is an ordination technique that is a projection of points onto axes that minimise the residual variation in the space of a chosen dissimilarity measure (Anderson et al 2008).

The PERMANOVA model detailed in section 4.3.1 was then run with addition of each outfall and the three reference locations. That initial model was then modified with 'Location(Control Impact)' as a random factor together with fixed factors 'Control Impact' and 'Year'. Inclusion of 'Control Impact' allowed the corresponding interaction terms 'Control Impact x Year' and 'Location(Control Impact) x Year'.

5.2.3 Community structure of the nine study locations

A non-metric multidimensional scaling (nMDS) ordination plot was run based on replicate data from the seven assessment years collected at the nine study locations. Then a Canonical Analysis of Principal Coordinates (CAP) (Anderson and Robinson, 2003) ordination plot was also raised. CAP is designed to find axes through the multivariate cloud of points that best discriminate among *a priori* groups (Anderson et al., 2008). In this case the *a priori* groups were the nine study locations. The corresponding output of Cross Validation Leave-one-out Allocation of Observations to Groups statistics were inspected to assess the validity and utility of this CAP modelling. CAP was run on the matrix raised for the nMDS of the nine locations.

The BVStep routine (Clarke and Warwick, 1998) was used to search for subsets of taxa that had a multivariate pattern that matched the original multivariate pattern from all 195 taxa that occurred across the nine study locations. This assessed structural redundancy in the benthic infauna dataset. Search criteria were 40 restarts with 10 starting variables, $\rho > 0.950$, with Spearman rank correlation selected.

A shade plot (Clarke, et al., 2014b) based on the first subset of taxa from the BVStep routine further examined the community structure of the nine study locations by location assessment year average counts of prior dispersion weighted and square root transformed data. To improve visualisation of data patterns in this shade plot, family level taxa were serially reordered from classification based on a data matrix raised with Whittaker's (1952) Index of Association resemblance measure.

5.2.4 Analysis of the relationship between change in metal concentrations and benthic community structure

Canonical correlation of principal coordinates (CAP) was used to specifically model for changes in the benthic assemblage correlated with change along a gradient (Anderson and Willis, 2003). A total sedimentary metal contaminant gradient was assessed. CAP uses principal coordinates (PCO) (Gower, 1966) from the resemblance matrix and a check on over parameterisation is needed (that is, to avoid including too many axes and finding spurious relationships). This was achieved by choosing the number of PCO axes (m) that minimised a leave-one-out residual sum of squares.

To base the CAP analysis, the companion benthic community dataset was dispersion weighted by site-year groupings. A square root transformation was then performed before a dissimilarity matrix based on the Bray-Curtis association measure was raised. Against the benthic community dataset in the CAP analysis PC1 from a Principal Components Analysis (PCA) of total sedimentary metal data of Al, Ag, As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, Se, and Zn was used in the model run to represent the metal contamination gradient. Before PCA was run, metal data were normalised (subtracting the mean and dividing by the standard deviation for each variable) to allow a correlation-based analysis.

5.2.5 Relationship between change in fine sediment and benthic community structure

A second CAP analysis was undertaken with percentage fine sediment as the gradient, replacing PC1 used in section 5.2.4. These two CAP model runs were made for all nine locations.

5.2.6 Examination of benthic macrofaunal community structure of the nine study locations to granulometry

This examination was based on the initial visual inspections of an mMDS ordination plot of granulometry based on Manhattan distance resemblance measure to the benthic community structure nMDS ordination plot raised in section 5.2.3. A second visual comparison was made against an overlay of three grain size classes (< 0.063 mm, 0.063 mm to 2 mm, > 2 mm) on the mMDS ordination plot of granulometry and on a summarised version of the benthic community structure nMDS ordination plot with reduced data points of site-year centroids.

A mMDS ordination plot was also raised on total sedimentary metal concentrations based on Euclidean distance with reduced data points of site-year centroids.

5.2.7 The modelled relationship between fine sediment metal concentrations and benthic community structure south of the Malabar outfall location

The ‘Distance-based linear models’ (DISTLM) routine (McArdle and Anderson, 2001) was used to assess taxonomic turnover between the Malabar outfall location and the five locations to the south. Data were analysed in two sets, a spatial geographic (distance between location samples) set and chemistry (various metals) set of predictor variables. By analysing the data in sets, one can explicitly examine the proportion of variation in the species data that is explained by the environmental variables over and above the amount explained by the spatial variables alone

(Anderson et al., 2008). This allows the hypothesis 'there is no relationship between the benthic community and sedimentary metal concentrations given the spatial variable' to be tested.

Two DISTLM model runs were made for the Malabar outfall location and the five locations to the south for total sedimentary metal concentrations and for metal concentrations normalised to the fine sediment component. Relatively well correlated metals (r >0.8 for total sedimentary metal concentrations and r > 0.84 for metal concentrations normalised to the fine fraction) were omitted to account for multi-collinearity.

5.2.8 Examination of taxonomic turnover to the south of the Malabar outfall location

An ordered-ANOSIM (Clarke et al., 2014a) tested for serial change in community structure with increasing distance away from the Malabar outfall location based on the factor 'Distance' calculated as units of distance apart for each location was run. This tested the null hypothesis of no differences between community structure of locations against an ordered alternative of Malabar outfall > Malabar 3 km > Malabar 5 km > Malabar 7 km > Port Hacking > Marley.

5.2.9 Assessing if the macrofaunal community structure of the Malabar outfall location is related to temporal fluctuations in fine fraction of sediment

Canonical Analysis of Principal coordinates (CAP) (Anderson and Willis, 2003) was used to model change in community structure of the Malabar outfall location from each year between 2000 to 2020 against companion samples of percentage fines in ambient sediment (the environmental variable of interest). In this case, CAP was used to find an axis through the multivariate data cloud, which had the strongest relationship with percentage fines in ambient sediment

Two plots were constructed, one with abundances and the other with the number of families for the above three higher taxonomic groups by year from 2000 to 2020 for the Malabar outfall location.

6 Results

6.1 Oceanography

In previous years the interpretation of oceanographic data for the ocean sediment program was done in-house. The interpretation for 2020 was provided by WQ Data Pty Ltd for Oceanographic Field Services Pty Ltd, and detailed in the Ocean Sediment Program Oceanographic Report. It contains oceanographic components of: plume dilution; the settling of particulate matter from the wastewater plumes; and likelihood of resuspension of settled material in the months of December 2019, January 2020, and February 2020. The WQ Data Pty Ltd report is presented in Appendix F.

A brief summary from that report is provided below along with a comparison of outcomes from a review of 2006 to 2017 oceanographic data conducted by Tate et al. (2019).

6.1.1 Wastewater plume dilution

WQ Data Pty Ltd (2020) indicated the information contained in Figure 4, Figure 5 and Figure 6 (Appendix F) for the North Head, Bondi and Malabar deepwater ocean outfalls, suggests the height of plume rise lies in the range 10-30 m for the period 1st December 2019 to 29th February 2020. Plume dilutions during this period were highly variable, lying between (approximately) 100:1 and 1000:1. Dilutions were greatest for the Bondi deepwater ocean outfall, and then for the North Head deepwater ocean outfall. At both locations dilutions routinely entered the thousands. The lowest dilution values were modelled for the Malabar deepwater ocean outfall where it was not uncommon for dilutions to drop below 100:1.

Near-field plume dilution results from the 1st December 2019 to 29th February 2020 appear reflective of the broader 2019-20 period (Table 6-1) provided by WQ Data Pty Ltd under contract with Oceanographic Field Services Pty Ltd. The percentage of time the 100:1 dilution was exceeded in 2019-20 was marginally higher than that determined by Tate et al. (2019) over 2006 to 2017 period the initial dilution zone value of 100:1 as being exceeded: 87% of time at Malabar deepwater ocean outfall; 94% of time at North Head deepwater ocean outfall; and 98% of time at Bondi deepwater ocean outfall.

Table 6-1 Plume dilution and percentage of time exceeded over 2019-20 financial year for the deepwater ocean outfalls of North Head, Bondi and Malabar

Percent of time exceeded	Dilutions		
	North Head	Bondi	Malabar
98%	77.9	104.7	70.1
95%	98.4	136.5	84.5
90%	121.7	166.1	101.3
75%	173.2	242.7	135.2
50%	262.5	374.0	190.8
25%	406.9	600.1	280.6
10%	649.3	977.5	426.5
5%	858.3	1292.6	562.6
2%	1168.3	1776.5	788.4

6.1.2 Particulate matter in plume

Estimates of the location at which negatively buoyant particles reach the sea floor are presented in Figure 4, Figure 5 and Figure 6 (Appendix F) for the North Head, Bondi and Malabar deepwater ocean outfalls respectively, for the period 1st December 2019 to 29th February 2020. Heavy particulate matter discharged from the deepwater ocean outfalls was modelled to reach the seabed within approximately 10 km of the outfall. The spatial distribution of such negatively buoyant particles around each outfall is approximately aligned with the bottom bathymetry (WQ Data Pty Ltd, 2020).

Negatively buoyant particle settling results for the period 1st December 2019 to 29th February 2020 align with the broader period of 2006 to 2017 modelled estimated location of negatively buoyant particles from the plume reaching the ocean floor within 3 km 50% of time, and within 5 km 80% of time and within 10 km 95% of time (Tate et al., 2019, Figure 10).

6.1.3 Resuspension of settled material

In the two months preceding the February 2020 sediment-sampling period, either currents (Figure 2, Appendix F) or waves (Figure 3, Appendix F) were likely to have caused substantial sediment movement (WQ Data Pty Ltd, 2020).

These active sea-bed conditions were also illustrated over the broader 11-year period (2006 to 2017) as sediments were modelled to resuspend about 2.5% of time. Sediment movement by currents alone (without wave action) was towards the south about 80% of time while wave induced movement of resuspended sediment was towards the north estimated to occur about 4% of time at 65 m depth and about 1% of time at 80 m depth (Tate et al., 2019).

6.2 Wastewater quality comparison to ANZECC guideline values

Dilution factors derived from the above models allowed comparison of modelled chemical concentrations of mixed wastewater at the edge of the near-field zone for each of the deepwater ocean outfalls to ANZECC (2000) guideline values for protection of 95% of marine species.

Out of the suite of parameters measured at each plant, eight chemicals had ANZECC (2000) water quality guideline values assigned. For the other chemical parameters monitored under EPA pollution monitoring licences no set values had been assigned by ANZECC (2000) to allow this comparison.

Modelled results of 2020 indicate diluted wastewater chemical concentrations in the ocean near all three deepwater outfalls were below the ANZECC (2000) guidelines for the protection of 95% of marine species except for copper at North Head and Malabar (Appendix B). Exceptions for copper in the water column have also been recorded in the past (Appendix B).

6.3 Sediment characterisation

6.3.1 Long-term trends in Total Organic Carbon

In 2020 the total organic carbon (TOC) content was less than 1.2% at all locations for all samples except for single replicates at Long Reef, Malabar 5 km and Malabar 7 km locations. No replicate sample values for TOC exceeded the NSW EPA specified trigger value of 1.2% (99th percentile) for the Malabar 0 km outfall location from the 2020 collection (Figure 6-1).

A total of 1440 samples have been collected over the 2001 to 2020 period. Only 23 of these samples had TOC values that equalled or exceeded 1.2% TOC (Table 6-2).

Table 6-2 Twenty three samples out of 1440 samples collected from all locations that had TOC % values equal or above 1.2% TOC NSW EPA trigger value set for the Malabar outfall location over the period 2001 to 2020

Year	Location	TOC %
2002	North Head outfall	1.5
2002	North Head outfall	1.9
2002	Long Reef reference	4.4
2003	North Head outfall	1.3
2003	Long Reef reference	1.5
2003	Long Reef reference	1.3
2005	Long Reef reference	1.9
2005	Long Reef reference	1.6
2005	Long Reef reference	1.8
2006	Bondi outfall	1.5
2006	Malabar 7 km	1.8
2007	North Head outfall	1.4
2009	Malabar 7 km	3.5
2011	North Head outfall	3.5
2016	Malabar 0 km outfall	1.2
2015	Bondi outfall	2.0
2017	North Head outfall	1.7
2017	North Head outfall	1.6
2018	North Head outfall	1.2
2018	North Head outfall	1.4
2020	Long Reef reference	1.4
2020	Malabar 5 km	1.9
2020	Malabar 7 km	1.2

To look for signs of build-up of TOC in the sediments, box plots were constructed by location and year (Figure 6-1). TOC was only measured at the three deepwater outfall locations in surveillance years of 2012, 2013, 2015, 2017, 2018 and 2019 under the NSW EPA modified study design ie the six non-outfalls locations were excluded from monitoring. This needs to be considered when interpreting Figure 6-1.

Box plots of TOC by location and year displayed variation between years with no apparent accumulation at eight of the nine study locations. At the Malabar 7 km location, median values recorded in sample years 2009, 2010, 2011, 2014, 2016 and 2020 were greater than those documented in earlier years for this location (Figure 6-1). The lack of sampling in years 2012, 2013, 2015, 2017, 2018 and 2019 due to a change in collection frequency for the six non-outfall locations may have contributed to the observed pattern.

The typical levels of sedimentary TOC at the southern two reference locations were generally greater than levels at the northern Long Reef reference location. Sediment at Long Reef typically contained the lowest overall median TOC levels (0.2%) of all locations compared. Median TOC levels at the southern two reference locations were 0.5% and 0.6% while the three gradient study locations (Malabar 3 km, Malabar 5 km, Malabar 7 km) had median TOC levels ranging from 0.6% to 0.7%. Median TOC concentrations of the three outfall locations ranged from 0.3% to 0.5% (Figure 6-1).

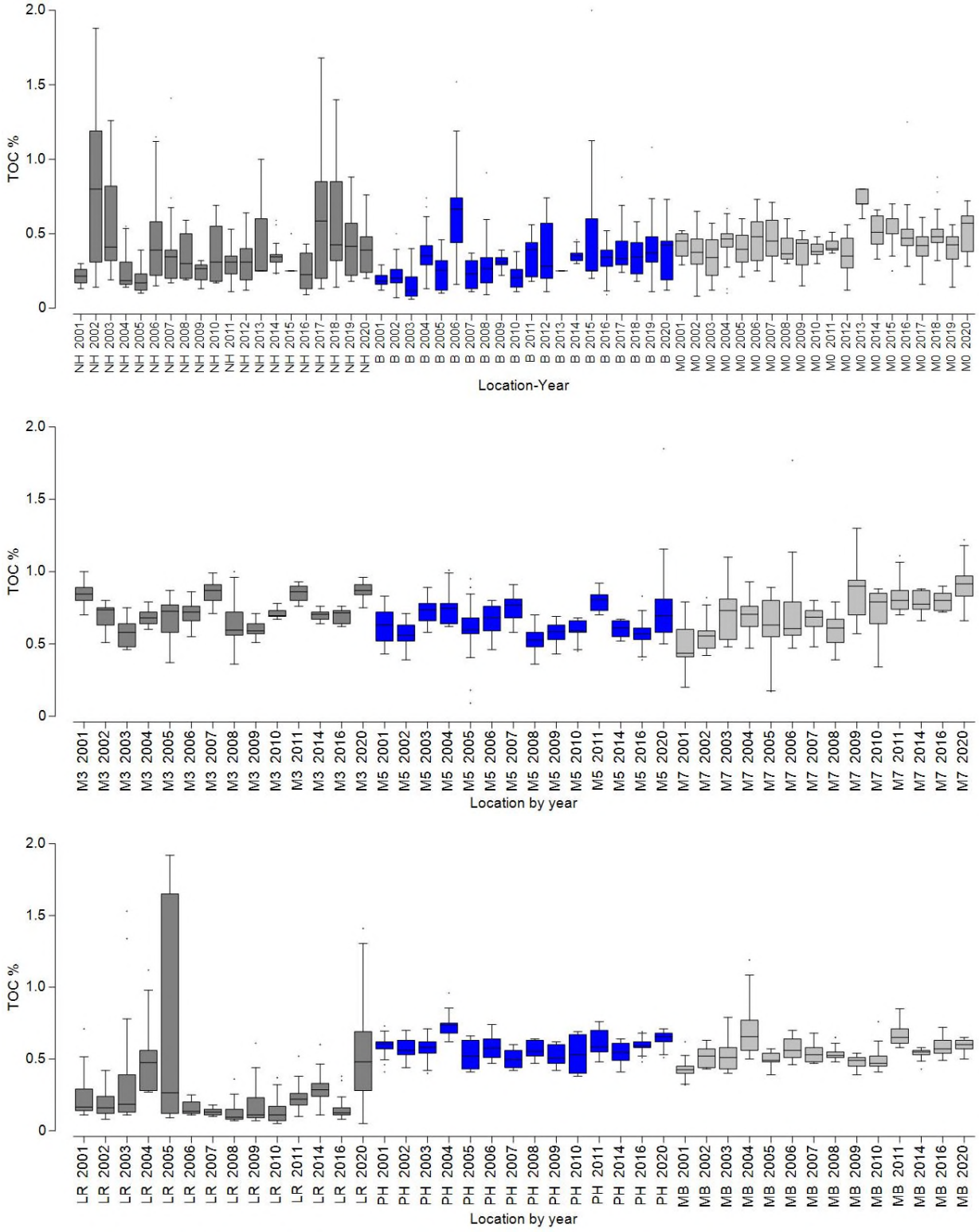


Figure 6-1 Box plot of TOC % for location by year: upper plot) North Head (NH), Bondi (B) and Malabar 0 km (M0) outfall locations; middle plot) Malabar 3 km (M3), Malabar 5 km (M5) and Malabar 7 km (M7) gradient study locations; lower plot), Long Reef (LR), Port Hacking (PH) and Marley (MB) reference locations

6.3.2 Long-term trends in sediment granulometry

Particle size data for three size classes were cumulatively plotted by location and year (Figure 6-2) from 2000 to 2011. Particle size was only measured at the three deepwater outfall locations in surveillance years of 2012, 2013, 2015, 2017, 2018 and 2019 under the NSW EPA modified study design. This needs to be considered when interpreting Figure 6-2 for the other six study locations.

In general, particle size was different at each outfall between the northern Long Reef reference location and the two southern reference locations of Port Hacking and Marley (Table 6-2). Particle size at the three gradient study locations was similar to the southern reference locations (Table 6-3).

The sediments at the Bondi outfall location contained the highest proportion of sand (95.7%) of the nine locations (Table 6-3). While the most gravel (2.3% and 6.6%) and least percentage of fines (2.5% and 3.0%) occurred at the northern Long Reef reference and North Head outfall locations at 60 m water depth (Table 6-3). Surficial material at the six most southern locations at 80 m water depth included the highest percentage of fines (6.6% to 11.9%) and almost no gravel, while sediment at the Bondi outfall location at 60 m water depth typically had more gravel (0.5%) and a similar low percentage of fines (3.5%) as recorded for the other two 60 m water depth locations of the Long Reef reference and North Head outfall (Table 6-3).

Longer-term (2000 to 2020) patterns of change in sediment size were only apparent in two of the nine locations. An increased median fine particle percentage over the 2003 to 2016 period occurred at the Malabar 7 km location, with a decline observed in 2020. A build-up of fine particles was also apparent for the 2001 to 2016 period for the Marley reference location some 17 km to the south of the Malabar outfall. A decline in fine particles at Marley was also recorded in 2020. As both of the Malabar 7 km location and Marley locations had increasing median values for the periods outlined followed by a decline in 2020, this suggested these upward fluctuations may have been natural as at the Marley location the highest median value of fine sediment was recorded in 2000 (Figure 6-2).

The metric MDS plot with multi segmented bubble plot overlay displayed a greater contribution of coarser particles at the Long Reef reference and North Head outfall locations on one tangent, while locations in the south of the study area were plotted on another tangent that highlighted a relatively greater contribution of fines (Figure 6-3). The Bondi outfall location was situated at the centre of these two tangents in the metric MDS ordination plot reflecting the highest contribution of intermediate sand-size particles. Also evident in this ordination plot was fluctuations in sediment composition through time, with the greatest fluctuations apparent for the Long Reef reference and North Head outfall locations (Figure 6-3).

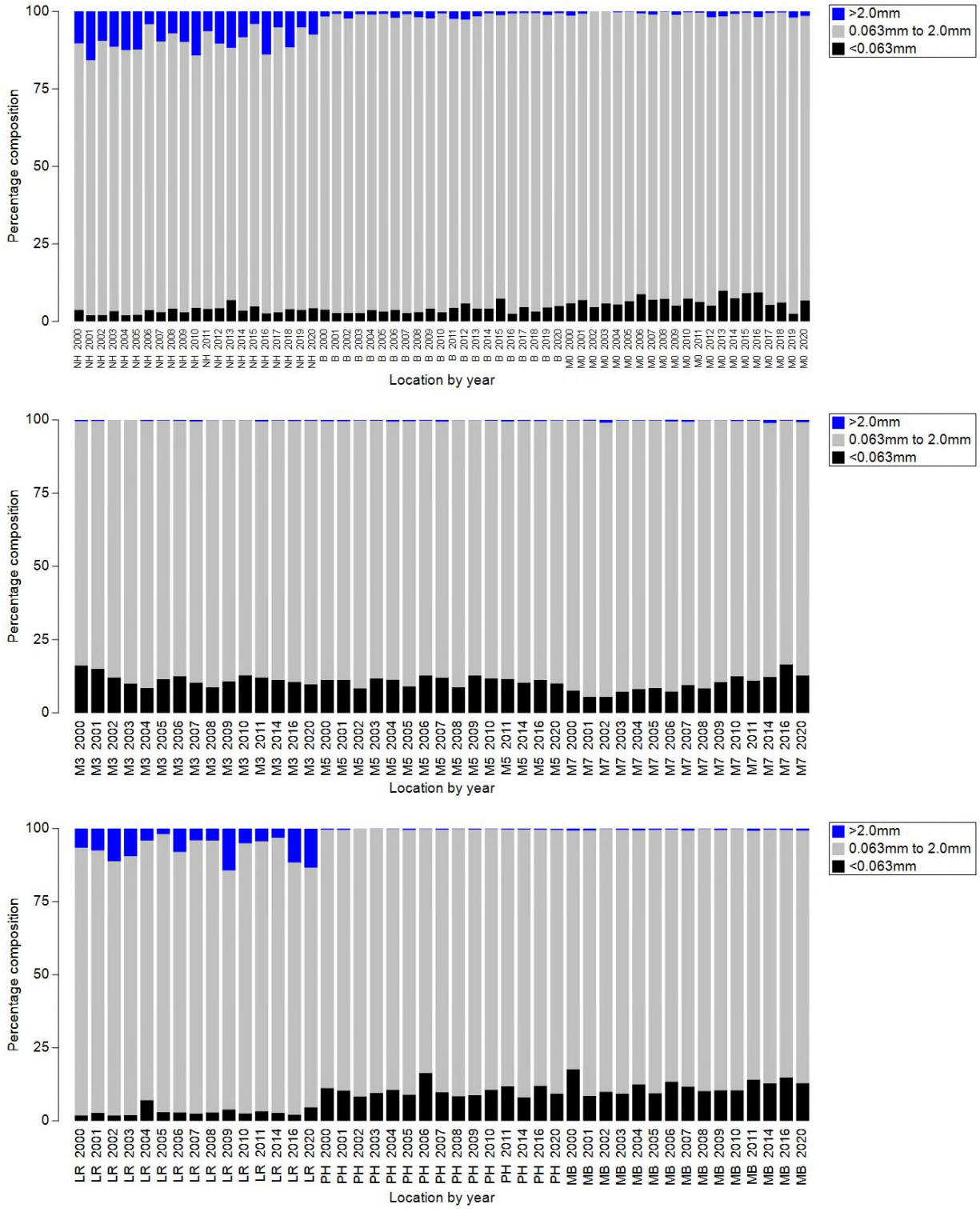


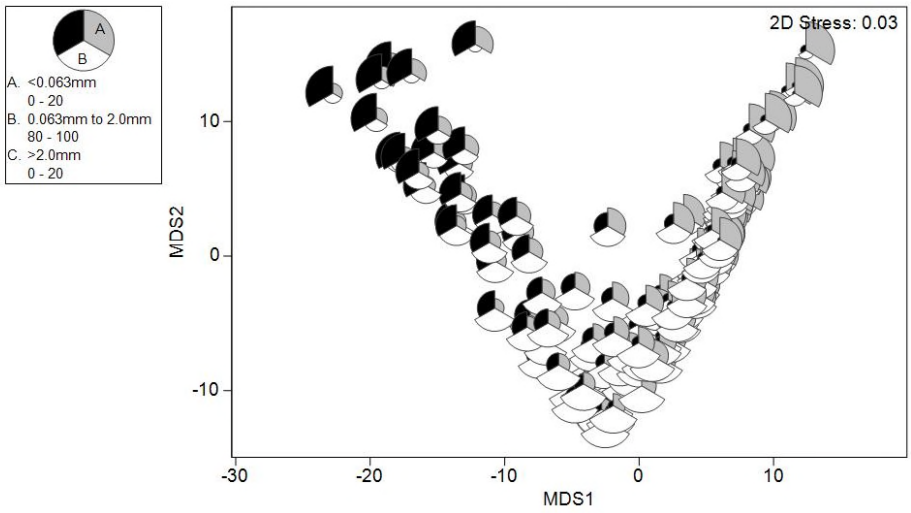
Figure 6-2 Particle size percentage composition for locations by year from 2000 to 2020 for outfall (NH = North Head, B = Bondi, M0 = Malabar) locations and for 2000 to 2011 and 2014, 2016 and 2020 at reference (LR = Long Reef, PH = Port Hacking, MB = Marley) and gradient study (M3 = Malabar 3 km, M5 = Malabar 5 km, M7 = Malabar 7 km) locations

Table 6-3 Particle size percentage composition for locations from 2000 to 2020 for North Head, Bondi and Malabar outfall locations and at six other locations from 2000 to 2011, 2014, 2016 and 2020

Location	Long Reef reference	North Head outfall	Bondi outfall	Malabar outfall	Malabar 3 km	Malabar 5 km	Malabar 7 km	Port Hacking reference	Marley reference
n	150	210	210	210	150	150	150	150	150
Fines (<0.063 mm)									
Minimum	0.3	0.7	0.2	0.4	0.1	1.6	0.4	0.6	3.0
Median	2.5	3.0	3.5	6.6	11.5	11.1	8.9	10.0	11.9
Maximum	15.0	28.5	17.8	14.4	18.6	20.2	21.4	41.9	28.0
Sand (0.063 mm to < 2 mm)									
Minimum	43.3	54.7	79.3	84.8	80.6	79.8	78.1	58.0	72.0
Median	94.1	89.1	95.7	92.7	88.2	88.6	90.6	89.7	87.8
Maximum	98.5	98.2	99.1	98.8	99.8	96.5	99.6	99.3	97.1
Gravel (>2 mm)									
Minimum	0	0	0	0	0	0	0	0	0
Median	2.3	6.6	0.5	0.5	0.1	0.2	0.1	0.1	0.3
Maximum	55.4	43.0	17.0	7.5	2.4	2.2	4.9	1.6	2.7

n = number of samples

a)



b)

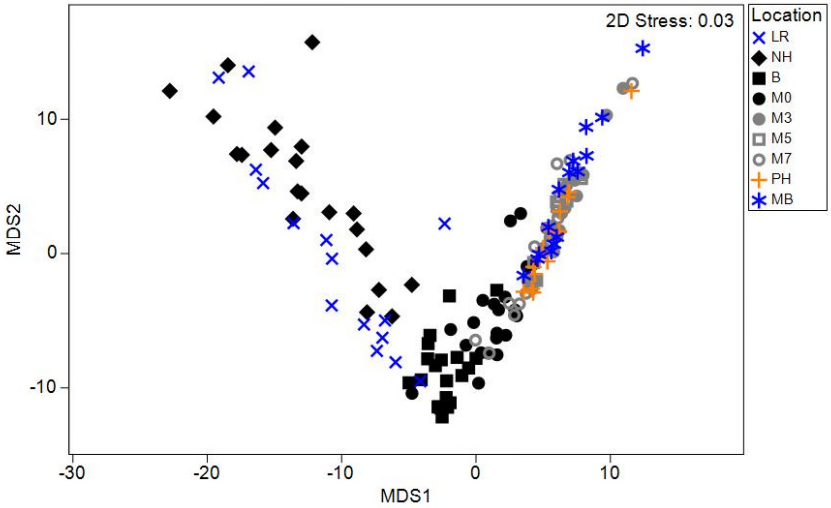


Figure 6-3 Metric MDS of particle size percentage composition from 2000 to 2020 for outfall locations and at other locations from 2000 to 2011 and 2014, 2016 and 2020 for samples averaged by location-year: a) coded by percentage composition of three granularity size classes; b) colour coded by location

Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference

6.3.3 Assessing potential risk of adverse biological effects from sedimentary metals

SQG values were available for eight sedimentary metals of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), silver (Ag) and zinc (Zn) for all nine locations and for each of the seven assessment years (2002, 2005, 2008, 2011, 2014, 2016 and 2020). Result ranges by assessment year are presented in (Appendix C).

SQG values were used to assess the potential risk by sedimentary metals to adverse effects to benthic infauna (Long et al., 1995; Birch et al., 2008). SQG values of ANZECC (2000) and the 2016 revision (Simpson and Batley, 2016) were used in this report. The ANZECC (2000) SQG value and high SQG value correspond to the effects range low (ERL) and effects range median (ERM) of Long et al. (1995). The ERL is the value below which adverse biological effects are seldom observed and ERM represents the value above which adverse biological effects are expected to occur frequently (Long et al., 1995), while concentrations between the two guidelines indicate an intermediate risk where effects would occur occasionally.

To assess potential risk of adverse effects the SQG values for the eight total sedimentary metals for the seven assessment years of data across the nine study locations were annotated onto respective box plots (Figure 6-4 to Figure 6-12). The bottom and top edges of the box are located at the sample 25th and 75th percentiles. The center horizontal line is drawn at the 50th percentile (median). Vertical lines, or whiskers, are drawn from the box to the most extreme point within 1.5 interquartile ranges. Values outside this range are marked with a circle. Two plots are provided for six of the eight metals with the upper plot providing context of data to the represented by dashed lines. While the lower plot presents the ERL and data that was well below that lower SQG value. In the case of As and Hg a single plot was provided context to SQG ERM and ERL values for each metal as some data values exceeded the ERL.

Total sediment Ag, Cd, Cr, Cu, Ni, Pb and Zn concentrations were less than ERLs for the seven assessment years for each of the nine locations (Figure 6-5, Figure 6-6, Figure 6-7, Figure 6-8, Figure 6-10, Figure 6-11, Figure 6-12) . Approximately half the As concentrations were between the ERL and ERM values for the North Head outfall location and some samples from the Long Reef reference location exceeded the ERL for As. Concentrations for the other seven locations were well below the ERL for this metal (Figure 6-4). Mercury concentrations were close to the ERL for the North Head outfall and Malabar 3 km gradient study location (Figure 6-9). While some Hg concentrations were infrequently above the ERL for the Bondi outfall location, the Long Reef reference location, the Malabar 5 km location and for the Malabar 7 km (Figure 6-9).

Within marine sediments, contaminants do not occur as single chemicals. A number of schemes have been developed to assess the effects of chemical mixtures for aquatic sediments (Long et al., 1998, 2000, 2006; Long and MacDonald, 2010; Fairey et al., 2001). The mean ERM quotient (MERMQ) scheme requires normalising the concentration of each chemical with respect to its ERM value, summing the quotients for each substance and dividing by the number of chemicals for which guidelines are being used. MERMQ values were calculated for each location and assessment year (Table 6-4).

MERMQs were used to quantify potentially harmful mixtures of metal contaminants present in ambient sediment. MERMQs for 2020 were within the range observed for the previous six

assessment years (Table 6-4). The MERMQ range was highest for the North Head outfall location (0.070 to 0.120) while the range of MERMQ values for the Malabar 3 km location (0.058 to 0.073) was intermediate between those of the North Head outfall location and the other seven locations that had similar MERQM ranges (Table 6-4). The MERMQ ranges for the other seven locations were for Bondi outfall 0.036 to 0.066, Malabar outfall 0.043 to 0.050, Long Reef reference 0.038 to 0.056, Port Hacking reference 0.043 to 0.058, Marley reference 0.026 to 0.057, Malabar 5 km location 0.048 to 0.059 and Malabar 7 km location 0.042 to 0.058 (Table 6-4).

A SNK multiple mean comparison test of MERMQs confirmed the above pattern for the North Head outfall location and the Malabar 3 km location that mean MERMQs of these two locations were significantly different, and those mean MERMQs were also significantly different to the mean MERMQs for the seven other locations (Table 6-5). Mean MERMQs of the seven other locations were not significantly different from each other.

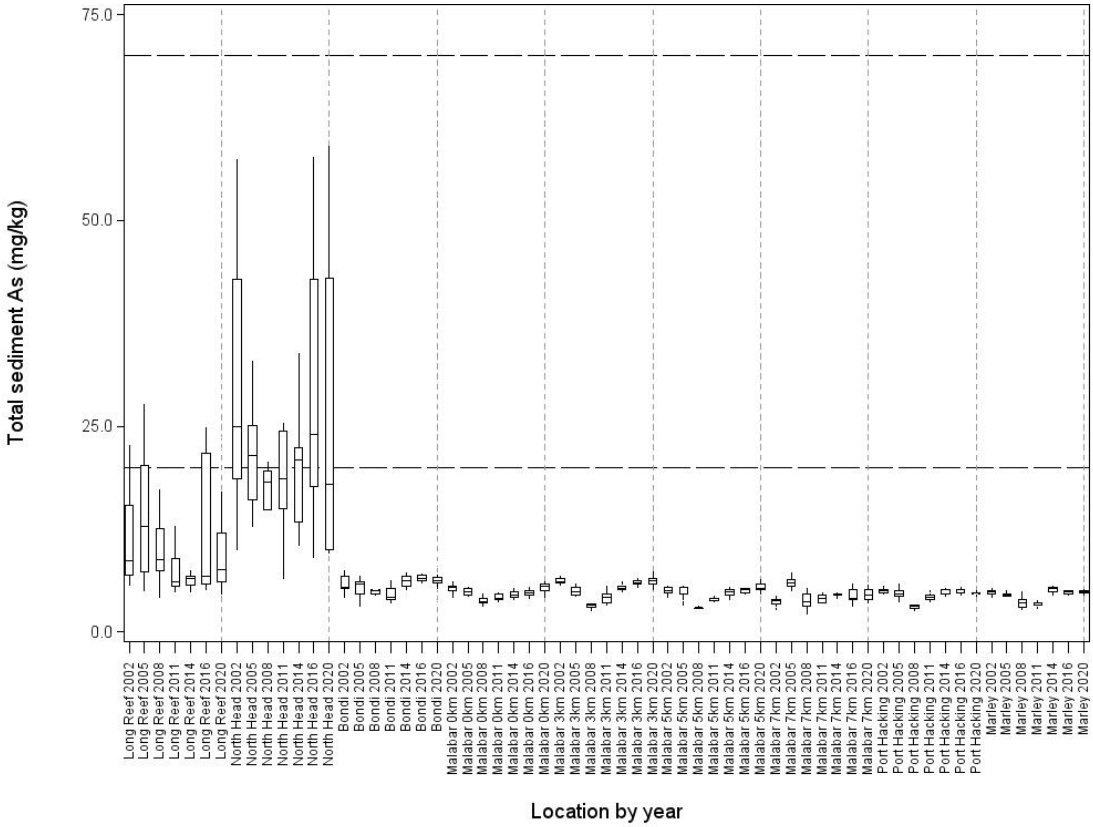


Figure 6-4 Total sedimentary arsenic (As) metal concentrations at each location by assessment year
Plot with SQG ERM and ERL values

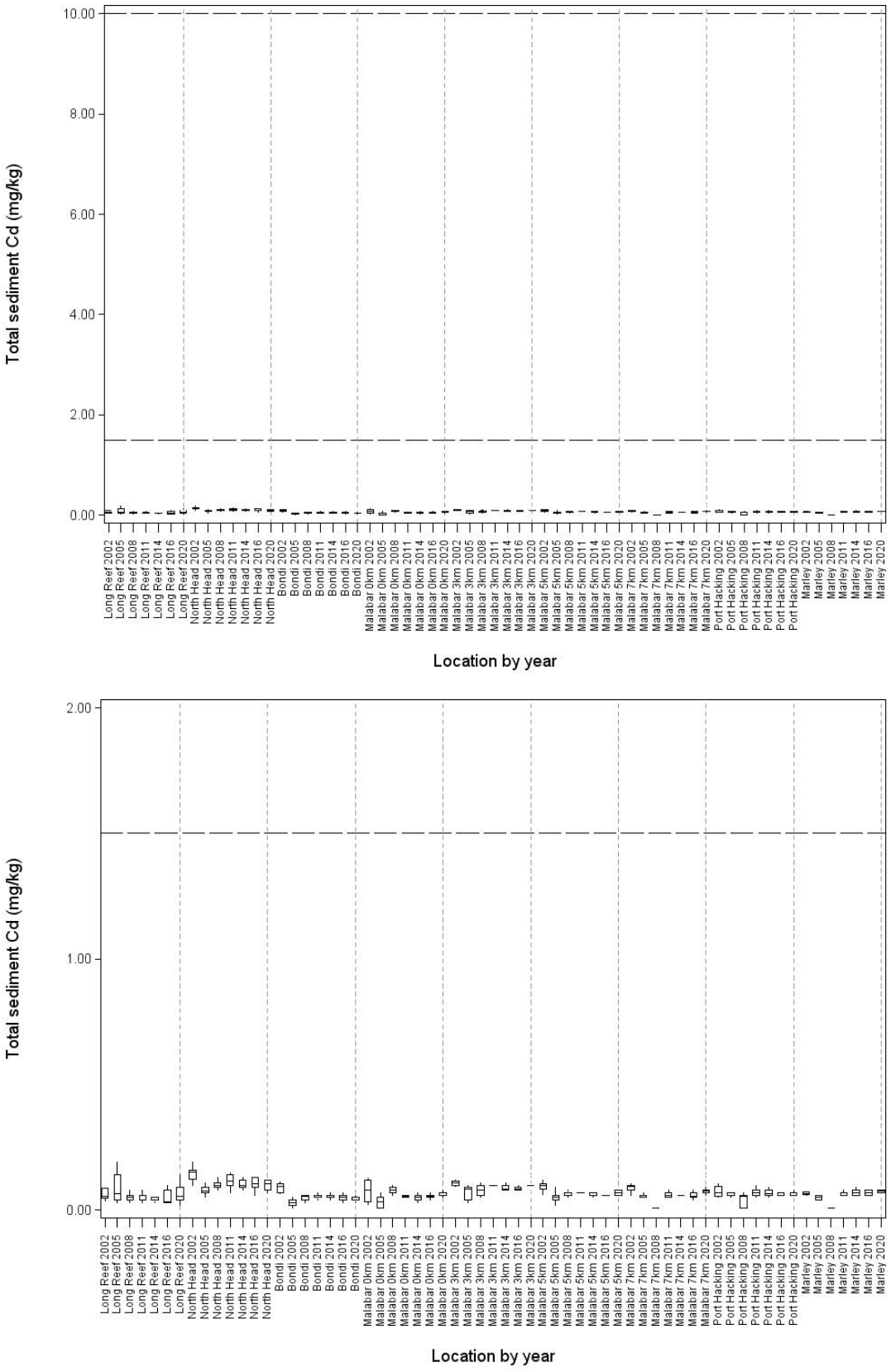


Figure 6-5 Total sedimentary cadmium (Cd) metal concentrations at each location by assessment year

Top plot with SQG ERM and ERL values; Bottom plot with SQG ERL value

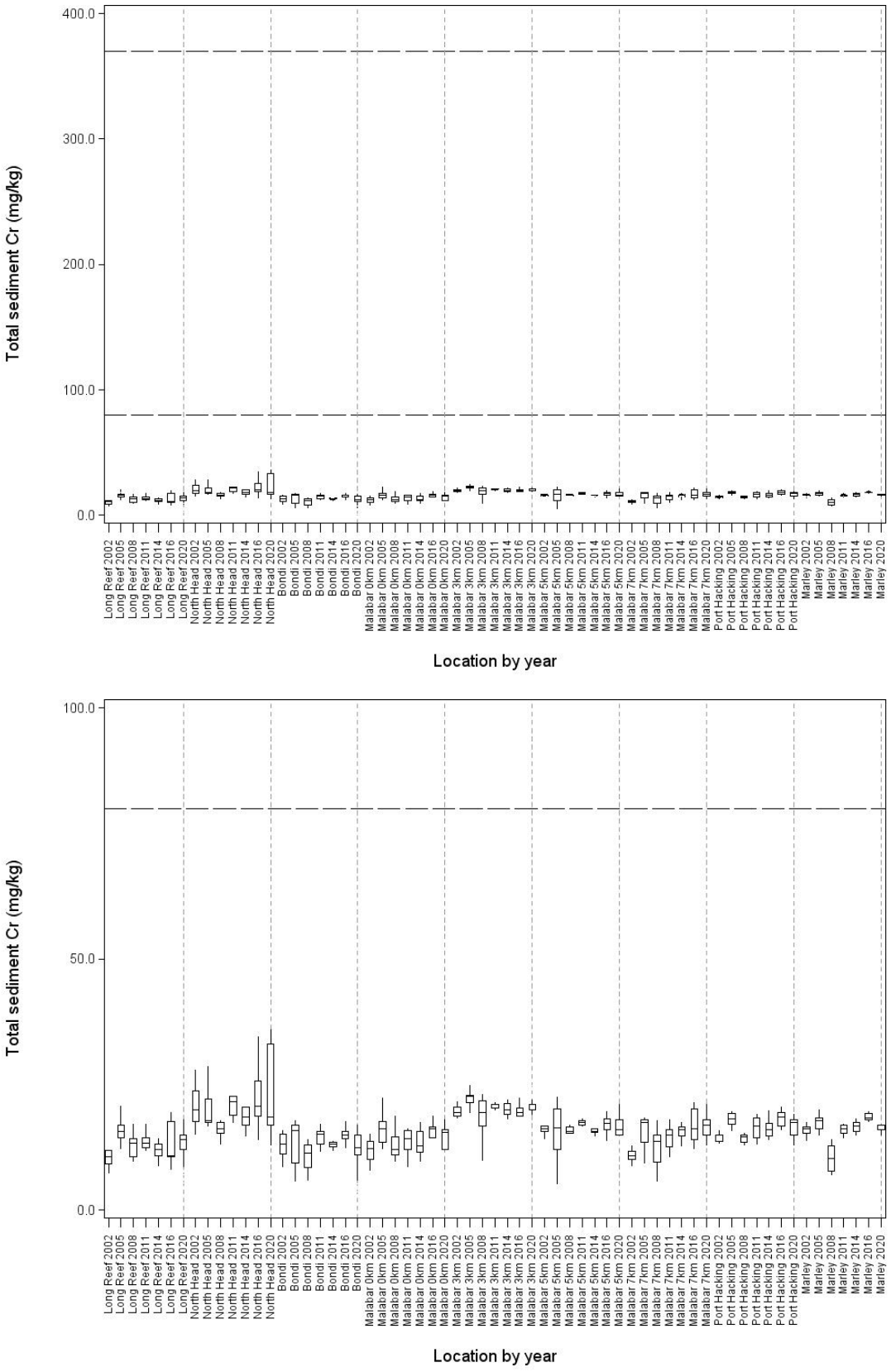


Figure 6-6 Total sedimentary chromium (Cr) metal concentrations at each location by assessment year

Top plot with SQG ERM and ERL values; Bottom plot with SQG ERL value

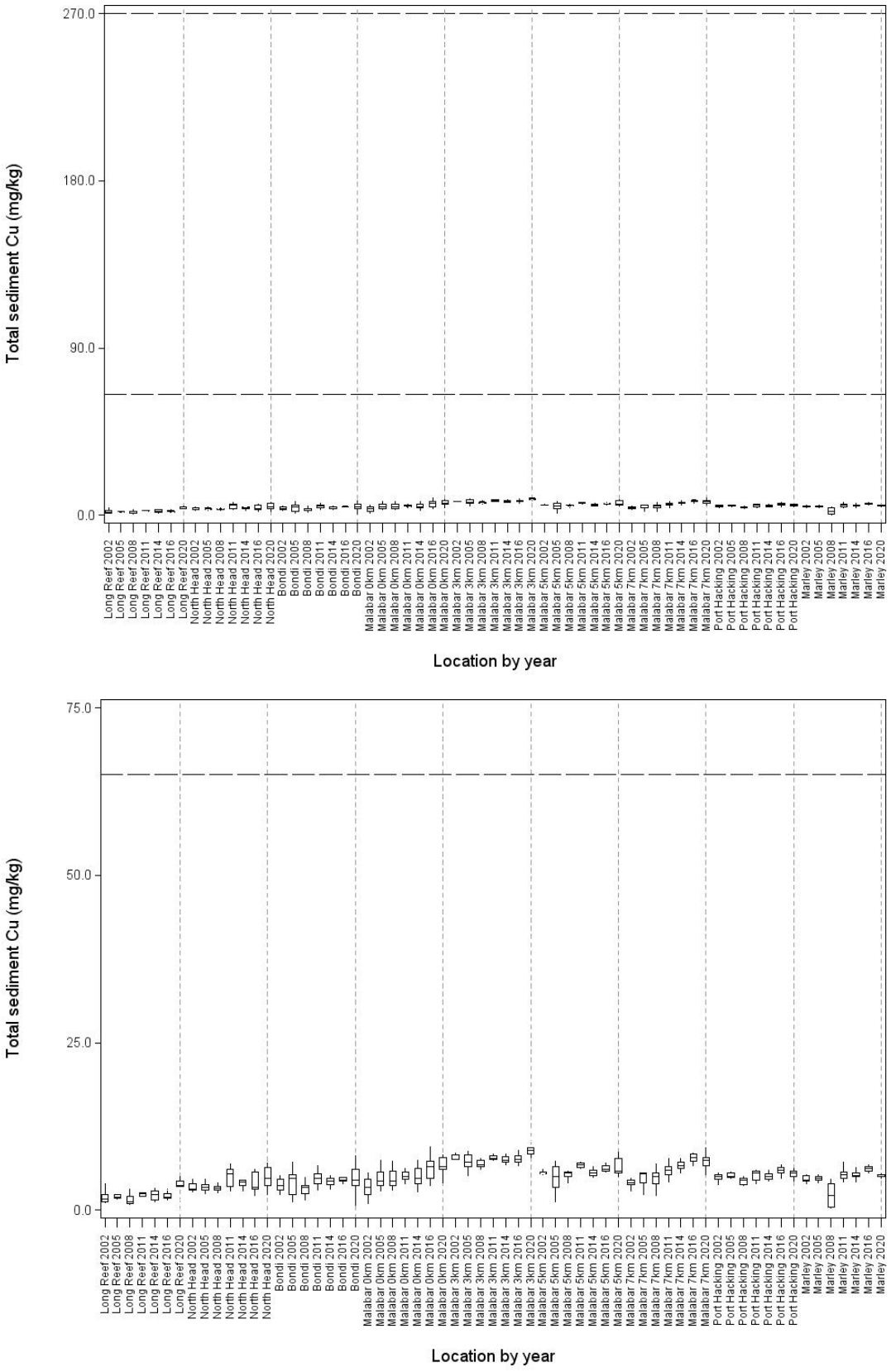


Figure 6-7 Total sedimentary copper (Cu) metal concentrations at each location by assessment year
Top plot with SQG ERM and ERL values; Bottom plot with SQG ERL value

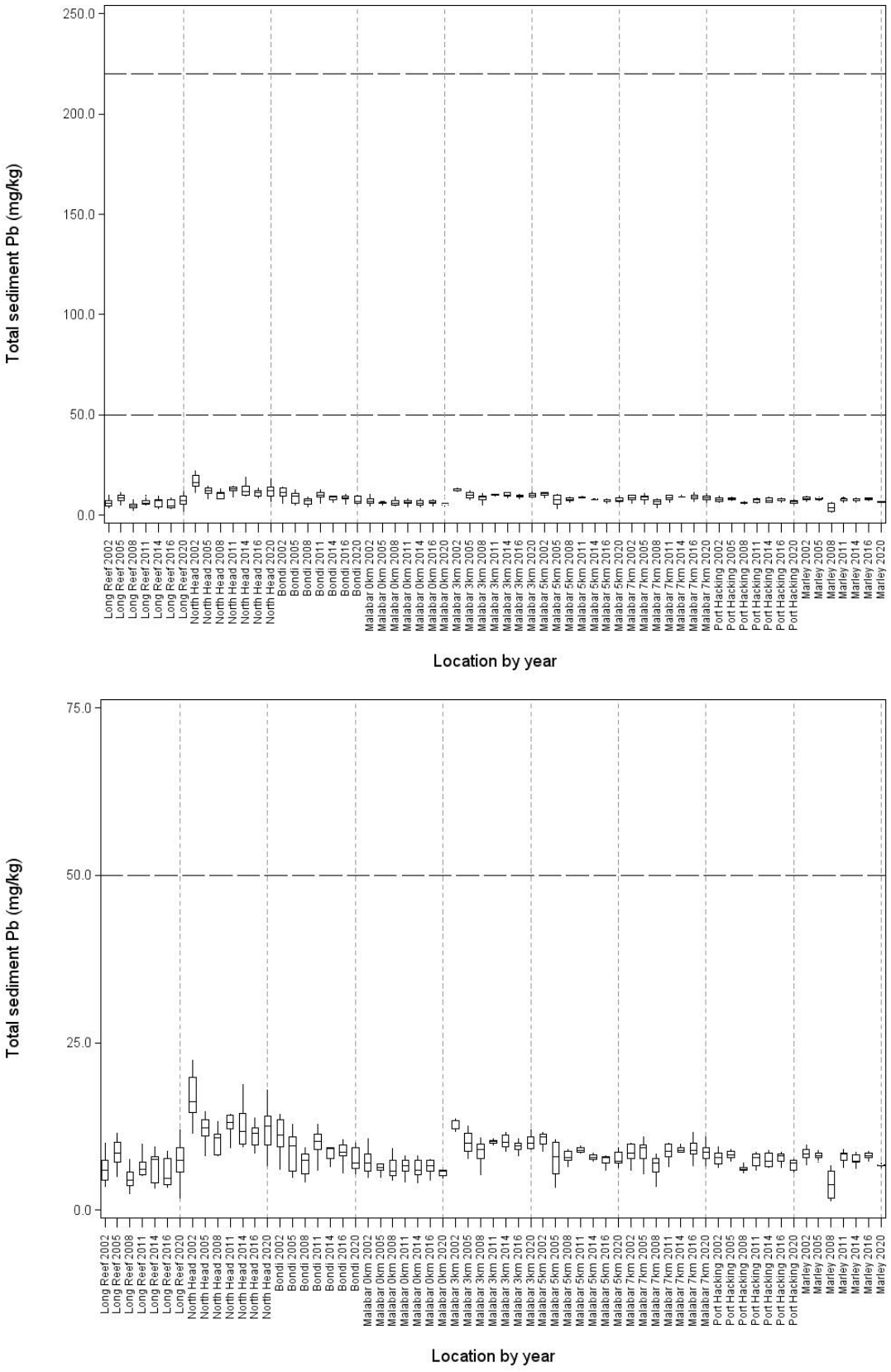


Figure 6-8 Total sedimentary lead (Pb) metal concentrations at each location by assessment year
Top plot with SQG ERM and ERL values; Bottom plot with SQG ERL value

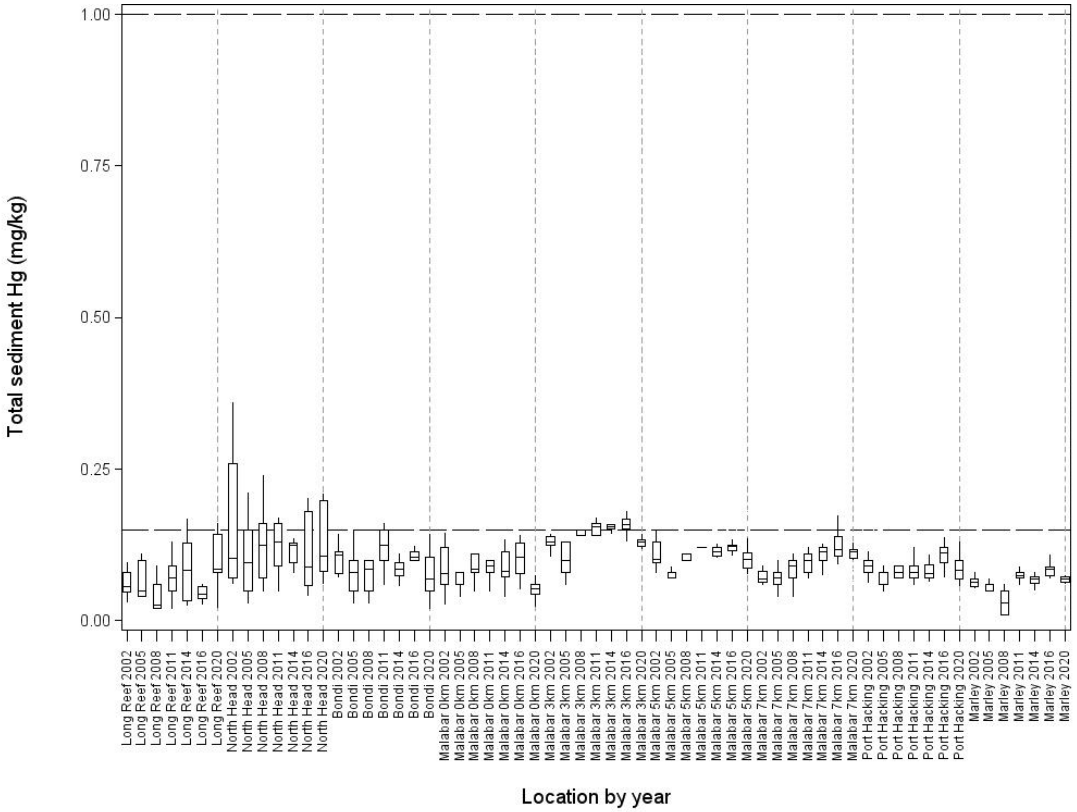


Figure 6-9 Total sedimentary mercury (Hg) metal concentrations at each location by assessment year
Plot with SQG ERM and ERL values

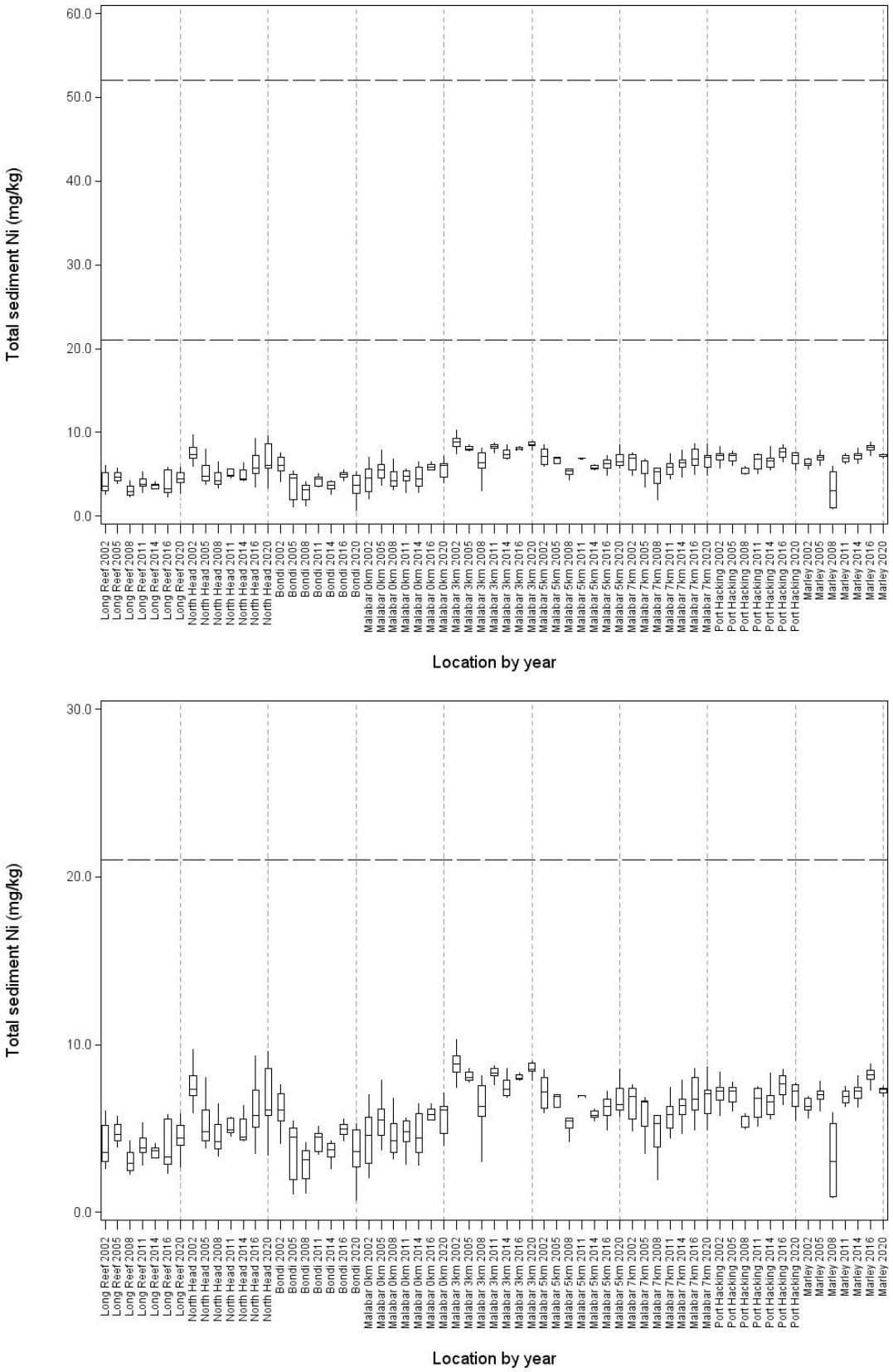


Figure 6-10 Total sedimentary nickel (Ni) metal concentrations at each location by assessment year
Top plot with SQG ERM and ERL values; Bottom plot with SQG ERL value

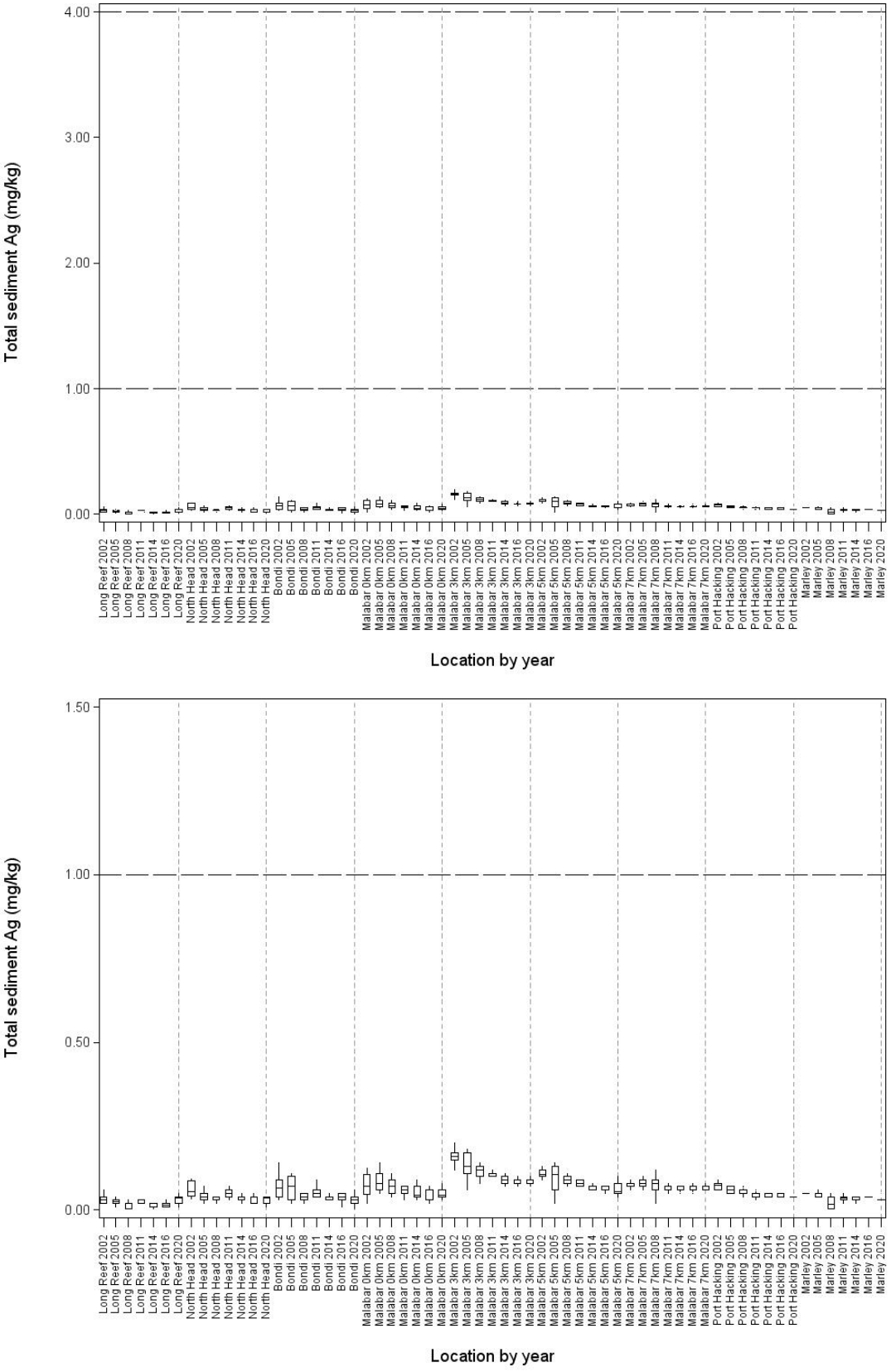
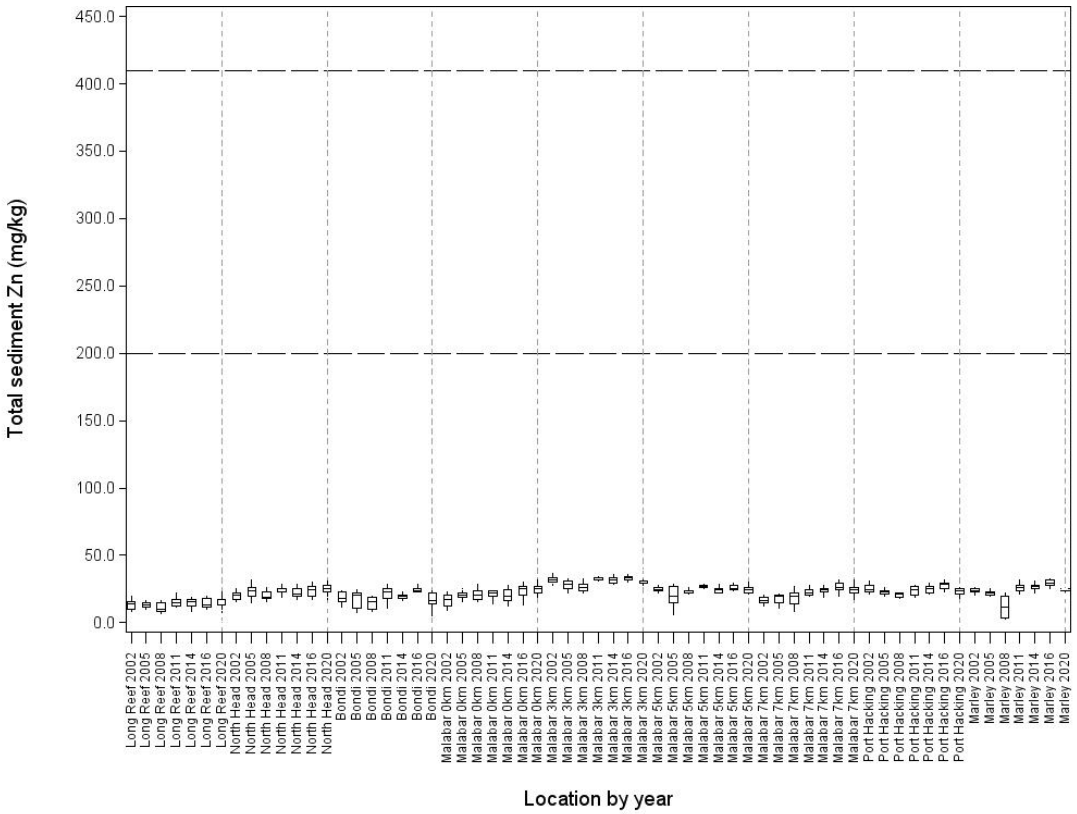


Figure 6-11 Total sedimentary sliver (Ag) metal concentrations at each location by assessment year
Top plot with SQG ERM and ERL values; Bottom plot with SQG ERL value



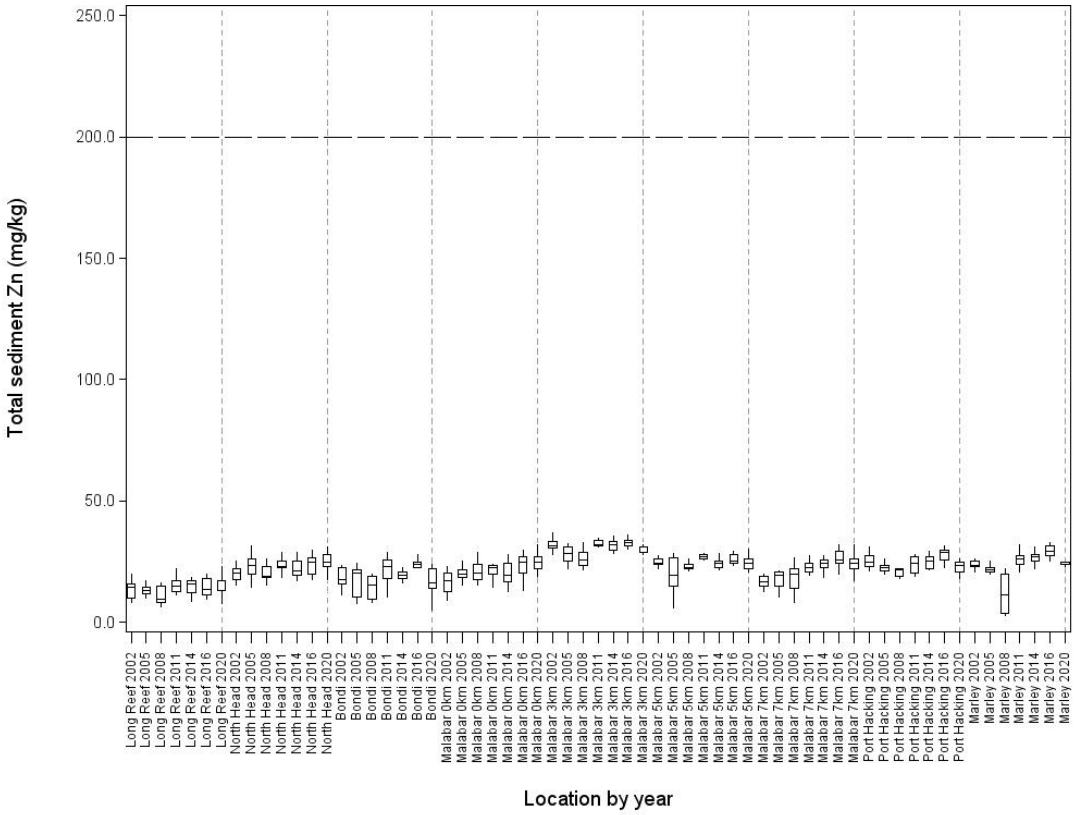


Figure 6-12 Total sedimentary zinc (Zn) metal concentrations at each location by assessment year
Top plot with SQG ERM and ERL values; Bottom plot with SQG ERL value.

Table 6-4 Location by assessment year Mean Effects Range Median Quoitent (MERMQ) values of potentially harmful mixtures of metal (Ag, As, Cd, Cr, Cu, Hg, Ni, Pb, Zn) contaminants in ambient sediment

Year	Long Reef reference	North Head outfall	Bondi outfall	Malabar outfall	Malabar 3km	Malabar 5km	Malabar 7km	Port Hacking reference	Marley reference
2002	0.047	0.112	0.066	0.044	0.073	0.059	0.045	0.054	0.049
2005	0.056	0.080	0.043	0.046	0.063	0.048	0.049	0.051	0.048
2008	0.038	0.070	0.036	0.043	0.058	0.048	0.042	0.043	0.026
2011	0.044	0.081	0.048	0.044	0.069	0.058	0.049	0.050	0.049
2014	0.043	0.120	0.045	0.043	0.069	0.053	0.054	0.050	0.051
2016	0.045	0.099	0.051	0.050	0.070	0.057	0.058	0.058	0.057
2020	0.050	0.095	0.041	0.046	0.069	0.055	0.055	0.051	0.049

Table 6-5 SNK multple mean comparison test of MERMQ values from nine locations and seven assessment years (2002, 2005, 2008, 2011, 2014, 2016, 2020) (for data in Table 6-4, Corresponding ANOVA df = 8, MS = 0.00175, F = 24.06, P = <0.0001)

SNK Grouping*	Mean	Location
A	0.094	North Head outfall
B	0.067	Malabar 3km
C	0.054	Malabar 5km
C	0.051	Port Hacking reference
C	0.050	Malabar 7km
C	0.047	Bondi outfall
C	0.047	Marley reference
C	0.046	Long Reef reference
C	0.045	Malabar outfall

*Means with the same letter are not significantly different

6.3.4 Assessing potential risk of adverse biological effects from sediment OC and PAH

The benthic sediment was analysed for organic chemicals at the North Head and Malabar outfall locations. Result ranges by assessment year are presented in (Appendix C).

SQG values were available for 19 organic chemicals. Of those organic chemicals, eight were OCs (chlordane, dieldrin, endrin, lindane, p.p'-DDD, p.p'-DDE, DDT, total PCBs) and 11 were PAHs (acenaphthene, anthracene, benzo(a)anthracene, benzo(a)pyrene, chrysene, dibenzo(a,h)anthracene, fluoranthene, fluorene, naphthalene, phenanthrene, pyrene). Results from North Head and Malabar were compared to SQG values. Only results from North Head exceeded the ERM and ERL values (Appendix C), and were tabulated by assessment year for the North Head outfall location to assess for temporal change in the potential risk of adverse effects (Table 6-6).

Concentrations were below detection for eight OCs (Aldrin, Total DDT, p,p'-DDE, Chlordane, Dieldrin, Endrin, Lindane and Total PCBs) for which ANZECC (2000) SQGs are available, for all 140 samples collected from North Head and Malabar outfall locations over the seven assessment years (Appendix C). Concentrations were recorded from these samples for the 11 PAHs for which SQGs are available, concentrations were below ERL values in sediment from the Malabar outfall location across the seven assessment years (Appendix C). In contrast, five chemicals (acenaphthene, anthracene, chrysene, fluoranthene, fluorene) exceeded ERL levels and another five (benzo(a)anthracene, benzo(a)pyrene, dibenzo(a,h)anthracene, phenanthrene, pyrene) exceeded ERM values from four of the ten samples collected from the North Head outfall location in 2002. Since 2002 only five samples from the North Head outfall location had concentrations between the respective ERL and ERM values for fluorene and benzo(a)anthracene (Table 6-6). Two ERL exceedances for fluorene occurred in 2008 and single sample exceedance occurred in 2005, 2008, 2016 and 2020 for benzo(a)anthracene. In the 2020 sample that had the exceedance for benzo(a)anthracene, single exceedances for fluorene and phenanthrene were also recorded (Table 6-6).

Table 6-6 Organic (PAH) chemicals minimum (µg/kg), maximum (µg/kg), and exceedances of ANZECC (2000) SQGs at North Head outfall location

	SQG		Year of SQG value exceedance						
PAH	ERL	ERM	2002	2005	2008	2011	2014	2016	2020
acenaphthene	16	500	<10-**115**	<10	<10-10	<10	<10	<10	<10
anthracene	85	1100	<10-**1000**	<10-23	<10-79	<10-37	<10-50	<10-68	<10-74
benzo(a)anthracene	261	1600	13-***2360***	23-**323**	39-**304**	13-156	132-258	<10-**331**	11-**315***
benzo(a)pyrene	430	1600	14-***2380***	<10-293	58-343	13-226	111-291	<10-320	<10-233
chrysene	384	2800	13-**2190**	<10-144	<10-307	13-155	46-127	<10-229	<10-165
dibenzo(a,h)anthracene	63	260	14-***463***	<10-28	<10-51	<10-12	<10-33	<10-30	<10-16
fluoranthene	600	5100	19-**4280**	43-367	55-444	18-273	131-273	16-515	12-528
fluorene	19	540	<10-**176**	<10	<10-**24**	<10-15	<10-14	<10-18	<10-**43***
phenanthrene	240	1500	<10-***2650***	20-122	18-219	<10-136	23-135	13-202	<10-**266***
pyrene	665	2600	22-***4280***	41-564	88-379	17-260	126-303	16-525	11-457

Bold = exceed ERL; Bold and italic = exceed ERM

*these values all from the same single sample of the ten samples collected

6.3.5 Analysis of covariance

Three ANCOVA models assessed total sedimentary metal chemical concentrations using the fine sediment fraction (percentage fines <0.063 mm in ambient sediment) as a covariate for the 2020 sedimentary metal data. The assumption of the ANCOVA was met (that is the interaction term was not significant) across all testing with the exception of two tests with percentage fines as the covariate (Appendix D). This resulted in contingency analysis (as outlined in Section 5.1.7) only required for testing of aluminium and copper under the Malabar 0 km to 7 km with TOC as the covariate.

Under the first ANCOVA model testing identified sedimentary zinc to represent a pattern that may indicate a change in sediment chemistry from wastewater discharge for the 60 m locations with Bondi and North Head being equivalent and significantly different to Long Reef (represented by letter pattern of A A B in Table 6-7). No significant difference was identified for sedimentary silver between these locations (Table 6-7). A pattern of North Head being significantly different to Bondi and Long Reef was identified for sedimentary metals of aluminium, arsenic, chromium, iron, lead, and nickel.

ANCOVA testing under the second model of the two 80 m reference locations and the Malabar 0 km outfall location identified a pattern of sedimentary metals of copper and selenium that may indicate a change in sediment chemistry. This was represented by Malabar 0 km results being significantly different to Port Hacking and Marley Beach (letters A B B in Table 6-8). No significant difference between locations was identified for sedimentary metal concentrations of cadmium, chromium, iron and zinc (Table 6-8).

No consistent pattern of diminishing total sedimentary metal concentrations with distance away from Malabar 0 km outfall location was identified under this third ANCOVA model that assessed the Malabar 0 km, Malabar 3 km, Malabar 5 km and Malabar 7 km locations. Such a pattern would be represented by A B C D in Table 6-9. Moreover, this analysis identified significantly higher concentrations at the Malabar 3 km location for 6 of the 12 total sedimentary metals (cadmium, chromium, iron, nickel, silver and zinc) when assessed against percentage fines as a covariate.

Table 6-7 Summary of statistical analysis on sedimentary metal data collected in 2020 from the North Head and Bondi outfall locations and the Long Reef reference location of 60 m depth

60 m depth sites (Long Reef, North Head, Bondi)	
SILVER - No significant difference between locations, ANCOVA with Fines - Pair-wise not conducted	LEAD - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - NH A - B B - LR B
CADMIUM - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - NH A - LR A B - B B	ALUMINIUM - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - NH A - B B - LR B
CHROMIUM - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - NH A - B B - LR B	IRON - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - NH A - B B - LR B
NICKEL - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - NH A - B B - LR B	ZINC - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - NH A - B A - LR B
COPPER - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - NH A - B A B - LR B	MERCURY - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - NH A - LR A B - B B
ARSENIC - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - NH A - B B - LR B	SELENIUM - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - NH A - LR A B - B B

Table 6-8 Summary of statistical analysis on sedimentary metal data collected in 2020 for the Malabar 0km outfall and reference locations of Port Hacking and Marley of 80 m depth

80 m depth sites (Malabar, Port Hacking, Marley Beach)	
SILVER - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - M0 A - PH A - MB B	LEAD - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - PH A - MB A B - M0 B
CADMIUM - No significant difference between locations, ANCOVA with Fines - Pair-wise not conducted	ALUMINIUM - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - M0 A - MB A B - PH B
CHROMIUM - No significant difference between locations, ANCOVA with Fines - Pair-wise not conducted	IRON - No significant difference between locations, ANCOVA with Fines - Pair-wise not conducted
NICKEL - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - M0 A - PH A - MB A	ZINC - No significant difference between locations, ANCOVA with Fines - Pair-wise not conducted
COPPER - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - M0 A - PH B - MB B	MERCURY - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - PH A - M0 B - MB B
ARSENIC - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - M0 A - MB A B - PH B	SELENIUM - Significant difference between locations, ANCOVA with Fines - Pair-wise summary - M0 A - PH B - MB B

Table 6-9 Summary of statistical analysis on sedimentary metal data collected in 2020 from locations to the south of the Malabar 0 km location at 80 m depth

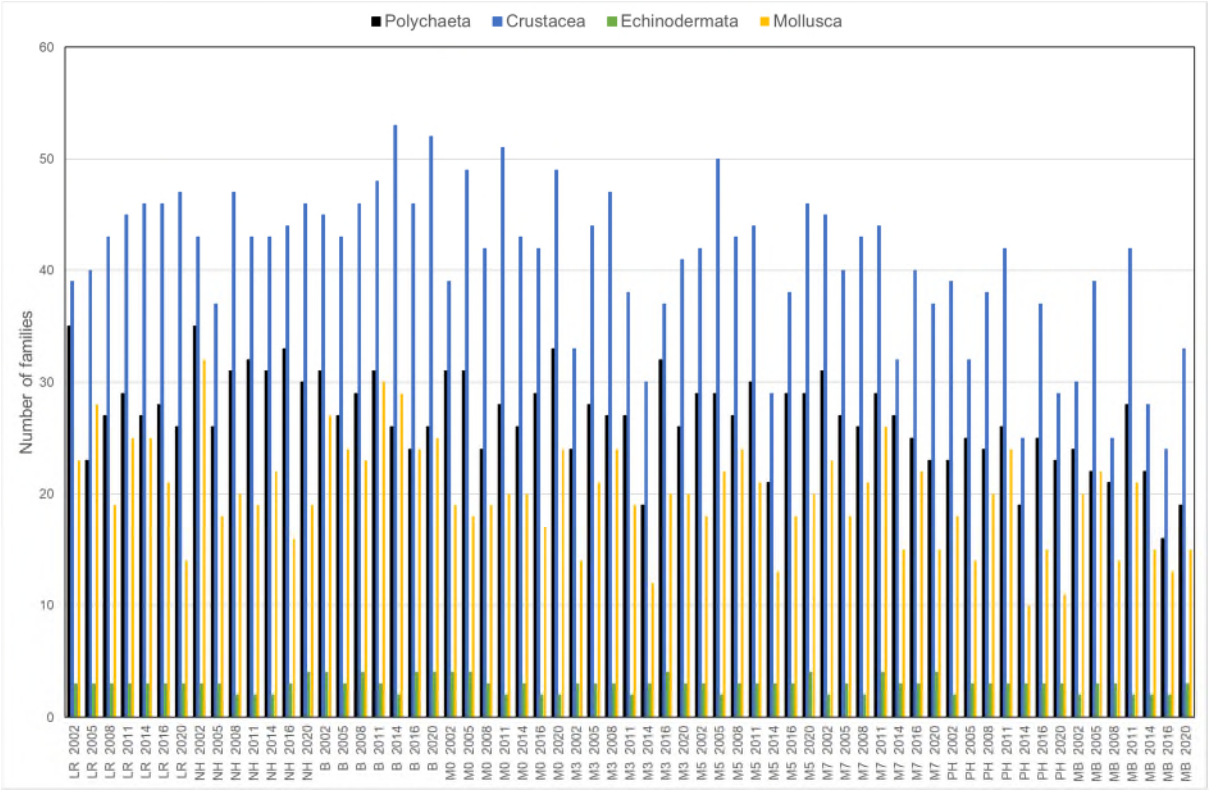
Malabar 0 km to 7 km	
SILVER - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M3 A - M0 B - M5 B - M7 B	LEAD - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M0 A - M3 B - M5 C - M7 C
CADMIUM - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M3 A - M0 B - M5 B - M7 B	ALUMINIUM - Significant difference between locations, ANCOVA with TOC - Pair-wise Summary - M3 A - M0 B - M7 B C - M5 C
CHROMIUM - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M3 A - M0 B - M5 B - M7 B	IRON - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M3 A - M0 B - M5 B - M7 B
NICKEL - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M3 A - M0 B - M5 B - M7 B	ZINC - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M3 A - M0 B - M5 B - M7 B
COPPER - Significant difference between locations, ANCOVA with TOC - Pair-wise Summary - M3 A - M5 A B - M7 A B - M0 A	MERCURY - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M0 A - M3 B - M5 C - M7 C
ARSENIC - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M0 A - M3 A - M5 A - M7 B	SELENIUM - Significant difference between locations, ANCOVA with Fines - Pair-wise Summary - M0 A - M3 A - M5 B - M7 B

6.4 Benthic infauna

6.4.1 Overview of benthic infauna collected across seven assessment years

A comparison of the number of families of Polychaeta, Crustacea and Mollusca and superfamilies of Echinodermata from nine locations by assessment year indicated data collected in 2020 was within the range of observation for the preceding six assessment years (Figure 6-13a). Similarly, the abundance counts pooled up to Polychaeta, Crustacea, Mollusca and Echinodermata, were within the range of observation for the preceding six assessment years (Figure 6-13b).

a)



b)

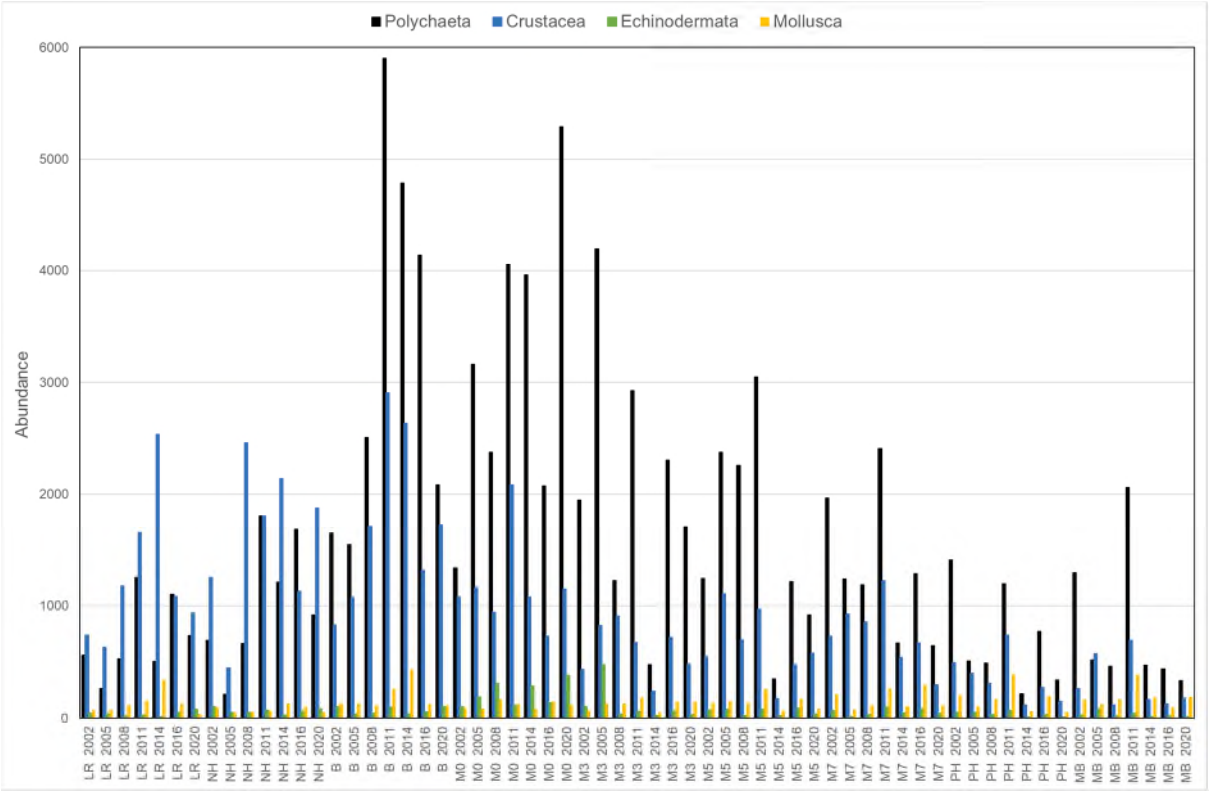


Figure 6-13 Comparison of a) number of families of Polychaeta, Crustacea and Mollusca and superfamilies of Echinodermata from nine locations by assessment year; b) family of level counts pooled up to Polychaeta, Crustacea and Mollusca and superfamily level counts pooled up to Echinodermata from nine locations by assessment year

6.4.2 Analysis of temporal and spatial differences in community structure at reference locations

The PERMANOVA model run for the three reference locations of Long Reef, Port Hacking and Marley returned significant differences for the interaction term 'Location x Year' and two factors 'Location' and 'Year' (Table 6-10). The corresponding nMDS ordination plot of location-year centroids with split trajectory overlays illustrated change in community structure of each reference location between assessment years. This plot also illustrated differences in community structure between the northern reference location of Long Reef and the southern two reference locations of Port Hacking and Marley (Figure 6-14). This plot reflected the significant difference returned for the PERMANOVA 'Location x Year' interaction term (Table 6-10).

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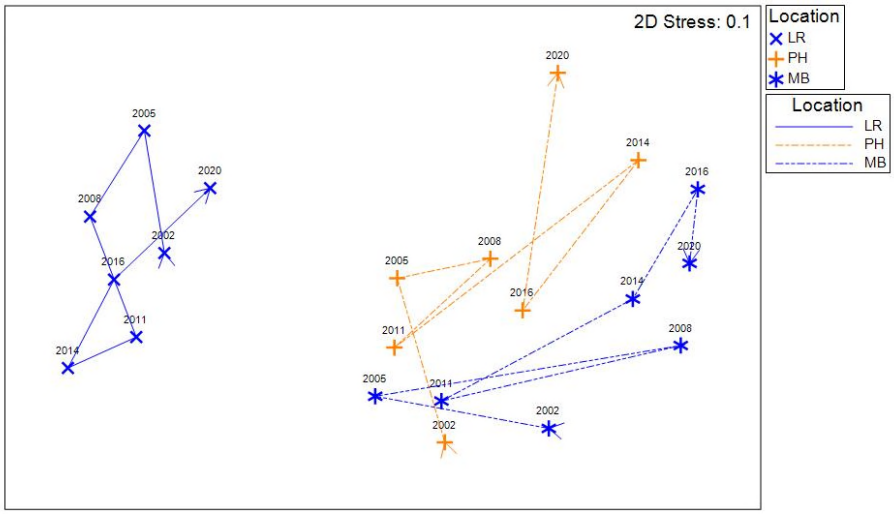


Figure 6-14 Two dimensional nMDS ordination plot of centroids for location-year benthic community sample groupings of three reference locations

Locations codes: LR = Long Reef; PH = Port Hacking; MB = Marley. Trajectories join location-year centroids with respective assessment years annotated

Table 6-10 PERMANOVA for differences in family level taxonomic composition across three reference locations (Long Reef, Port Hacking and Marley) and years

Source	df	P(perm)	Var	SD
Location	2	0.0001*	499.35	22.3
Year	6	0.0001	342.99	18.5
Location x Year	12	0.0001	294.26	17.1
Residual	189		1339.3	36.6

Based on Bray-Curtis dissimilarity matrix formed after initial dispersion weighting on site-year groupings of replicate samples and subsequent square root transformation. P-values obtained using 9999 permutations of given permutable units for each term. Var gives the estimated sizes of components of variation, based on multivariate analogues to the classical ANOVA unbiased estimators. SD gives the square root of these values, in Bray-Curtis units

6.4.3 Analysis of differences in community structure at each outfall to the three reference locations

Inclusion of each outfall with the three reference locations presented in Figure 6-15 also illustrated change in community structure of each reference location between assessment years with similar change between assessment years in community structure of each outfall location. These plots (Figure 6-15) also displayed differences in community structure between the northern and southern reference locations as observed in the ordination plot of reference locations (Figure 6-14). A notable feature across the three ordination plots presented in Figure 6-15 were the relatively static positions of location-year centroids for the reference locations, with each outfall location having a relatively different position for respective location-year centroids.

The changes in location-year centroids through the assessment years (Figure 6-15) illustrates the 'Location x Year' interaction of the initial PERMANOVA model run for each outfall location and the three reference locations (Table 6-11) and for the 'Location(Control Impact) x Year' interaction of the second PERMANOVA model (Table 6-12).

Output from the second PERMANOVA model returned non-significant results for the interaction term 'Control Impact x Year' under each of three runs for each outfall location and three reference locations (Table 6-12). As a negative estimate of the component of variation was returned for the 'Control Impact x Year' interaction term for all three model runs, this suggested the 'Control Impact x Year' interaction had no contribution to the model outcomes (Table 6-12). The 'Control-Impact' factor was also returned as non-significant for each of the three PERMANOVA model runs (Table 6-12). These non-significant outcomes suggest additional partitioning of data under the second PERMANOVA model (Table 6-12) was not successful at drawing out further data patterns, as significant results of the second PERMANOVA model reflected outcomes of the initial PERMANOVA model (Table 6-11). Across the six model runs from the two PERMANOVA models the estimates of the components of variation were largest for residual, second largest for 'Location' and 'Location(Control Impact)' and third largest for 'Location x Year' and 'Location(Control Impact) x Year' (Table 6-11 and Table 6-12).

Visual inspection of dendrograms based on Location-Year centroids did not indicate an early division that separated the outfall location from all three reference locations. Rather, in each of the three dendrograms the first division separated the two southern reference locations Location-Year centroids from the northern reference location Location-Year centroids and outfall location Location-Year centroids (Figure 6-16).

The amounts of variation explained by first two dimensions relatively low run for PCO run on the same datasets as for the three nMDS ordination plots in Figure 6-15. The total amount of variation explained were 28.1% for the analysis with North Head, 27.8% for Bondi and 26.7% for Malabar. In each PCO analysis 40 axes were required to see 100% of cumulative variation explained.

Table 6-11 PERMANOVA for differences in family level taxonomic composition across three reference locations (Long Reef, Port Hacking and Marley) and each respective outfall location and years

Source	df	P(perm)	Var	SD
a)	3 reference locations and North Head outfall location			
Location	3	0.0001	582.04	24.1
Year	6	0.0001	251.11	15.8
Location x Year	18	0.0001	291.67	17.1
Residual	252		1395.10	37.3
b)	3 reference locations and Bondi outfall location			
Location	3	0.0001	578.18	24.0
Year	6	0.0001	261.85	16.1
Location x Year	18	0.0001	280.68	16.5
Residual	252		1312.60	36.2
c)	3 reference locations and Malabar outfall location			
Location	3	0.0001	529.72	23.0
Year	6	0.0001	262.25	16.2
Location x Year	18	0.0001	283.55	16.8
Residual	252		1277.00	35.7

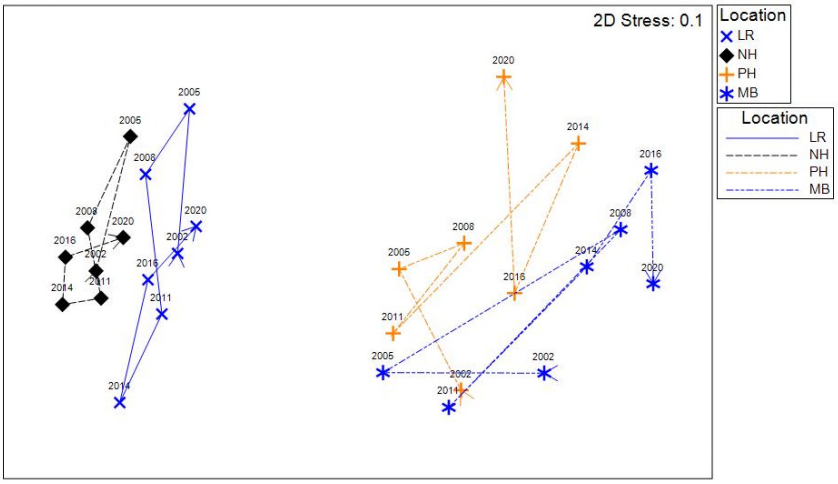
Based on Bray-Curtis dissimilarity matrix formed after initial dispersion weighting on site-year groupings of replicate samples and subsequent square root transformation. P-values obtained using 9999 permutations of given permutable units for each term. Var gives the estimated sizes of components of variation, based on multivariate analogues to the classical ANOVA unbiased estimators. SD gives the square root of these values, in Bray-Curtis units.

Table 6-12 PERMANOVA for differences in family level taxonomic composition of replicate samples across Control Impact groups of locations and years

Source	df	P(perm)	Var	SD
a)			North Head	
Control Impact	1	0.1721*	167.09	12.9
Year	6	0.0008	115.16	10.7
Location(Control Impact)	2	0.0001	498.50	22.3
Control Impact x Year	6	0.4891	-0.38	-0.6
Location(Control Impact) x Year	12	0.0001	291.86	17.1
Residual	252		1395.10	37.4
b)			Bondi	
Control Impact	1	0.1943*	143.62	12.0
Year	6	0.0002	130.71	11.4
Location(Control Impact)	2	0.0001	506.37	22.5
Control Impact x Year	6	0.7224	-28.69	-5.3
Location(Control Impact) x Year	12	0.0001	295.03	17.2
Residual	252		1312.60	36.2
c)			Malabar	
Control Impact	1	0.3591*	43.72	6.3
Year	6	0.0005	128.71	11.7
Location(Control Impact)	2	0.0001	507.86	22.2
Control Impact x Year	6	0.8046	-41.63	-6.3
Location(Control Impact) x Year	12	0.0001	304.37	17.2
Residual	252		1277.00	35.4

Based on Bray-Curtis dissimilarity matrix formed after initial dispersion weighting on site-year groupings of replicate samples and subsequent square root transformation for three reference locations (Long Reef, Port Hacking and Marley) compared to: a) North Head outfall; b) Bondi outfall; c) Malabar outfall. P-values obtained using 9999 permutations of given permutable units for each term or using 9999 Monte Carlo samples from the asymptotic permutation distribution (marked by *) where there were few possible permutations. Var gives the estimated sizes of components of variation, based on multivariate analogues to the classical ANOVA unbiased estimators. SD gives the square root of these values, in Bray-Curtis units

a)



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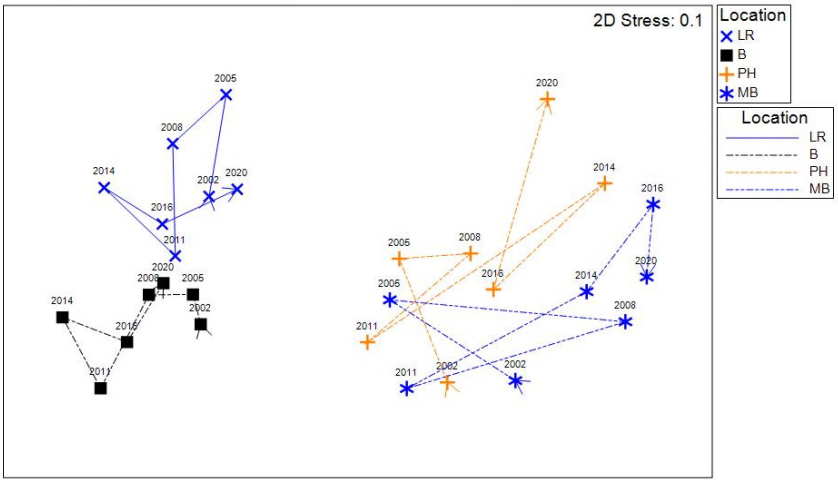


c)

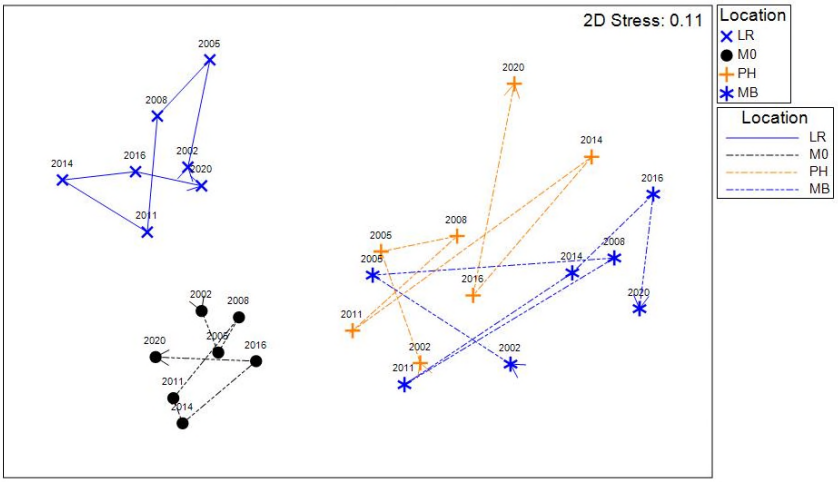


Figure 6-15 Two dimensional nMDS ordination plots of centroids for location-year benthic community sample groupings of three reference locations separately to each outfall: a) North Head; b) Bondi; c) Malabar

Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; PH = Port Hacking reference; MB = Marley reference. Trajectories join location-year centroids with respective assessment years annotated

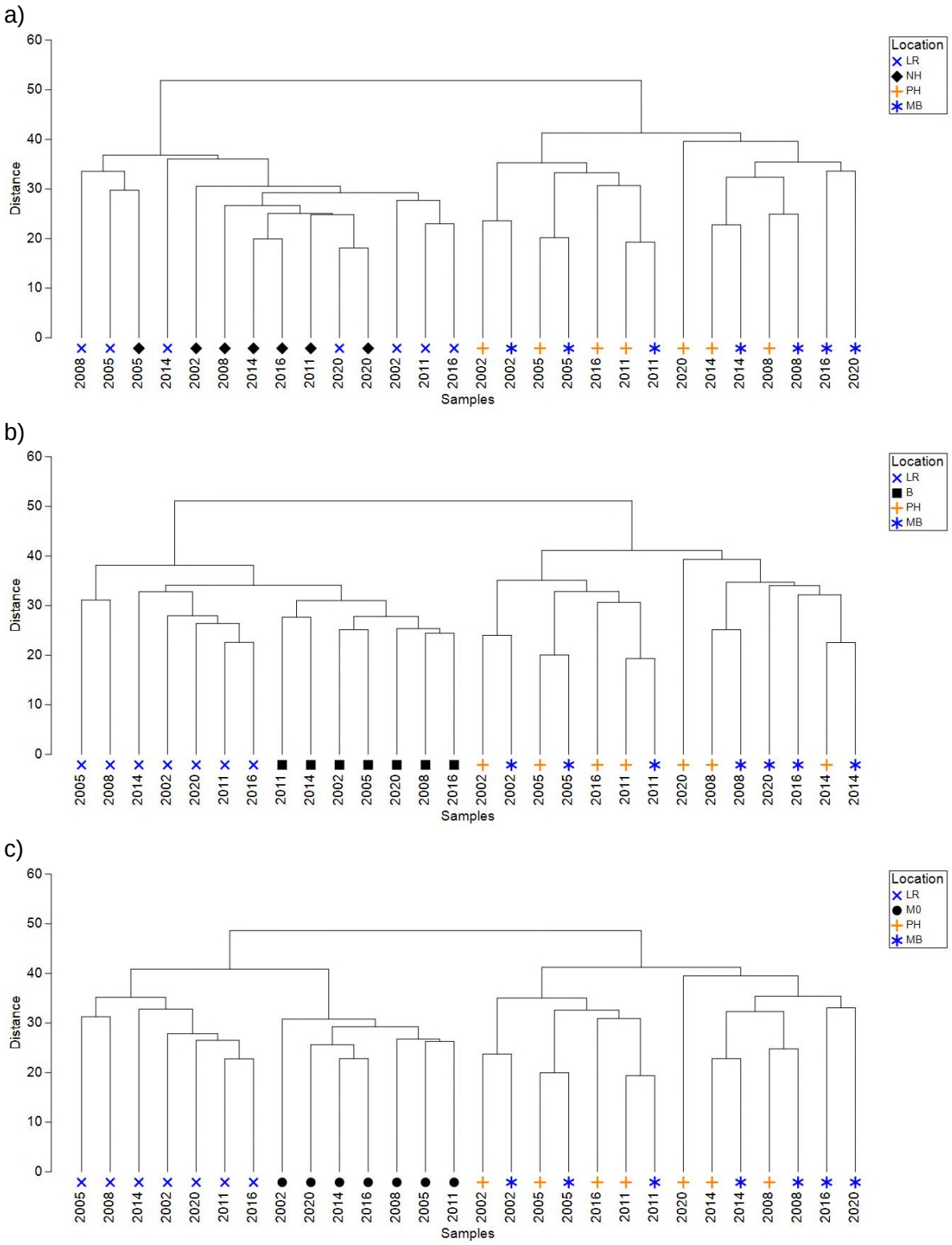


Figure 6-16 Tree diagram from classification analysis of centroids for location-year benthic community sample groupings of three reference locations separately to each outfall: a) North Head; b) Bondi; c) Malabar

Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; PH = Port Hacking reference; MB = Marley reference. Trajectories join location-year centroids with respective assessment years annotated

6.4.4 Community structure of the nine study locations

After viewing diagnostic statistics from the first run of the CAP routine an 'm' value of 17 was chosen to make the second run. The second run indicated a 60% allocation success and the first squared canonical correlation was reasonably large ($\delta 1^2 = 0.85$). The Pillar's trace statistic was significant (2.4398 p = 0.001) and indicated there was more than one group of samples in multivariate space. The Cross-Validation Leave-one-out Allocation of Observations to Groups statistic reflected a number of overlapped and mixed groups of samples with no one location having all of its samples being allocated solely to it (Table 6-13). The misclassified samples were mostly assigned to locations immediately north, or south of that location suggesting a north to south gradient of gradual change in community structure. Although a broader allocation of misclassified samples was evident for the gradient study locations (Malabar: 3 km; 5 km; 7 km) and the reference location of Port Hacking and had a lower individual allocation success percentage (Table 6-13). The resultant CAP ordination pattern (Figure 6-18) reflected the patterns displayed in the corresponding nMDS plot (Figure 6-17), which indicates CAP was unable to uncover additional dimensionality above that found by the nMDS ordination.

The BVSTEP routine identified a subset of 46 taxa ($\rho = 0.950$). A nMDS ordination plot based on those 46 taxa displayed a multivariate pattern (Figure 6-19) that matched the original multivariate pattern from all 195 taxa that occurred across the nine study locations (Figure 6-17). Removal of these 46 influential taxa and rerunning BVSTEP identified another 47 taxa ($\rho = 0.951$). A subsequent nMDS ordination plot of these 47 taxa produced a degenerate pattern of random noise as indicated by the stress value of 0.33 (Figure 6-20).

A gradual change in community structure was illustrated across the nine locations when ordered from north to south in the shade plot based on the subset of 46 taxa (Figure 6-21). In this plot, an obvious simplification of taxa at the outfall locations was not evident. The pattern displayed by this subset of 46 taxa was evident within the shade plot of all 195 taxa for location by assessment year consolidated samples (Appendix E). Almost all taxa that had been collected from each of the nine locations in at least one of the seven assessment years were displayed in the subset shade plot (Figure 6-21). The change in intensity of the grey cell shading illustrated the fluctuation in abundance where taxa were present in each assessment year (Figure 6-21).

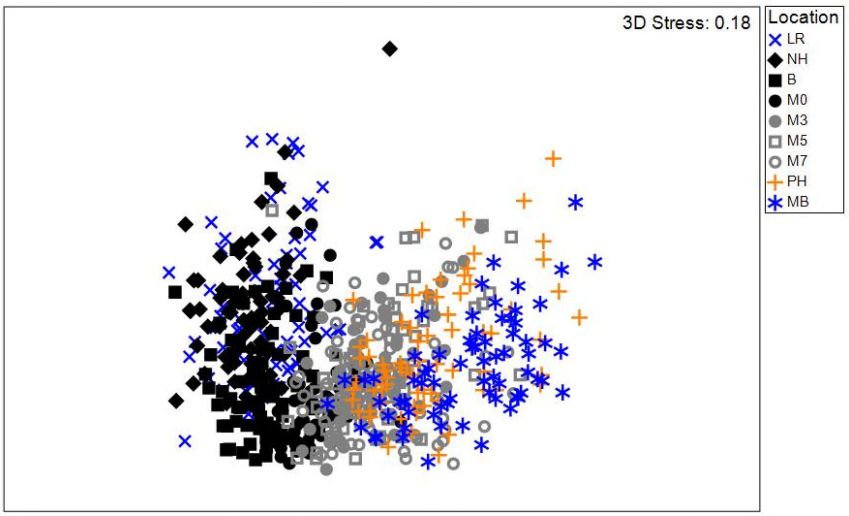


Figure 6-17 Dimensions 1 and 2 of three dimensional nMDS ordination plot of benthic community samples of nine study locations from six periodic assessment years

Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference

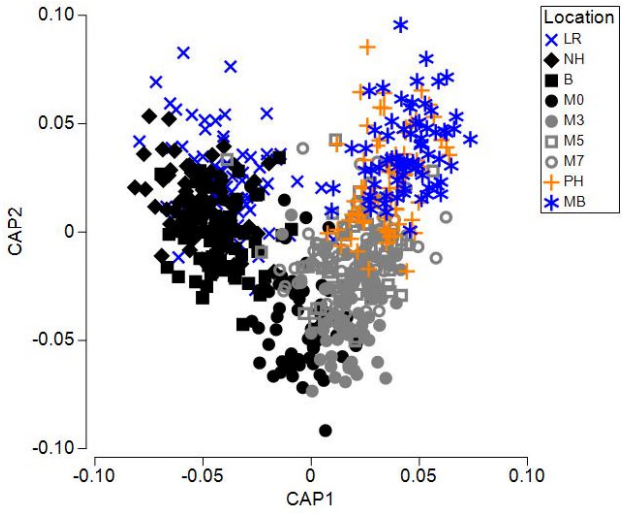


Figure 6-18 CAP ordination plot of nine study locations based on family level replicates for six periodic assessment years (2002, 2005, 2008, 2011, 2014, 2016 and 2020)

Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference

Table 6-13 CAP Cross Validation Leave-one-out Allocation of Observations to Groups statistics of nine study locations

	Allocated group										
Original group	LR	NH	B	M0	M3	M5	M7	PH	MB	Total	%correct
LR	49	15	4	0	0	1	1	0	0	70	70
NH	10	51	8	1	0	0	0	0	0	70	73
B	4	8	57	1	0	0	0	0	0	70	81
M0	3	3	3	50	5	4	2	0	0	70	71
M3	1	0	0	8	45	12	3	1	0	70	64
M5	2	0	0	6	14	23	19	4	2	70	32
M7	1	0	1	3	9	17	29	8	2	70	41
PH	0	0	0	0	1	8	11	26	24	70	37
MB	0	0	0	0	0	0	3	16	51	70	72

Based on family level replicates for combined seven periodic assessment years (2002, 2005, 2008, 2011, 2014, 2016 and 2020). Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference

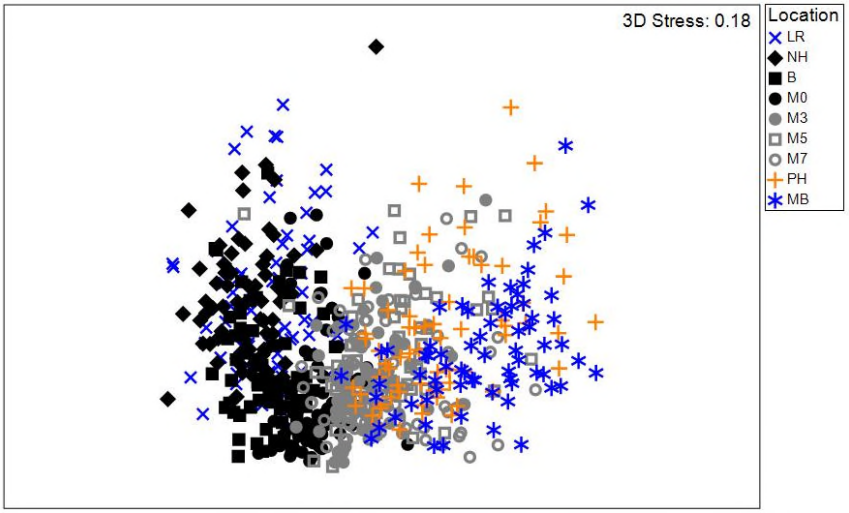


Figure 6-19 Dimensions 1 and 2 of three dimensional nMDS ordination plot based on first BVSTEP subset of 46 family level taxa whose multivariate pattern matches that of the full set of 195 family level taxa.

Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference

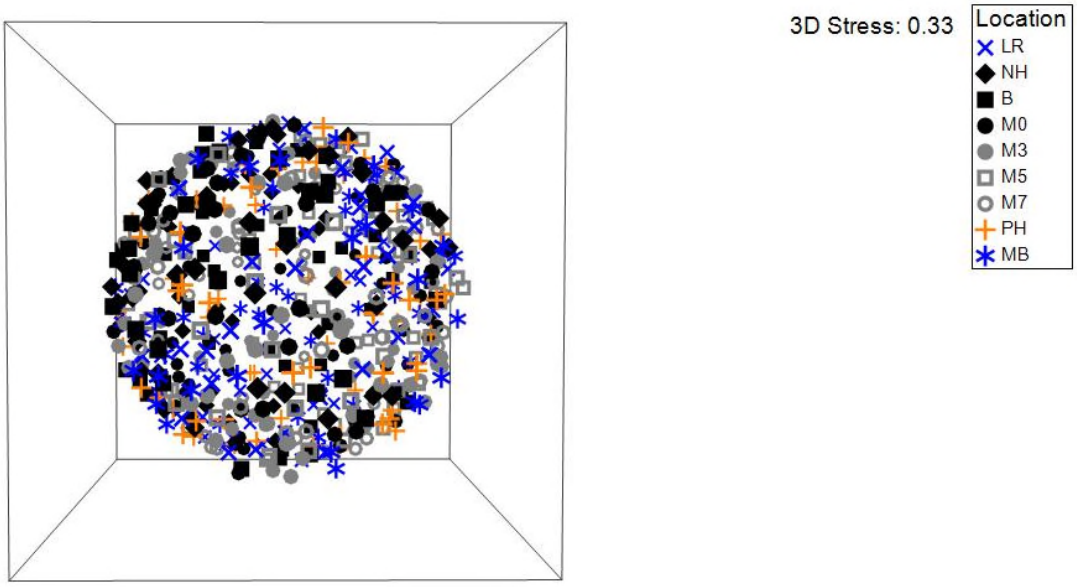


Figure 6-20 Three dimensional nMDS ordination plot based on second set of BVSTEP subset of 47 family level taxa.

Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference

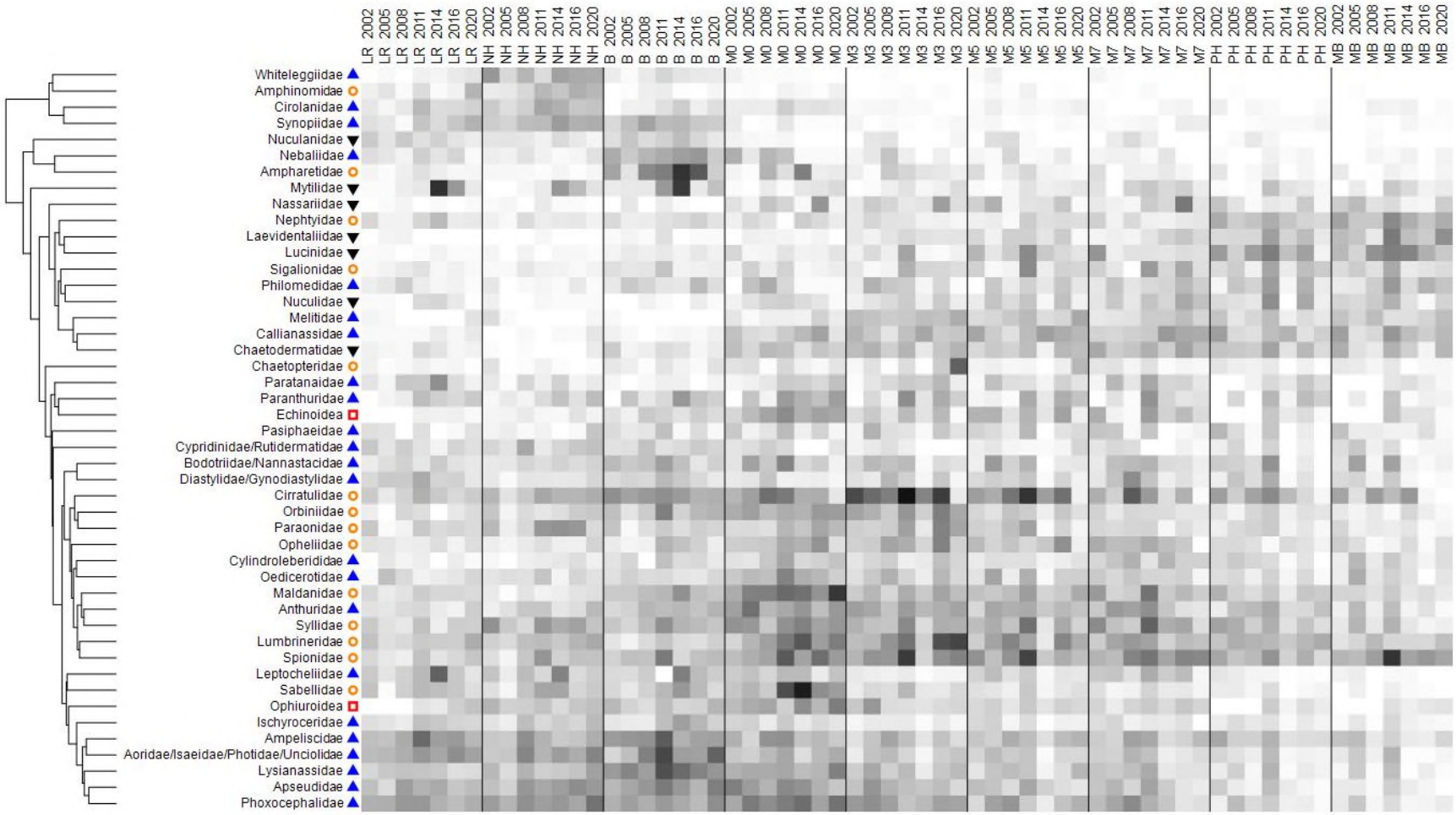


Figure 6-21 Shade plot based on first BVSTEP subset of 46 family level taxa for location by assessment year with family level taxa serially reordered from classification based on a data matrix raised with Whittaker's (1952) Index of Association resemblance measure

Locations: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference. White spaces represent absence of family while depth of grey scale is linearly proportional to dispersion weighted, square root transformed and averged by location-year abundance counts. Maximum grey scale value was 3. Circles = families of Polychaeta; Upward trianges = families of Crustacea; Downward triangles = families of Mollusca; Square = superfamily of Echinodermata

6.4.5 Analysis of the relationship between change in metal concentrations and benthic community structure

The PCA analysis of total sedimentary metal concentrations returned the proportion of the variance of PC1 as 56%. The subsequent CAP analysis of total sedimentary metal concentrations based on PC1 that represented a metal contamination gradient (Al, Ag, As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, Se, Zn) indicated a weak relationship (δ = 0.30, m = 14) as described by the squared canonical correlation to the benthic community structure (Figure 6-22a).

6.4.6 Relationship between change in fine sediment and benthic community structure

The Canonical Analysis of Principal coordinates (CAP) of benthic community structure to percentage fines (< 0.063 mm) in ambient sediment returned a higher squared canonical correlation (δ = 0.70, m = 14) (Figure 6-22b) compared to the CAP analysis of total sedimentary metal concentrations based on PC1 (Figure 6-22a).

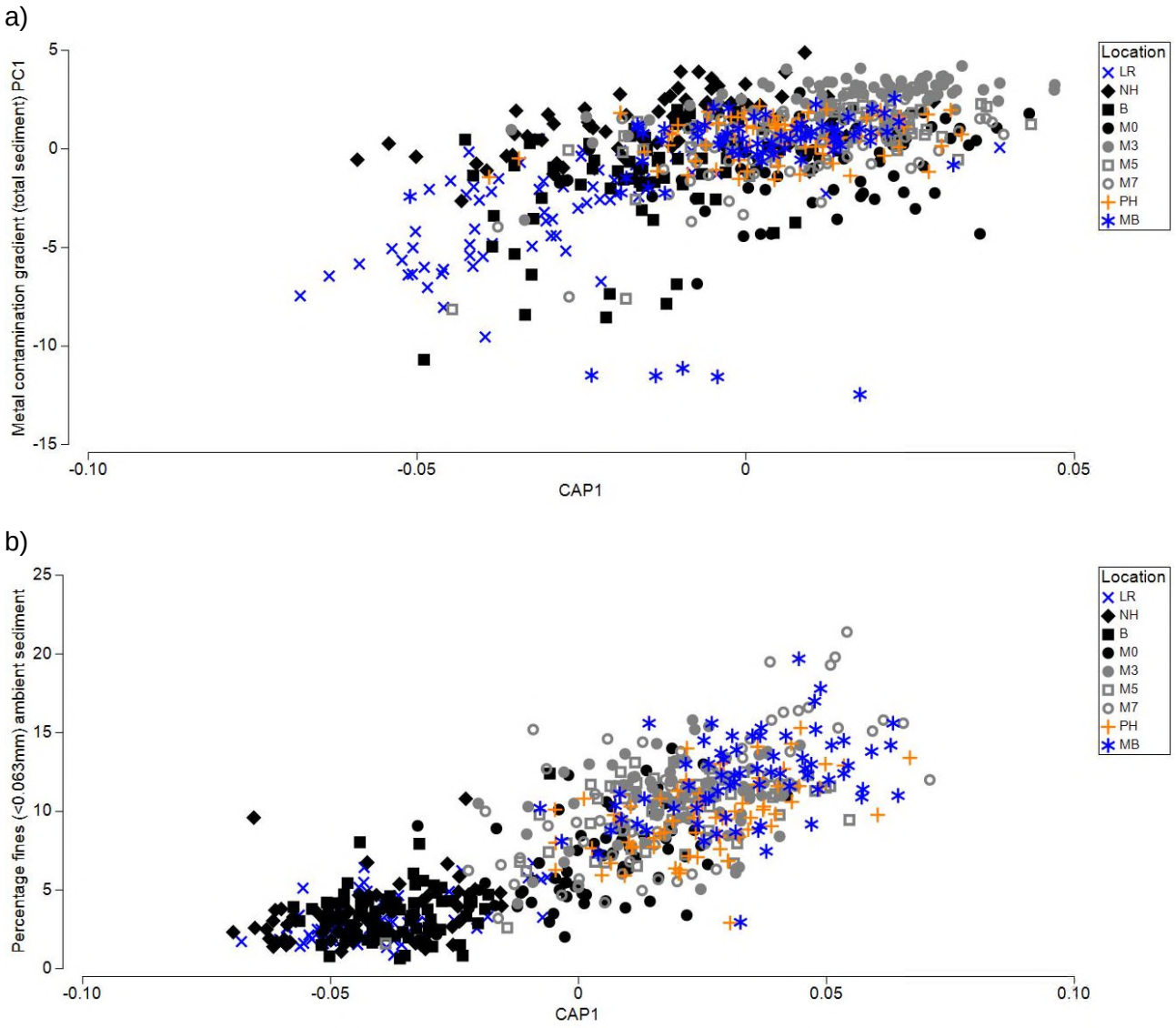


Figure 6-22 CAP ordination showing relationship between biota and : a) PC1 metal contamination gradient of total sedimentary metal concentrations δ = 0.30, m = 14, Var* = 57%; b) percentage fines (< 0.063 mm) in ambient sediment δ = 0.70, m = 14, Var* = 57%.

All model runs based on 999 permutations. *% Var = the percentage of the total variation explained by the m principle coordinate axes. Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference

6.4.7 Examination of benthic macrofaunal community structure of the nine study locations to granulometry

Comparable patterns of change in grainsize from northern to southern locations can be seen from visual inspection of the overlays of grain size classes on the sediment granulometry ordination plot (Figure 6-23c) and on the summarised benthic infauna ordination plot (Figure 6-23d). The lack of an exact pattern match is possibly due to granulometry samples being collected each year across the 21 study years while benthic infauna samples were only collected across the seven periodic assessment years.

A contrasting sample pattern was shown for the ordination plot of total sedimentary metal concentrations (Figure 6-24).

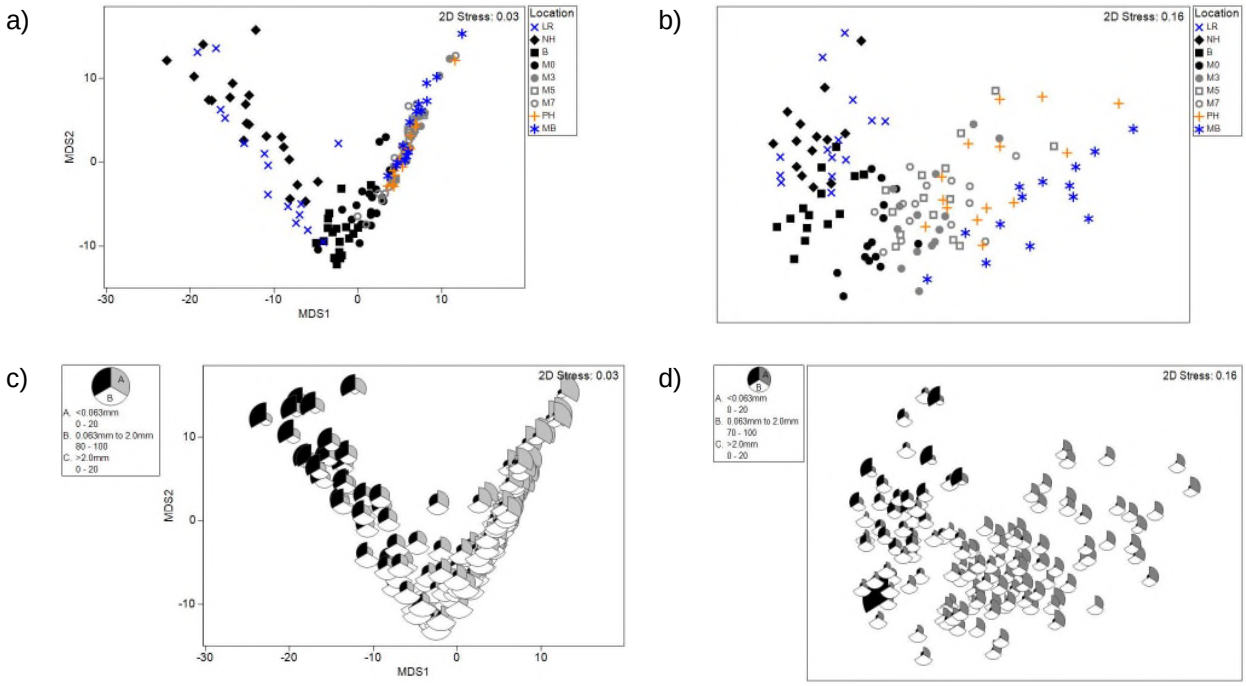


Figure 6-23 Ordination plots of: a) metric MDS of a Manhattan distance resemblance matrix of grain size percentage composition from 2000 to 2020 for outfall locations and at other locations from 2000 to 2011 and 2014, 2016 and 2020 for samples averaged by location-year; b) non-metric MDS of a Bray-Curtis resemblance matrix of benthic community site-year centroids; c) overlay of three grain size classes onto Fig. 7a; d) overlay of three grain size classes onto Fig. 7b.
Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking; MB = Marley

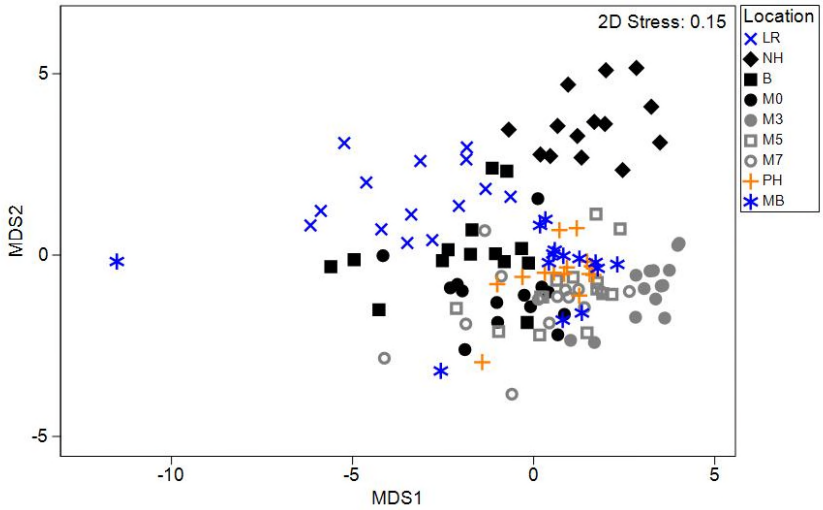


Figure 6-24 Metric MDS ordination plot of centroids for site-year sample groupings of nine study locations of total sedimentary metal concentrations

Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking; MB = Marley

6.4.8 The modelled relationship between fine sediment metal concentrations and benthic community structure south of the Malabar outfall location

In the four DISTLM model runs outputted fitted variation was acceptable, ranging from 62-67% based on adjusted R^2 values (Table 6-14). However, total variation only explained about 13% of the variation in the multivariate data cloud. Of this 13% total variation, the geographic variable accounted for about 10% and the chemistry set of variables accounted for about 3% (Table 6-14).

Table 6-14 Summary statistics from DISTLM model run to assess taxonomic turnover between the Malabar outfall location and the five locations to the south (Malabar 3 km, Malabar 5 km, Malabar 7 km, Port Hacking and Marley)

Model run	Correlation cut off	Adjusted R^2	% fitted variation dbRDA1	% fitted variation dbRDA2	% total variation dbRDA1	% total variation dbRDA2
Total sedimentary metal concentrations Ln	0.90	0.18	47.34	15.03	9.89	3.14
Total sedimentary metal concentrations Ln	0.81*	0.17	51.48	15.52	9.87	2.97
Total sedimentary metal concentrations L10	0.88	0.18	47.02	15.26	9.88	3.31
Total sedimentary metal concentrations L10	0.83*	0.17	51.34	15.49	9.85	2.97

*to allow for multi-collinearity Zn = Cu and Ni, Cr=Fe

6.4.9 Examination of taxonomic turnover to the south of the Malabar outfall location

A significant result was returned for the ordered-ANOSIM test for serial-change in community structure with increasing distance from the Malabar outfall location that tested the null hypothesis of no differences between community structure of locations against an ordered serration model (Malabar outfall > Malabar 3 km > Malabar 5 km > Malabar 7 km > Port Hacking > Marley). A weak slope confirming the existence of a gradient pattern was indicated by the returned global R^o statistic (0.292). Corresponding pairwise test results reflect locations one step apart were more similar than those locations 2 or more steps apart, with increasing dissimilarity with more steps apart (Table 6-15). Although pairwise comparisons of two steps apart returned similar R^o values, as did those comparisons three steps apart and a similar trend was exhibited for pairwise comparisons four steps apart (Table 6-15).

Table 6-15 Pairwise test results from ordered-ANOSIM test of units of distance

Groups	Seriation model steps apart	R^o	P(perm)
M0, M3	1	0.23	0.0001
M0, M5	2	0.22	0.0001
M0, M7	3	0.24	0.0001
M0, PH	4	0.46	0.0001
M0, MB	5	0.67	0.0001
M3, M5	1	0.07	0.0001
M3, M7	2	0.15	0.0001
M3, PH	3	0.25	0.0001
M3, MB	4	0.47	0.0001
M5, M7	1	0.04	0.0010
M5, PH	2	0.13	0.0001
M5, MB	3	0.31	0.0001
M7, PH	1	0.15	0.0001
M7, MB	2	0.34	0.0001
PH, MB	1	0.07	0.0002

Based on Bray-Curtis resemblance measure (global R^o = 0.292, p =0.0001). Locations codes: M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference. P-values obtained using 9999 permutations.

6.4.10 Assessing if the macrofaunal community structure of the Malabar outfall location is related to temporal fluctuations in fine fraction of sediment

The Canonical Analysis of Principal coordinates (CAP) of benthic community structure of each year between 2000 to 2020 to percentage fines (< 0.063 mm) in ambient sediment returned a moderate squared canonical correlation (δ = 0.54; m = 21; Pillar's Trace statistic 0.5406 p = 0.0001). In the CAP ordination plot, fluctuation in community composition between years was displayed (Figure 6-25a). This pattern was influenced by rises and falls in the percentage of fines that occurred in ambient sediment across the 21 years of the study (Figure 6-25b). Not evident in the CAP plot was a display of year samples from left to right in the plot, which would be expected if community structure was influenced by increasing fines through time (Figure 6-25a).

In the plot of abundances of the higher taxonomic groups of Polychaeta, Crustacea and Mollusca (pooled from family level measurement) by year from 2000 to 2020 for the Malabar outfall location, variability (fluctuation) in abundances between years was evident (Figure 6-26a). The plot lacked a clear pattern of increase or decrease of abundance with time. The highest and most variable abundances were for polychaetes (1338 to 7207 specimens) while crustaceans were next most abundant (728 to 2269 specimens). Although in some years crustacean abundances were comparable to those of polychaetes (Figure 6-26a). The plot showing the number of families also displayed fluctuation through time (Figure 6-26b), comparable to that shown in the plot of abundances of the three higher taxonomic groups (Figure 6-26a).

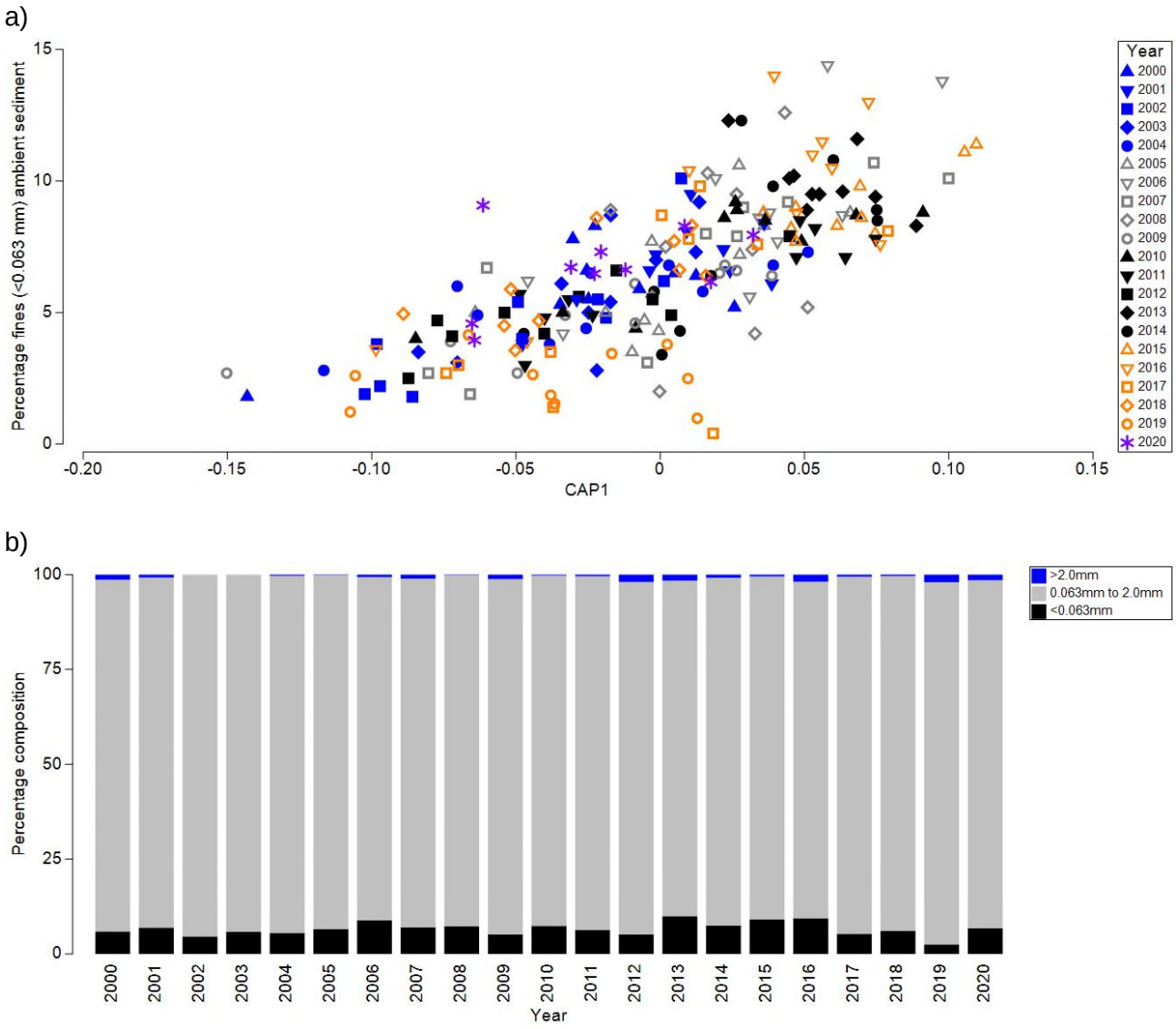
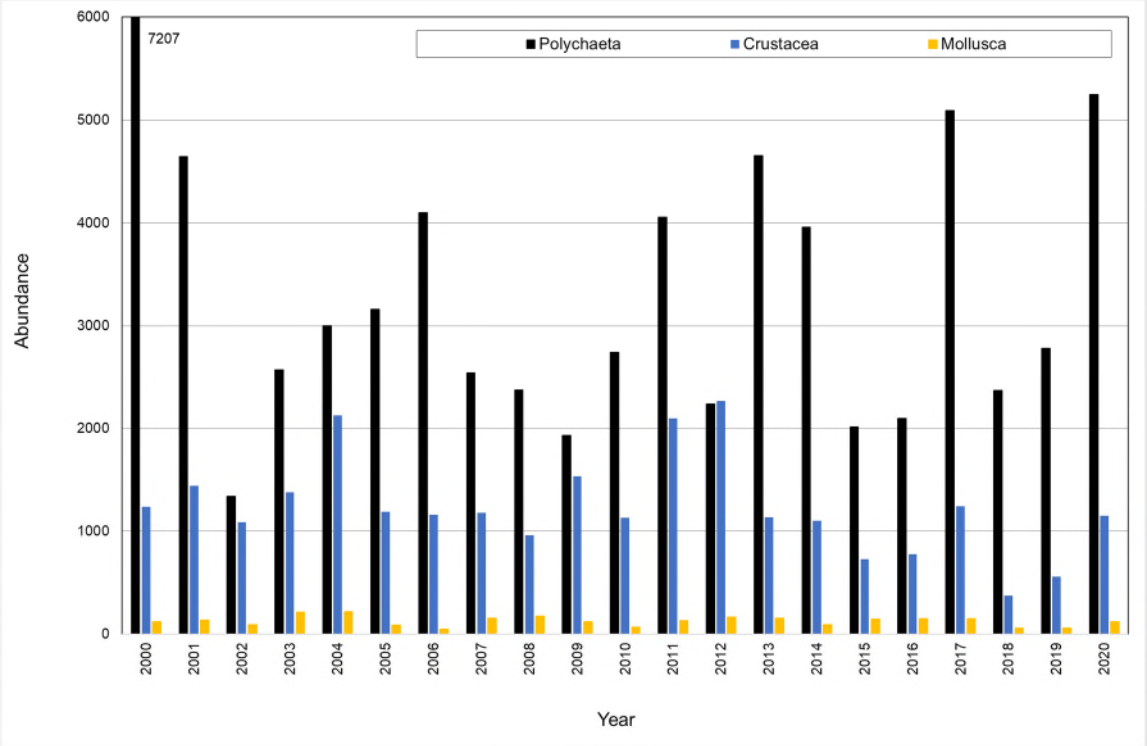


Figure 6-25 For Malabar outfall location: a) CAP ordination plot showing relationship between benthic infauna (family level replicate samples) and percentage fines (<0.063 mm) in ambient sediment from 2001 to 2020 by year: δ = 0.54, m = 21; Percentage of variation explained by m principle coordinate axes = 75%; All model runs based on 9999 permutations; b) Average grain size percentage composition by year from 2000 to 2020

a)



b)

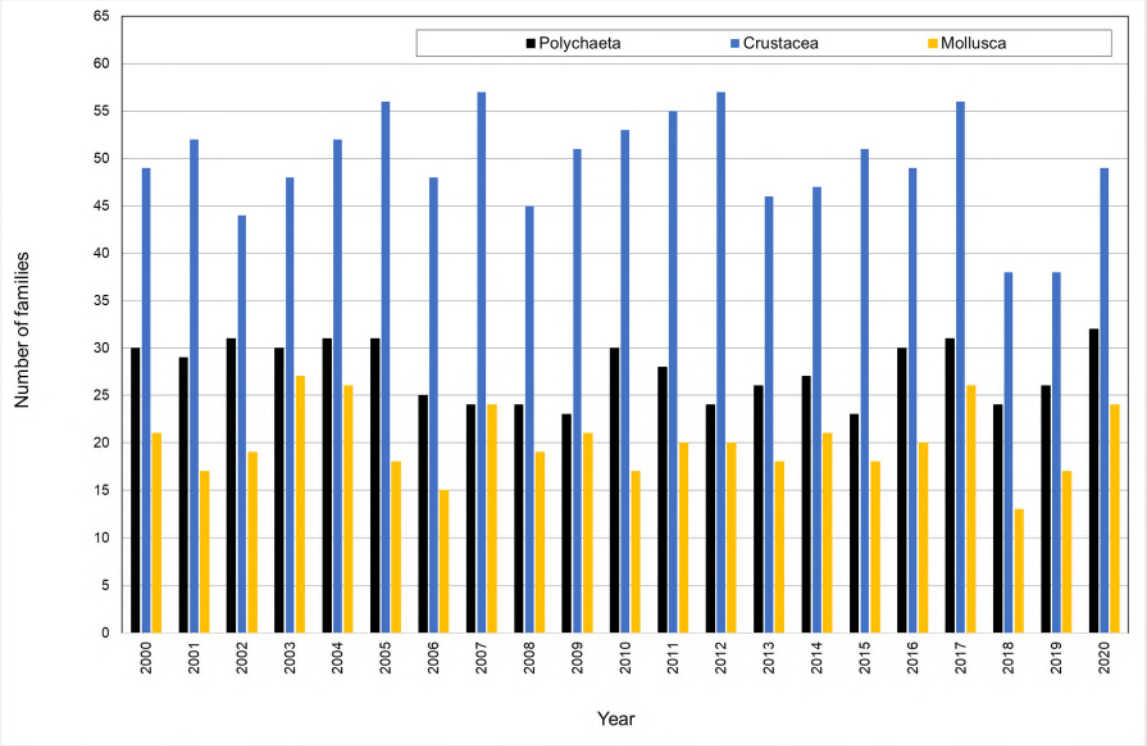


Figure 6-26 Comparison of a) family level counts pooled up to Polychaeta, Crustacea and Mollusca from Malabar outfall location by year from 2000 to 2020; b) number of families of Polychaeta, Crustacea and Mollusca from Malabar outfall location by year from 2000 to 2020

7 Discussion

Multivariate techniques described in Section 5 have been used in a weight-of-evidence approach to assess the impact of discharges from each of the outfalls. Multivariate techniques allow a more extensive search of high dimensional information for patterns that may not be manifest in the original variables, which can be a limitation of individual variable approaches (Anderson and Walsh, 2013). Clark et al. (2014a) states 'community data are usually highly multivariate (large numbers of species, each subject to high statistical noise) and need to be analysed *en masse* in order to elicit the important biological signal and its relationship to the environment'.

7.1 Oceanography

Data collected from the ocean reference station for the three months of December 2019 to February 2020 indicated substantial sediment movement from either wave or currents was likely at both 65 m and 80 m depths. This suggests active sea-bed conditions persisted as Tate et al. (2019) determined for a broader 11-year period (2006 to 2017). WQ Data Pty Ltd (2020) modelling of this three-month period also indicated the settling of particulate matter from the wastewater plumes to be within the spatial range reported by Tate et al. (2019). Near-field plume dilution results from this three-month period reflected the broader 2019-20 period (Table 6-1). The percentage of time the 100:1 dilution was exceeded in 2019-20 was marginally higher than that determined by Tate et al. (2019) over 2006 to 2017 period.

7.2 Sediment characterisation

Measurement of total organic carbon (TOC) helped identify signs of excessive organic matter accumulation, that when combined with a high fines content, may result in lower oxygen permeation increased microbial oxygen uptake/demand and a subsequent accumulation of toxic by-products (Florek and Rowe, 1983; Santschi et al., 1990; Fenchel et al., 1998). These conditions may become harmful and lead to an impoverished benthic community (Diaz and Rosenberg, 1995; Como et al., 2007). Measurement of sediment granulometry assessed potential accumulation in sedimentary metal concentrations. Sedimentary metals and organic chemicals, such as organochlorine pesticides (OCs) and polycyclic aromatic hydrocarbons (PAH), were monitored to assess the potential risk of adverse biological effects.

7.2.1 Long-term trends in TOC

Dean (2008) suggested sewage input is the greatest source of organic material to coastal waters and it is often not the total amount of organic material deposited into a region, but the amount relative to the ability of that region to disaggregate and disperse that material. Dean (2008) also suggested that excessive organic input may lead to anoxic conditions in the sediments and affect the benthic community.

No long-term trend of TOC accumulation was apparent in the data at eight of the nine study locations, which comprised the three outfall locations, the three reference locations, and the two

gradient study locations (Malabar 3 km and Malabar 5 km) nearest the Malabar outfall. Only the Malabar 7 km location exhibited increased mean TOC concentrations.

Relatively low organic conditions persisted across the study region over the 2001 to 2020 study period as only 23 of 1440 TOC analyses from all nine study locations were above the local trigger value of 1.2% TOC set by the NSW EPA for the Malabar outfall location. The occurrence of low TOC across the study area suggests that an accumulation of sedimentary contaminants was unlikely at the outfall locations, and that adverse effects to the benthic invertebrate community was doubtful.

Organic carbon concentrations typically increase with a decline in sediment grain size, (Forstner, 1982; Loring 1991; Marchand et al., 2008; Coppola et al., 2007; Soto-Jemenez et al., 2003), which may explain the observed pattern of relatively higher percentage TOC for the five (three gradient study and two reference) locations south of the Malabar outfall location that contain a relatively higher fines content.

7.2.2 Long-term trends in sediment granulometry

The potential for build-up in sedimentary metal concentrations was suggested to be unlikely as no long-term trend in grain size was apparent at the three outfall locations over the 21 years of granulometry study.

A different granulometric distribution was characteristic of each outfall location. Variation between years was also evident. A clear difference in granulometric composition was also apparent between the northern reference location at Long Reef and the two southern reference locations of Port Hacking and Marley. The granulometric composition at the Long Reef location was similar to that at the North Head outfall location, which was relatively high in gravel (2.3%; 6.6% respectively) and low in fines (2.3%; 2.5% respectively) (Table 6-3). Sediment at the southern reference locations contained the highest percentage of fines (10% to 11.9%), similar to the three gradient study locations south of the Malabar outfall location (8.9% to 11.5%) (Table 6-3). A directly comparable granulometric composition was not provided by the three reference locations to either of the Malabar or Bondi outfall locations.

The overall sediment fining from north to south of the study area may be partly explained by the nature of the sea floor and water depth. The three northern most locations of Long Reef, North Head and Bondi were situated in sediment-filled valleys amongst extensive rocky reefs, while the Malabar outfall and locations to the south were situated within a large sediment-filled valley (Figure 3-1). The three northernmost locations were situated at a depth of approximately 60 m, while the six locations to the south were situated at about 80 m water depth. Besley and Birch (2019b) suggested ambient energy, sediment movement and reworking is likely to be lower at the 80 m water depth and this may have contributed to relatively higher percentage fines at these six southern locations. In the study area wave induced sediment movement is estimated to be 3% less at 80 m compared to 65 m (Tate et al., 2019).

There was also no apparent long-term trend of increasing fine sediment concentration at the Malabar 3 km, Malabar 5 km and Port Hacking locations over the 21 years of monitoring. Modelling of settling of negatively-buoyant particles indicated that over most years deposition would occur within 4 km from the outfalls. This modelling outcome, together with fine sediment results for the

Malabar 3 km and Malabar 5 km locations, suggests that the observed increase in median percentage fines at the Malabar 7 km location over the 2003 to 2016 period was unlikely to be sourced from the Malabar outfall. Besley and Birch (2019b) stated 'if substantial amounts of negatively-buoyant particles were settling at about 7 km distance from the Malabar outfall over time, then a pattern of build-up at the Bondi location could be expected as it is about 8 km south of the North Head outfall. In contrast to this possible pattern, there was no apparent build-up of fine sediment around the Bondi outfall, rather fines were at similar levels for both the North Head and Bondi outfall locations, although this would assume similar oceanographic conditions and seafloor morphology. Without a gradient study to the south of the North Head outfall, it is difficult to draw a definitive conclusion from these results at Bondi.' The fluctuation in fine sediment at the Malabar 7 km may be natural and part of a longer-term natural fluctuation. This is supported by temporal variance of fine sediment at the Marley reference location (some 17 km from the Malabar outfall location). Although fine sediment steadily increased from 2001 to 2016 followed by a decline in 2020, the highest level of fines was observed in 2000 at Marley.

7.2.3 Potential risk of adverse biological effects due to sedimentary metals

A sediment study conducted by Schneider et al. (1994) prior to operation of the deepwater ocean outfalls recorded varying sedimentary metal contaminants within 1 km of two of the three cliff-face outfalls with Cr recorded at the Malabar cliff-face outfall and Cd, Cu, Pb, Hg and Zn documented at the North Head cliff-face outfall.

The risk of adverse effects from sedimentary metals near the deepwater ocean outfalls were assessed with ERL and ERM values. This assessment indicated a minimal risk of adverse biological effects for seven of the nine metals (Ag, Cd, Cr, Cu, Ni, Pb, and Zn) as total sediment concentrations were below respective ERL values. At the North Head outfall location an intermediate risk of biological effects was suggested for As. Arsenic concentrations also exceeded the ERL to a minimal extent at the Long Reef reference location, some 9 km to the north of the North Head outfall. The observed patterns of elevated As concentrations at the North Head outfall location and also at the Long Reef reference location are similar to Schneider et al., (1994) pre-commissioning observations at these locations. Exceedance of the ERL for total sedimentary Hg concentrations occurred at six locations (northern reference of Long Reef, North Head outfall, Bondi outfall, and at the Malabar 3 km, Malabar 5 km and Malabar 7 km gradient study locations). The minimal degree to which Hg exceeded the ERL value suggests a minor risk to the benthic infauna. The Schneider et al. (1994) pre-commissioning study, reported similar Hg concentrations in offshore sediments before the deepwater ocean outfalls were commissioned.

Overall assessment of metal concentrations under MERMQs did not separate the three outfall locations from the reference locations. Rather, seven of the nine locations were statistically similar with MERMQs statistically highest for the North Head outfall location and intermediate for the Malabar 3 km location situated to the north of Botany Bay off Cape Banks (Figure 3-1). This statistical pattern of MERMQs was the same as determined by Besley and Birch (2019b) on the 2002 to 2016 assessment year data and is unsurprising as MERMQs of 2020 assessment year data fell within the range of MERMQs observed across the previous six assessment years (2002 to 2016).

Besley and Birch (2019b) suggested these significantly different MERQMs results may be explained by legacy contamination of the sediments. The relatively higher sedimentary metal concentrations of the North Head outfall location, and to a lesser extent the Long Reef reference location, were most likely related to historic off-shore dumped material that occurred prior to commissioning of the deepwater ocean outfalls. Plunkett (2003) stated until 1932, ships routinely dumped loads of waste just off the coast of Sydney, which included ashes of burnt material. In one month alone (November 1932) 3,426 tons of ash were dumped 4.8 km (three) miles east off Sydney Heads. Under the pre-commissioning study of Schneider et al., (1994), gravel-sized material adjacent to Sydney Harbour was documented as non-biogenic in origin and composed of materials as diverse as coal, timber, sandstone and porcelain. In the North Head area of the Schneider et al. (1994) study, eight sediment cores contained burnt coal residue (clinker) collected from 43 m to 63 m water depth. Schneider et al. (1994) suggested pyrollised material, such as incinerator waste, is likely to contain elevated concentrations of metals. Besley and Birch (2019b) suggested metal concentrations at the North Head outfall location are elevated due to historic ocean dumping and metals bound up in the coarse fraction are non-bioavailable and the moderately high MERMQ values associated with this material is thus inconsequential. Results from the Malabar 3 km location may have also been influenced by past dumping of material, as the Schneider et al. (1994) pre-commissioning study also documented non-biogenic material in the coarse (gravel) fraction to the northeast of Cape Banks, which is nearest the Malabar 3 km location of the current study.

7.2.4 Potential risk of adverse effects due to sediment OC and PAH

The benthic sediment study of Schneider et al. (1994) conducted within 1 km off the Malabar cliff-face outfall prior to operation of the deepwater ocean outfalls, recorded elevated chlordane, DDT, DDE, Aldrin and heptachlor epoxide concentrations. Within a similar distance off the North Head cliff-face outfall, high chlordane, DDT, DDD, DDE and lindane concentrations were also recorded.

OCs are unlikely to pose a risk to benthic animals as results were below detection limit for 18 OCs measured across the seven assessment years (2002 to 2020). Disposal through the sewage system would have reduced following the deregistration of OCs in the mid-late 1980s for general use in Australia (Dept. of Environment, 1997), with remaining uses banned in 1992 (Radcliffe, 2002).

Concentrations of PAHs observed in sediment at the Malabar outfall location in each of the seven assessment years posed a minimal risk of adverse biological effects. In contrast, PAHs at the North Head outfall location in 2002 posed an intermediate risk of adverse biological effect. This risk diminished through 2005 and 2008 assessment years with only a single sample ERL exceedance in 2016 and 2020 at the North Head outfall location, suggesting the risk of adverse biological effect has declined substantially in later assessment years. Besley and Birch (2019a) suggested the reduction in PAH concentrations in ambient sediment may reflect reduced disposal through the sewage system of PAHs from the trade waste reduction program implemented by Sydney Water during construction of the deepwater ocean outfalls. This program had the goal of achieving the quality of industrial waste discharged to the sewerage system to be equivalent in concentration to domestic sewage by 1994 (Fagan et al., 1992). Additional reduction in the concentration of these contaminants over the 14-year study period in the vicinity of the outfall may also be due to

reworking and removal of bottom sediment from the area and possible decay due to a relatively short half-life of these organic contaminants (32-2048 day) (Wlodarczyk-Makula, 2012).

7.2.5 ANCOVA of 2020 data and comments on sedimentary fines

Three ANCOVA models assessed total sedimentary metal chemical concentrations using the fine sediment fraction (percentage fines <0.063 mm in ambient sediment) as the covariate for 2020 collected data for 34 out of 36 conducted tests. ANCOVA testing of the two 80 m reference locations and the Malabar 0 km outfall location identified total sedimentary metals of copper and selenium with a pattern that may indicate a change due to wastewater discharge. The 60 m locations at Bondi and North Head also displayed a pattern that may also indicate wastewater discharge with sedimentary zinc being equivalent and significantly different to Long Reef. Under this model, other test outcomes for six sedimentary metals of aluminium, arsenic, chromium, iron, lead, and nickel identified a pattern of North Head being significantly different to Bondi and Long Reef. This pattern may reflect historic ocean dumping discussed in Section 7.2.3 Similarly, the pattern of significantly higher sedimentary metal concentrations at the Malabar 3 km location for six of the 12 sedimentary metals (cadmium, chromium, iron, nickel, silver and zinc) may also represent historic ocean dumping (as discussed in Section 7.2.3).

Besley and Birch (2019b) explored total sedimentary metals normalised to the fine fraction for the 2002 to 2016 dataset, which displayed higher concentrations for the North Head outfall, the Bondi outfall and Long Reef reference 60 m locations than at the six southern locations situated at 80 m depth. Although this approach of normalising sedimentary metals data to the fine fraction to reduce the confounding of variable grain size is useful in identifying differences in temporal and spatial concentrations of contaminants, it is not without difficulties. Sedimentary metal concentrations normalised to percentage fines were adversely influenced in conversion from total sedimentary metal concentrations when samples contained low percentage fines (<10%) from analysis of 2002 to 2016 dataset (Besley and Birch, 2019b). Also evident was a trend of reduced metal concentrations from earlier to latter assessment years that became apparent when total sediment metal concentrations were normalised to the fine fraction for seven of the nine study locations. This trend corresponded to more fines present in later assessment years at those seven locations than in earlier assessment years, and was an artefact of individual years selected as periodic assessment years, as intervening surveillance years displayed fluctuating percentages of fines (as discussed in section 3.4 of Besley and Birch 2019b). These outlined artefacts together with the influence of elevated total sedimentary metal concentrations due to historic ocean dumping with metals bound to the coarse fraction of total sediment will have had some influence on ANCOVA results across assessment years where the fine sediment fraction has been used as the covariate in analysis with total sedimentary metal concentrations.

To allow more meaningful outcomes under ANCOVA and, or to allow for additional tracking of potential accumulation (at outfall locations) of metals associated with the fine sediment fraction, the additional inclusion of measurement of the sedimentary metals in the fine sediment fraction would be an improvement to the assessment program. If measurement of metals in the fine sediment was included in the program, then measurement in the intervening surveillance years would enable an understanding of variation between years and across all nine study locations. The monitoring cost to provide this additional line of evidence would need to be weighed up against information

already provided by MERMQs based upon total sedimentary metal concentrations collected across the past seven assessment years. The MERMQ scheme has enabled the risk of adverse effects of metal mixtures in ambient sediment to be assessed/estimated. Assessment of MERMQs have illustrated fluctuation in potential risk posed by sedimentary metal mixtures at each of the nine study locations over the past seven assessment years (Table 6-4). Moreover, these location-specific ranges of MERMQs provide a basis going forward to evaluate the potential increased combined risk of adverse effects from sedimentary metal mixtures near the deepwater ocean outfalls, if long-term build-up (accumulation) of sedimentary metals was to occur. Hence, continued measurement of total sedimentary metal concentrations is considered important to allow calculation of MERMQs under this line of evidence.

7.3 Benthic infauna

7.3.1 Assessment of temporal and spatial differences in community structure at reference locations

Fagan et al. (1992) suggested meaningful measurement of anthropogenic impacts on the environment requires an understanding of the inherent variability and long-term trends associated with natural systems.

Otway et al. (1996) recorded change in community structure at both reference and (at the then future) outfall locations over the pre-commissioning component of the EMP sampling events conducted in winter 1989, summer 1990 and autumn 1990.

The current post-commissioning study (2002 to 2020) determined significant differences in community structure between assessment years and reference locations. The corresponding nMDS ordination plot illustrated temporal change across the seven periodic assessment years at each reference location. Also illustrated within this plot was a difference in community structure between the northern and two southern reference locations that persisted through the 19-year study period.

Examples of differences in taxa between the northern and two southern reference locations were illustrated by the first five cluster groups of taxa in the subset shade plot and by the last five taxa cluster at the bottom of the shade plot (Figure 6-21). The last five taxa (from Ampeliscidae to Phoxocephalidae, Figure 6-21) had relatively higher abundances on most sampling occasions at the northern reference location. The opposite pattern to this was seen in the fifth cluster group (from Nassariidae to Chaetodermatidae, Figure 6-21) of ten taxa that were relatively more abundant on most sampling occasions at the southern two reference locations. In the first four cluster groups (from Whiteleggiidae to Synopiidae, Figure 6-21), four taxa were generally collected on most sampling occasions at the northern reference location, whereas these taxa were collected on only a few differing occasions at the southern two reference locations. These taxa differences will have contributed to the separation pattern between the northern and southern two reference locations evident in Figure 6-14. Taxa that comprised these three above described groups were the same as those identified by Besley and Birch (2019c, Figure 6) from the 2002 to 2016 dataset.

An example of temporal change in taxa abundance across assessment years within a location was displayed in the subset shade plot (Figure 6-21) by the crustacean Ampeliscidae. Relative abundances of Ampeliscidae increased from lowest levels in 2002 and 2005 to highest in 2011. In 2020 abundance had declined to levels recorded in 2002 and 2005. Another example is provided by the molluscan Mytilidae at the northern reference location that had relatively highest abundance in 2014 and 2016, and then declined in 2020 to levels observed in 2008 and 2011 (Figure 6-21). At the southern reference location of Marley, Mytilidae was collected in 2005 and then in the last four assessment years (2011, 2014, 2016 and 2020), although abundance in 2020 was most similar to levels observed in 2005. Taxa with this type of temporal occurrence will have contributed to the spread of location-year centroids evident in Figure 6-14 between earlier and latter assessment years for the three reference locations.

7.3.2 Assessment of differences in community structure at each outfall to the three reference locations

Fagan et al. (1992) referred to the Pearson and Rosenberg (1978) model of potential impacts of the effluent from outfalls on the benthic communities included development of a nutrient-enriched zone around the outfalls due to the settlement of suspended particles from the effluent, where such zones usually contain an abundant, but species-poor community. Otway (1995) proposed if impacts persisted in time, it is conceivable that many of the soft-bottom organisms close to the Sydney outfalls will decrease in abundance as the sediments in the surrounding regions would become greatly enriched with nutrients.

A review of ocean discharging outfalls by Puente and Diaz (2015) suggest the Pearson and Rosenberg (1978) paradigm of infauna successional change with distance from a source of organic material does not adequately describe the response of benthos in higher energy, dispersive sea floor environments and suggest this model be revised for coastal areas. They believe that the balance between the total organic mass loading to bottom waters and the energy of the system are probably the key factors in determining benthic impacts. Thus, in the open sea, the high initial dilution (at least 100:1), the intense mixing and large surface area available for reaeration, make it difficult to generate hypoxia, especially in those environments with high wave height, and/or strong currents (Puente and Diaz, 2015). Dean (2008) suggested it is not the total amount of organic material deposited into a region, but the amount relative to the ability of that region to disaggregate and disperse that material. It has been suggested by Roberts et al. (2010) that properly designed outfalls do not cause significant ecological impacts.

Studies of the effects of organic enrichment beneath aquaculture facilities on polychaete species have been suggested by Dean (2008) to present a much clearer picture of the response of the benthos to only organic input as this material does not contain metallic, or organic chemicals that are present in wastewater. Dean (2008) cited studies by Tsutsumi (1995), Yokoyama (2002) and Lee et al. (2006), which illustrated that the degree of anoxia created by excess organic material was the main determinant of the benthic response and where input of organic matter did not result in anoxia, there seemed to be little effect on the benthos. Borja et al. (2006) concluded the first factor controlling benthic structure in the Nervion estuary, Spain, was bottom water oxygen saturation and associated hypoxia and or, anoxia of sediments. The second factor was high sedimentary metal concentrations in some areas of the estuary (Borja et al., 2006).

Dilutions exceeding 100:1 were considered by Puente and Diaz (2015) to produce intensive mixing from the large surface area provided by a diffuser array for re-aeration and when in the presence of high currents makes it difficult for hypoxia to develop. Tate et al. (2019) determined the modelled initial dilution zone value of at least 100:1 for the 2006 to 2017 period was exceeded 94%, 98% and 87% of the time for North Head, Bondi and Malabar outfalls, respectively. This suggested hypoxia was unlikely to have developed around Sydney's deepwater ocean outfalls.

The above sediment characterisation indicated low organic conditions prevailed across the study region over the 2001 to 2020 period, which suggested that discharges from the deepwater ocean outfalls did not contribute to anoxia. This sediment characterisation also indicated deepwater ocean discharges have not contributed to an accumulation of fines, or to increased metallic/non-

metallic chemicals of concern with no elevated risk of adverse biological effects beyond pre-commissioning conditions.

Outcomes from the initial PERMANOVA model of the three outfall locations compared to each of the three reference locations indicated differences in community structure between locations and within locations across assessment years. Under the second PERMANOVA model the additional partitioning of data (Table 6-12) was not successful at drawing out further data patterns, as non-significant results were returned for the additional factor of 'Control Impact' and interaction term 'Control Impact x Year', which were not included in the initial PERMANOVA model (Table 6-11). Temporal change across the seven assessment years for each outfall location and for the three reference locations was illustrated in corresponding nMDS ordination plots. The reference location patterns in each of the three comparisons with each outfall (Figure 6-15) mirrored those patterns illustrated in the analysis of the three reference locations (Figure 6-14). Companion dendrograms illustrated the first separation was not from outfall samples but did displayed the north-south separation of reference location samples, supporting nMDS and PERMANOVA results. These results suggested community composition at each outfall has not been affected by anoxic conditions.

7.3.3 Community structure of the nine study locations

A north to south gradient of gradual change in community structure was suggested by results of the CAP Cross-Validation Leave-one-out Allocation of Observations to Groups statistic. The corresponding CAP ordination plot did not uncover additional dimensionality above that found in the overall nine location nMDS ordination plot. This overall nine location nMDS ordination plot also displayed a north to south pattern in community structure.

Investigation of structural taxonomic redundancy under BVSTEP identified a single set of 46 (family level) taxa with a matching coefficient of $\rho > 0.95$ to the original 195 taxa pattern. This solitary group suggested a low level of structural redundancy when compared to Clarke and Warwick (1998) two marine location examples (the Bay of Morlaix, France and an area off Northumberland coast, England) that had four successful subsets, although those examples were based upon species level data. Mistri et al. (2001) study of two coastal lagoons in the Adriatic Sea determined a single successful subset in one lagoon and two successful subsets in another lagoon with matching coefficients $\rho > 0.95$ and subsequent ordination patterns that mirrored their full species ordination patterns. Mistri et al. (2001) suggested reduced structural redundancy may be from a restricted number of taxa that had evolved to be capable of tolerating the physiologically stressful fluctuating environmental parameters in the lagoon systems. Besley and Birch (2019c) suggested under the Ocean Sediment Program study the reduced structural redundancy may be driven by the fluctuating sedimentary composition observed across the assessment years together with the pre-existing sediment metal contamination of offshore sediments.

The pattern in the overall nine location nMDS ordination plot of all 195 taxa was mirrored in the companion nMDS ordination plot of the 46 taxa subset identified under BVSTEP.

The shade plot of the 46 taxa subset lacked an obvious simplification of taxa at the outfall locations. The shade plot clearly showed fluctuation in abundance between assessment years

across the crustacean, molluscan and polychaete families as illustrated by lighter and darker grey shaded columns and cells of the plot.

Temporal variation between the seven periodic assessment years (2002, 2005, 2008, 2011, 2014, 2016, and 2020) was suggested by significant results under PERMANOVA testing for interaction model terms that included the factor 'Year' (Table 6-11, Table 6-12). The shade plot temporal pattern was contained within a pattern of gradual spatial change in community composition across the north to south locations. This temporal pattern within a spatial pattern has been noted by Van Hoey et al. (2004) as they suggested temporal variability should be considered as subordinate to spatial variation where the main habitat characteristics do not change drastically.

Dean (2008) from his review of polychaetes suggested other taxa as well as polychaetes differ greatly in their responses to environmental pollutants and the idea that a single polychaete species or groups of species will always occur in an environmentally stressed or benign situation is incorrect, as numerically dominant species may change temporally in dynamic systems. Tate et al. (2019) oceanographic modelling of the Sydney deepwater ocean outfalls from 2006 to 2017 indicated that the offshore study area was dynamic and that ocean current and or wave induced shear stress may be sufficient to re-suspend bottom sediments at times. Recent oceanographic modelling of WQ Data Pty Ltd (2020) also indicated in the two months preceding the February 2020 sediment-sampling period, either currents or waves are likely to have caused substantial sediment movement. Besley and Birch (2019c) suggested temporal fluctuation in community composition was possibly influenced by fluctuations in sediment granulometry that has been observed within each location of the nine locations of the Ocean Sediment Program.

Examples of granulometric preferences of some taxa were illustrated within the first five cluster groups of taxa in the subset shade plot (Figure 6-21). The three crustaceans Cirolanidae, Synopiidae and Whiteleggiidae together with the polychaete Amphinomidae comprised the first cluster group at the top of the shade plot. These four taxa were most consistently collected from the North Head outfall and Long Reef reference locations where the two highest median percentages of gravel and the two lowest median percentage of fines were recorded (Table 6-3). Relatively higher abundances of these four taxa were collected from the North Head outfall location, which could reflect a response to organic input at this location. The fifth cluster group of ten taxa were most consistently collected from the six most southern locations that had at least twice to four times the median percentage of fines of the three most northern locations (Table 6-3). These ten taxa comprised two polychaetes Nephtyidae and Sigalionidae, three crustaceans Callianassidae, Melitidae and Philomedidae, and five molluscans Chaetodermatidae, Laevidentaliidae, Lucinidae, Nassariidae and Nuculidae.

Four taxa in cluster groups two, three and four were more regularly collected and abundant at Bondi, usually collected in lower numbers from the North Head outfall and Long Reef reference locations, and sporadically collected from the Malabar outfall location and other southern locations. This suggested these taxa may prefer areas with predominantly sand as the highest median percentage of sand was recorded for the Bondi location (Table 6-3). These four taxa were comprised of the polychaete Ampharetidae, the crustacean Nebaliidae, and two molluscans of Mytilidae and Nuculanidae.

Besley and Birch (2019c) suggested an alternative explanation for higher abundance of some taxa at the North Head and Bondi outfall locations, which was due to the regions ability to assimilate organic input is discounted for two reasons, ie, the modelled initial dilution zone values (as discussed in section 7.3.2), and on the spatial positioning of outfall sample sites to each diffuser array. Puente and Diaz (2015) concluded most significant ocean outfall effects detected were limited to <500 m from the outfall in the near-field zone. The closest part of the sampling grid at each of the two sites of the North Head deepwater ocean outfall location and Bondi deepwater ocean outfall location were positioned 929 m and 1979 m and 609 m and 2030 m, respectively from the outfall diffuser arrays due to rocky reef constraints. Moreover, samples were collected closer to the Malabar deepwater ocean outfall diffuser array (200-500m), which did not have a similar obvious abundance pattern of a relatively few taxa (Besley and Birch 2019c).

Many studies have demonstrated that sediment type, including organic matter, play an important role in the spatial distribution of benthic fauna (Wieser, 1959; Flint and Rabalais, 1980; Fresi et al., 1983; Junoy and Vieitez, 1989; Mendez and Ruiz, 1998; Martins et al., 2013). Santos Brasil and Silva (2000) described polychaete worms as always being closely related to grain size and other factors, such as organic content, as organic matter represents a major food source of many detritivores (Rodriguez, 1972).

7.3.4 Modelled change in benthic community structure of the nine study locations

Gray (1996) assessed the first few years of operation of the Sydney deepwater ocean outfalls and concluded that there had not been a significant effect on the concentration of trace metals in the sediments surrounding the outfalls. Gray (1996) also indicated concentrations of trace metals in the whole sediment generally reflected the distribution of fine sediment.

CAP was used to model changes in the benthic assemblage correlated with change along a metal contaminant gradient, or along a gradient of change in percentage fines of ambient sediment. The CAP analyses of benthic community structure to percentage fines returned the highest correlation (δ = 0.70) of the two model runs. The model run based on total sedimentary metal concentrations to benthic community structure yielded a weak correlation (δ = 0.30).

The moderately strong correlation returned for the benthic community comparison to the fine sediment fraction reflected the change in sediment texture between the three northern 60 m depth locations (North Head outfall, Bondi outfall, Long Reef reference) and the six southern locations at 80 m depth. This reflects the well-known phenomenon of strong association between the structure of benthic communities and the texture of the ambient marine sediments these animals inhabit as outlined in Gray (1974). Anderson (2008) described that work as a landmark paper.

If sedimentary metal concentrations were accumulating from wastewater discharge and exerting an impact on benthic community structure, then a pattern of the three outfall locations being distinct from reference locations would be expected. This pattern was not displayed. Tate et al. (2019) suggested it is difficult to clearly attribute contaminants found in the sediments to specific deepwater ocean outfalls as estimates of wastewater particles depositing on the sea floor was to an accumulative depth of < 1 cm over 150 km^2 for the first 25 years of operation of the deepwater ocean outfalls. This estimate was based on highly conservative assumptions of no further sediment movement and a wastewater particle density of 1200 kg/m^3.

Anderson (2008) suggested that while the existence of animal-sediment relationships is undisputed, many other factors can also play important roles in structuring the temporal and spatial heterogeneity of soft-sediment community structure. Besley and Birch (2019b) suggested the pre-existing sediment metal contamination in offshore sediment detected before commissioning of the deepwater ocean outfalls in the areas of the present-day outfalls by Schneider and Davey (1995) and Schneider et al. (1994) may have posed a long-term, low risk of adverse biologic effects that has influenced benthic community structure together with sediment granularity at all nine locations in the Ocean Sediment Program study.

7.3.5 Benthic macrofaunal community structure of the nine study locations and granulometry

Addition of the 2020 assessment year data with the other six assessment years of data (2002 to 2016) produced the same visual trends as those identified by Besley and Birch (2019b, 2019c). Visual inspection revealed the ordination plots of granulometry and benthic community structure were relatively alike when compared to the differing pattern displayed in the ordination plot of total sedimentary metal concentrations. The overlay of three grain size classes onto sediment granulometry and benthic community structure ordination plots showed comparable patterns of change in grainsize from northern to more southern locations. This suggested sediment granulometry was more influential in shaping benthic community structure across the nine study locations than accumulation of chemicals of concern near the deepwater ocean outfalls (Besley and Birch 2019c). This visual comparison was supported by CAP modelling of percentage fines and total sedimentary metal concentrations outlined above.

7.3.6 Sediment metal concentrations and benthic community structure at spatially distant locations from the Malabar outfall

Oceanographic modelling of negatively-buoyant particle settling indicated that particles first settle within 3 km 50% of time, and within 5 km 80% of time and within 10 km 95% of time (Tate et al., 2019 Fig. 10). This suggested increased sedimentary metal concentrations were most likely nearer the Malabar outfall, which may relate to an increased risk of adverse effects to the benthic community.

Total sedimentary metal concentrations were used to assess the taxonomic turnover between the Malabar outfall location and the five locations to the south. DISTLM modelling was used to examine the proportion of variation in the benthic community data that was explained by the set of sedimentary metals over and above the amount explained by the spatial variables alone. Under the DISTLM model runs, fitted variation was returned at acceptable levels, however, the amount of total variation was low, suggesting about 3% of the total variation was explained by the sedimentary metals. The amount of total variation is important to consider in DISTLM modelling. If the total variation is very small (13%, see Table 6-14), then the outputted dbRDA plots maybe of little overall relevance in the multivariate system as a whole (Anderson et al., 2008), hence plots were not presented here. Addition of the 2020 assessment year data to the other six assessment years of data (2002 to 2016) produced very similar outcomes to those determined by Besley and Birch 2019b). As such, the Besley and Birch (2019b) suggestion is still applicable, which was ‘The returned low total variation for sediment metals may reflect the overall low risk of adverse effects of

metals in ambient sediment that has been present since before commissioning of the deepwater ocean outfalls.'

7.3.7 Examination of taxonomic turnover south of the Malabar outfall location

Otway (1995) suggested that if impacts were confined to the immediate (<500 m radius) area around the diffusers, it could be argued that the spatial scale of the impact is acceptable, but if the impacts extend some kilometres from the outfall, such a scenario might not be viewed favourably. To explore this aspect, examination of taxonomic turnover with an ordered seriation model to the south of the Malabar outfall was conducted.

Results of the ordered-ANOSIM pairwise tests based on the seven assessment years of data (2002 to 2020) produced the same data trends as determined by Besley and Birch (2019c) based on six assessment years of data (2002 to 2016). These results indicated locations immediately to the north, or south (one step apart) were most similar in community structure, while those more than one step apart were more distinct. However, pairwise comparisons of locations that were two steps apart returned similar R^o values, as did those comparisons of locations three steps apart and a similar trend was exhibited for pairwise comparisons of locations that were four steps apart (Table 6-15). These pairwise tests suggested a gradient of gradual change in community structure from north to south, rather than a strong pattern of change south of the Malabar outfall. Support for this trend was provided by results of the CAP Cross-Validation Leave-one-out Allocation of Observations to Groups statistics that also suggested a north to south gradient of gradual change in community structure across all nine study locations (Table 6-13 and Section 6.4.4).

Support for these serration model results was provided by DISTLM modelling that suggested sedimentary metals originating from the Malabar outfall were an unlikely source of influence on benthic community structure to the south of the Malabar outfall.

7.3.8 Relationship between temporal (yearly) change in fine sediment and benthic community structure at Malabar outfall location

The yearly collection (2000 to 2020) from the Malabar outfall location of benthic infauna along with grain size measurements enabled an analysis of the relationship of percentage fines in ambient sediment to benthic infauna community structure over a 21-year period.

A moderate correlation was found under the CAP model of change in community structure of the Malabar outfall location to companion samples of percentage fines in ambient sediment. Besley and Birch (2019c) assessment of the first 18 years (2000 to 2017) of this dataset found a similar moderate correlation. What was not evident in the corresponding CAP ordination plot was a pattern of year samples from left to right in the CAP ordination plot of earliest to latest that would have suggested an impact from this outfall. Rather fluctuation in community composition was evident between years influenced by rises and falls in the percentage of fines in ambient sediment that occurred across the 21 years of the study. This fluctuation was also observed by Besley and Birch (2019c).

This association suggested the design of the near field dilution and dispersion from the diffuser array was sufficient. The pattern in the CAP ordination may be explained by the fluctuation in both abundance and in the number of families of the three higher taxonomic groups (Polychaeta,

Crustacea and Mollusca) across these 21 years. Fluctuation at varying spatial and temporal scales was also observed in the pre-commissioning study of Otway et al. (1996) for these same three taxonomic groups.

Otway (1995) post-commissioning study observed a decrease in the number of polychaete families near the Malabar outfall. Besley and Birch (2019b) suggested this may have been an artefact of survey periods, as the number of families recorded in the Ocean Sediment Program study at the Malabar outfall was shown to fluctuate through time. EPA (1997) concluded the benthic community of the Malabar outfall location was highly variable at a monthly temporal scale from a 12-month study conducted six years post-commissioning of this outfall. They also suggested most of the variability appeared to be driven by sediment structure, and percentage of fines appeared to have the single greatest influence on benthic community structure.

8 Conclusions

Extended time-series monitoring to understand anthropogenic impacts and potential longer-term change in benthic marine communities has been advocated for deepwater ocean outfalls in other parts of the globe (Currie and Parry, 1999; Rees et al., 2006). The EPA (1998) '*Study Design for Long-term Monitoring of Benthic Ecosystems Near Sydney's Deepwater Ocean Outfalls'* enables periodic assessment of the longer-term performance of the Sydney deepwater ocean outfalls and provides a mechanism to alert for development of possible long-term accumulative effects. Sydney Water has implemented that program design under the Ocean Sediment Program, which monitors both sediment chemistry and benthic infauna. As outlined in Section 2.1 the two overarching objectives were: to assess if there is a chronic impact occurring; and to evaluate if any potential existing impact is spreading around the Malabar outfall. Outcomes from statistical and graphical analyses under the 13 sub-objectives raised from the above two objectives have formed lines of evidence to allow a weight-of-evidence assessment.

Besley and Birch (2019c) determined low organic concentrations (median TOC of nine locations ranged from 0.2% to 0.7%) and a lack of anoxia have persisted across the Sydney Deepwater Outfall study region over the 2001 to 2017 period due to ocean currents and internal ocean waves being sufficiently large at times to re-suspend bottom sediments (Tate et al., 2019). TOC concentrations subsequently measured in 2018, 2019 and 2020 indicated the same low organic concentrations have persisted. WQ Data Pty Ltd (2020) determined substantial sediment movement from either wave or currents was likely in the two months immediately before and through February 2020 in which sediment collection occurred for this assessment report. Besley and Birch (2019c) suggested the apparent lack of hypoxia was also due to low initial dilution values of at least 100:1 being exceeded 94%, 98% and 87% of the time (2006 to 2017) for North Head, Bondi and Malabar outfalls, respectively (Tate et al., 2019). The most recent 2019-20 oceanographic modelling indicates the percentage of time the 100:1 dilution was exceeded in 2019-20 was marginally higher than that determined by Tate et al. (2019). This 100:1 dilution criterion is based upon Puente and Diaz (2015) who considered it is difficult for hypoxia to develop at or above that dilution level in the open sea where intense mixing from wave and currents enable a large surface area for re-aeration.

The potential for build-up in sedimentary metal concentrations was suggested to be unlikely as no long-term trend in grain size was apparent at the three outfall locations over the 21 years of granulometry study. Moreover, a sediment-granulometry gradient was observed with increased fining to the south across the nine study locations.

Addition of 2020 sedimentary metal, PAH and OC data did not alter the conclusion of Besley and Birch (2019b) from their assessment of contaminants of concern collected in the six previous periodic assessment years (2002, 2005, 2008, 2011, 2014, and 2016) of no apparent build-up of sedimentary metals, PAHs or OCs at the deepwater ocean outfall locations. In 2020 PAH chemicals posed a low risk to benthic animals, while testing of the 1992-banned OC chemicals returned results below the detection level suggesting OCs were unlikely to pose a risk to benthic animals.

At all nine study locations, a minimal risk of adverse biological effects was indicated for seven (Ag, Cd, Cr, Cu, Ni, Pb and Zn) of the nine sedimentary metals. A minor risk to the benthic infauna was posed by Hg as some results slightly exceeded the ERL at six of the nine study locations. Arsenic concentrations at the North Head outfall location suggested an intermediate risk of adverse biological effects. This assessment of sedimentary metals based on the seven periodic assessment years (2002, 2005, 2008, 2011, 2014, 2016, and 2020) was the same as ascertained under the assessment of the six periodic assessment years (2002 to 2016) by Besley and Birch (2019b). Similar pre-commissioning sedimentary metal concentrations were reported by the earlier Schneider et al. (1994) pre-commissioning study.

Inclusion of the MERMQ scheme as a line of evidence has enabled the risk of adverse effects of metal mixtures in ambient sediment to be assessed. Assessment of MERMQs have illustrated fluctuation in potential risk posed by sedimentary metal mixtures at each of the nine study locations over the past seven assessment years (Table 6-4). Moreover, the location-specific ranges of MERMQs provide a basis going forward to evaluate the potential increased combined risk of adverse effects from sedimentary metal mixtures near the deepwater ocean outfalls, if long-term build-up (accumulation) of sedimentary metals was to occur. Hence, continued measurement of total sedimentary metal concentrations is considered important to allow calculation of MERMQs under this line of evidence. Statistically distinct MERMQs for the North Head outfall location and the Malabar 3 km location are possibly explained by the historic practice of routinely dumping waste just off the coast of Sydney near these two locations. The dumped waste included burnt material that had potentially high concentrations of metals. Besley and Birch (2019b) suggested these coarse dumped materials are likely to be non-bioavailable and are of little biological consequence.

The influence of elevated total sedimentary metal concentrations due to historic ocean dumping with metals bound to the coarse fraction of total sediment influenced the ANCOVA results across assessment years where the fine sediment fraction has been used as the covariate in analysis with total sedimentary metal concentrations. Direct measurement of sedimentary metals in the fine sediment fraction would improve reliability of test outcomes from ANCOVA in the future.

Assessment of infauna based on the seven periodic assessment years (2002, 2005, 2008, 2011, 2014, 2016 and 2020) determined significant differences in community structure, both temporally and spatially between northern and southern reference locations. These differences persisted through the post-commissioning 2002 to 2020 study period. Spatial and temporal fluctuation in community structure were also observed in the pre-commissioning component of the EMP at both reference and (at the then future) outfall locations (Otway et al., 1996).

Examination of each outfall and the reference locations based on infauna data collected over the seven assessment years, produced the same conclusion of Besley and Birch (2019c) that community structure at each outfall was unlikely to be influenced by anoxic conditions.

Assessment of all nine study locations suggested a north to south pattern of change in community structure, which was highly correlated with percentage fine sediment. This conclusion is the same as reached by Besley and Birch (2019c) based on examination of the 2002 to 2016 assessment year dataset. Besley and Birch (2019b) suggested the pre-existing sediment metal enrichment in offshore sediment detected before commissioning of the deepwater ocean outfalls in the areas of

the present-day outfalls may have posed a long-term, low risk of adverse biologic effects that has influenced benthic community structure together with sediment granularity at all nine locations in the Ocean Sediment Program study.

Visual inspection revealed the ordination plots of granulometry and benthic community structure, were relatively alike when compared to the differing patterns displayed in the ordination plot of total sedimentary metal concentrations. This visual inspection also suggested that sediment granulometry was more influential in shaping the benthic community structure across the nine study locations than accumulation of chemicals of concern near the deepwater ocean outfalls.

DISTLM modelling based on the 2002 to 2020 assessment year dataset, suggested sedimentary metals originating from the Malabar deepwater ocean outfall were an unlikely source of influence on benthic community structure to the south of the Malabar deepwater ocean outfall. The same conclusion was reached from assessment of the 2002 to 2016 assessment year dataset (Besley and Birch 2019c).

Examination of taxonomic turnover to the south of the Malabar deepwater ocean outfall suggested a gradient of change in community structure from north to south, with gradual change in community structure across locations evident, rather than a strong pattern of change south of the Malabar outfall. This conclusion is the same as that reached after examination of taxonomic turnover by Besley and Birch (2019c) on the 2002 to 2016 assessment year data.

The yearly collection (2000 to 2020) from the Malabar deepwater ocean outfall location of benthic infauna along with grain size measurements provided 21 years of data for the comparison of community structure and fine sediment at the Malabar outfall location. This comparison returned a moderate correlation with a pattern of temporal fluctuation in community composition as the percentage of fines varied by year. This suggested the design of the near field dilution and dispersion from the diffuser array was sufficient to avoid accumulation of chemicals of concern. This conclusion supports other global studies (Roberts et al., 2010), which demonstrate that properly designed outfalls do not cause significant ecological impacts.

The Ocean Sediment Program has provided over 20 years of data to examine possible long-term accumulative effects in this 2020 assessment report. The weight-of-evidence provided by this study suggests accumulation of contaminants in offshore ambient sediments has not increased and that the risk of adverse biological effects have not increased beyond pre-commissioning concentrations. Evidence from analyses of companion infauna data suggest that the three Sydney deepwater ocean outfalls have not caused significant ecological impact.

9 Appendices

9.1 Appendix A Coordinates for grid centre locations

Location	Easting (grid centre)	Northing (grid centre)	Easting (converted to represent 0 co-ord, x value)	Northing (converted to represent 0 co-ord, y value)	Random number - x co-ord (0-5)	Random number - y co-ord (0-5)	Grid Easting	Grid Northing
Long Reef 1								
Site 1C	349791.41	6266903.05	349666.4	6266778	3	1	349805.2	6266821
Site 2C	349791.41	6266903.05	349666.4	6266778	4	1	349853.6	6266804
Site 3C	349791.41	6266903.05	349666.4	6266778	3	3	349796.3	6266921
Site 4C	349791.41	6266903.05	349666.4	6266778	2	5	349756.5	6267011
Site 5C	349791.41	6266903.05	349666.4	6266778	5	0	349899.6	6266782
Long Reef 2								
Site 1C	349315.23	6264892.5	349190.2	6264768	3	4	349326.1	6264950
Site 2C	349315.23	6264892.5	349190.2	6264768	3	4	349361.2	6264987
Site 3C	349315.23	6264892.5	349190.2	6264768	0	2	349210.0	6264847
Site 4C	349315.23	6264892.5	349190.2	6264768	4	1	349380.1	6264797
Site 5C	349315.23	6264892.5	349190.2	6264768	1	2	349239.8	6264859
North Head 1								
Site 1C	347436.95	6257934.94	347312	6257810	1	3	347375.0	6257950
Site 2C	347436.95	6257934.94	347312	6257810	3	2	347474.0	6257935
Site 3C	347436.95	6257934.94	347312	6257810	1	0	347351.4	6257835
Site 4C	347436.95	6257934.94	347312	6257810	3	2	347441.8	6257898
Site 5C	347436.95	6257934.94	347312	6257810	4	4	347491.7	6258026
North Head 2								
Site 1C	347463.41	6256056.66	347338.4	6255932	3	4	347512.1	6256113
Site 2C	347463.41	6256056.66	347338.4	6255932	3	3	347508.7	6256064
Site 3C	347463.41	6256056.66	347338.4	6255932	2	2	347454.8	6256027

Location	Easting (grid centre)	Northing (grid centre)	Easting (converted to represent 0 co-ord, x value)	Northing (converted to represent 0 co-ord, y value)	Random number - x co-ord (0-5)	Random number - y co-ord (0-5)	Grid Easting	Grid Northing
Site 4C	347463.41	6256056.66	347338.4	6255932	5	0	347568.1	6255936
Site 5C	347463.41	6256056.66	347338.4	6255932	4	2	347561.2	6256039
Bondi 1								
Site 1C	343415.85	6248226.1	343290.9	6248101	5	3	343531.8	6248265
Site 2C	343415.85	6248226.1	343290.9	6248101	1	2	343352.5	6248193
Site 3C	343415.85	6248226.1	343290.9	6248101	2	1	343409.7	6248128
Site 4C	343415.85	6248226.1	343290.9	6248101	4	0	343475.3	6248115
Site 5C	343415.85	6248226.1	343290.9	6248101	5	4	343535.9	6248296
Bondi 2								
Site 1C	344024.31	6250792.2	343899.3	6250667	0	4	343901.5	6250852
Site 2C	344024.31	6250792.2	343899.3	6250667	3	1	344068.4	6250711
Site 3C	344024.31	6250792.2	343899.3	6250667	4	4	344112.1	6250869
Site 4C	344024.31	6250792.2	343899.3	6250667	3	1	344035.3	6250732
Site 5C	344024.31	6250792.2	343899.3	6250667	1	4	343973.3	6250880
Malabar (0 km) 1								
Site 1C	342807.4	6238966.99	342682.4	6238842	3	5	342808.4	6239075
Site 2C	342807.4	6238966.99	342682.4	6238842	1	2	342754.5	6238926
Site 3C	342807.4	6238966.99	342682.4	6238842	1	4	342720.7	6239048
Site 4C	342807.4	6238966.99	342682.4	6238842	4	4	342877.1	6239024
Site 5C	342807.4	6238966.99	342682.4	6238842	3	2	342849.6	6238930
Site 1A	342807.4	6238966.99	342682.4	6238842	4	1	342861.8	6238894
Site 2A	342807.4	6238966.99	342682.4	6238842	1	1	342707.5	6238907
Site 3A	342807.4	6238966.99	342682.4	6238842	1	2	342709.0	6238957
Site 4A	342807.4	6238966.99	342682.4	6238842	1	5	342723.9	6239069

Location	Easting (grid centre)	Northing (grid centre)	Easting (converted to represent 0 co-ord, x value)	Northing (converted to represent 0 co-ord, y value)	Random number - x co-ord (0-5)	Random number - y co-ord (0-5)	Grid Easting	Grid Northing
Site 5A	342807.4	6238966.99	342682.4	6238842	5	4	342931.2	6239018
Malabar (0 km) 2								
Site 1C	343468.76	6239125.72	343343.8	6239001	1	2	343409.0	6239103
Site 2C	343468.76	6239125.72	343343.8	6239001	2	5	343452.5	6239226
Site 3C	343468.76	6239125.72	343343.8	6239001	4	4	343528.6	6239205
Site 4C	343468.76	6239125.72	343343.8	6239001	0	5	343347.3	6239250
Site 5C	343468.76	6239125.72	343343.8	6239001	2	4	343419.1	6239215
Site 1A	343468.76	6239125.72	343343.8	6239001	3	3	343506.4	6239137
Site 2A	343468.76	6239125.72	343343.8	6239001	1	5	343410.4	6239237
Site 3A	343468.76	6239125.72	343343.8	6239001	2	0	343438.4	6239004
Site 4A	343468.76	6239125.72	343343.8	6239001	4	5	343529.1	6239246
Site 5A	343468.76	6239125.72	343343.8	6239001	4	1	343519.6	6239064
Malabar (3 km) 1								
Site 1C	341378.85	6236506.71	341253.9	6236382	3	5	341393.7	6236615
Site 2C	341378.85	6236506.71	341253.9	6236382	4	2	341442.7	6236494
Site 3C	341378.85	6236506.71	341253.9	6236382	1	0	341286.7	6236392
Site 4C	341378.85	6236506.71	341253.9	6236382	0	0	341275.1	6236386
Site 5C	341378.85	6236506.71	341253.9	6236382	0	1	341254.1	6236421
Malabar (3 km) 2								
Site 1C	341590.48	6236612.53	341465.5	6236488	2	3	341586.7	6236620
Site 2C	341590.48	6236612.53	341465.5	6236488	5	4	341694.3	6236674
Site 3C	341590.48	6236612.53	341465.5	6236488	5	4	341706.4	6236706
Site 4C	341590.48	6236612.53	341465.5	6236488	1	1	341533.9	6236552
Site 5C	341590.48	6236612.53	341465.5	6236488	1	1	341498.4	6236513

Location	Easting (grid centre)	Northing (grid centre)	Easting (converted to represent 0 co-ord, x value)	Northing (converted to represent 0 co-ord, y value)	Random number - x co-ord (0-5)	Random number - y co-ord (0-5)	Grid Easting	Grid Northing
Malabar (5 km) 1								
Site 1C	340638.12	6234628.44	340513.1	6234503	1	1	340538.2	6234568
Site 2C	340638.12	6234628.44	340513.1	6234503	1	2	340539.8	6234619
Site 3C	340638.12	6234628.44	340513.1	6234503	1	5	340554.6	6234731
Site 4C	340638.12	6234628.44	340513.1	6234503	5	4	340761.9	6234680
Site 5C	340638.12	6234628.44	340513.1	6234503	4	0	340704.1	6234521
Malabar (5 km) 2								
Site 1C	340902.67	6234469.71	340777.7	6234345	1	5	340844.3	6234581
Site 2C	340902.67	6234469.71	340777.7	6234345	2	0	340872.3	6234348
Site 3C	340902.67	6234469.71	340777.7	6234345	4	5	340963.0	6234590
Site 4C	340902.67	6234469.71	340777.7	6234345	4	1	340953.5	6234408
Site 5C	340902.67	6234469.71	340777.7	6234345	1	3	340836.5	6234517
Malabar (7 km) 1								
Site 1C	339527.03	6233041.16	339402	6232916	2	4	339504.9	6233119
Site 2C	339527.03	6233041.16	339402	6232916	0	5	339408.7	6233149
Site 3C	339527.03	6233041.16	339402	6232916	5	2	339635.3	6233034
Site 4C	339527.03	6233041.16	339402	6232916	3	1	339555.3	6232950
Site 5C	339527.03	6233041.16	339402	6232916	3	2	339563.3	6233034
Malabar (7 km) 2								
Site 1C	339394.75	6232723.7	339269.8	6232599	2	5	339383.6	6232830
Site 2C	339394.75	6232723.7	339269.8	6232599	2	3	339389.3	6232757
Site 3C	339394.75	6232723.7	339269.8	6232599	1	0	339298.9	6232622
Site 4C	339394.75	6232723.7	339269.8	6232599	4	5	339493.6	6232848
Site 5C	339394.75	6232723.7	339269.8	6232599	5	1	339514.1	6232634
Port Hacking 1								

Location	Easting (grid centre)	Northing (grid centre)	Easting (converted to represent 0 co-ord, x value)	Northing (converted to represent 0 co-ord, y value)	Random number - x co-ord (0-5)	Random number - y co-ord (0-5)	Grid Easting	Grid Northing
Site 1C	336749.29	6228649.7	336624.3	6228525	1	4	336664.0	6228715
Site 2C	336749.29	6228649.7	336624.3	6228525	1	1	336671.0	6228587
Site 3C	336749.29	6228649.7	336624.3	6228525	2	4	336710.3	6228710
Site 4C	336749.29	6228649.7	336624.3	6228525	3	4	336759.7	6228714
Site 5C	336749.29	6228649.7	336624.3	6228525	1	2	336655.7	6228639
Port Hacking 2								
Site 1C	336749.29	6228411.6	336624.3	6228287	2	1	336700.5	6228361
Site 2C	336749.29	6228411.6	336624.3	6228287	0	1	336642.4	6228329
Site 3C	336749.29	6228411.6	336624.3	6228287	3	5	336764.6	6228521
Site 4C	336749.29	6228411.6	336624.3	6228287	2	2	336705.3	6228399
Site 5C	336749.29	6228411.6	336624.3	6228287	2	1	336738.3	6228360
Marley 1								
Site 1C	331643.55	6221348.22	331518.6	6221223	3	0	331647.3	6221239
Site 2C	331643.55	6221348.22	331518.6	6221223	3	1	331664.3	6221288
Site 3C	331643.55	6221348.22	331518.6	6221223	2	1	331632.9	6221267
Site 4C	331643.55	6221348.22	331518.6	6221223	1	3	331566.9	6221381
Site 5C	331643.55	6221348.22	331518.6	6221223	4	3	331694.3	6221383
Marley 2								
Site 1C	331722.92	6221163.04	331597.9	6221038	4	4	331815.0	6221247
Site 2C	331722.92	6221163.04	331597.9	6221038	4	4	331794.1	6221255
Site 3C	331722.92	6221163.04	331597.9	6221038	3	2	331746.9	6221143
Site 4C	331722.92	6221163.04	331597.9	6221038	3	3	331749.1	6221209
Site 5C	331722.92	6221163.04	331597.9	6221038	2	0	331694.2	6221063

9.2 Appendix B Wastewater quality comparison with available water quality guideline values

Table 9-1 Comparison of modelled chemical concentrations near the deepwater ocean outfalls for (financial years) to ANZECC (2000) guideline values for North Head

North Head		Chemical concentration (µg/L)							
		cadmium	chromium	Copper	mercury	lead	zinc	endosulphan	chlorpyrifos
Guideline 95th %ile for protection of marine species		5.5	27.4	1.3	0.4	4.4	15	0.01	0.009
2019-20 undiluted wastewater average value		<0.1	5.4	132	0.03	2.6	129	<0.01	<0.05
Dilution exceeded 98% of time	78:1	0.001	0.07	1.7	0.0004	0.03	1.7	0.0001	0.0006
Dilution exceeded 10% of time	649:1	0.0002	0.008	0.2	0.00005	0.004	0.2	0.00002	0.00008
2018-19 undiluted wastewater average value		0.1	6.3	135	0.04	2.5	114	<0.01	<0.05
Dilution exceeded 98% of time	69:1	0.002	0.09	1.9	0.0006	0.04	1.6	0.0001	0.0007
Dilution exceeded 10% of time	685:1	0.0002	0.009	0.2	0.00006	0.004	0.2	0.00001	0.00007
2017-18 undiluted wastewater average value		0.1	7.4	123	0.05	3.0	115	<0.01	<0.05
Dilution exceeded 98% of time	92:1	0.001	0.08	1.3	0.0005	0.03	1.3	0.0001	0.0005
Dilution exceeded 10% of time	1245:1	0.00008	0.006	0.1	0.00004	0.002	0.1	0.00001	0.00004
2016-17 undiluted wastewater average value		0.1	5.3	111	0.05	2.8	109	<0.01	<0.05
Dilution exceeded 98% of time	68:1	0.002	0.1	1.6	0.0007	0.040	1.6	0.0001	0.0007
Dilution exceeded 10% of time	712:1	0.0002	0.007	0.2	0.00007	0.004	0.2	0.00001	0.00007
2015-16 undiluted wastewater average value		0.2	8.8	111	0.04	2.9	102	<0.01	<0.05
Dilution exceeded 98% of time	71:1	0.002	0.1	1.6	0.0006	0.04	1.4	0.0001	0.0007
Dilution exceeded 10% of time	421:1	0.0004	0.02	0.3	0.0001	0.007	0.2	0.00002	0.0001
2014-15 undiluted wastewater average value		0.2	6.3	138	0.1	3.5	127	<0.01	<0.05
Dilution exceeded 98% of time	85:1	0.002	0.07	1.6	0.001	0.04	1.5	0.0001	0.0006
Dilution exceeded 10% of time	873:1	0.0002	0.007	0.2	0.0001	0.004	0.15	0.00001	0.00006

North Head		Chemical concentration (µg/L)							
		cadmium	chromium	Copper	mercury	lead	zinc	endosulphan	chlorpyrifos
Guideline 95th %ile for protection of marine species		5.5	27.4	1.3	0.4	4.4	15	0.01	0.009
2013-14 undiluted wastewater average value		0.2	3.8	104	0.2	2.6	109	<0.01	<0.05
Dilution exceeded 98% of time	72:1	0.003	0.05	1.4	0.003	0.04	1.5	0.0001	0.0007
Dilution exceeded 10% of time	690:1	0.0003	0.01	0.2	0.0004	0.004	0.16	0.00001	0.00007
2012-13 undiluted wastewater average value		0.2	6.3	101	0.08	3.7	115	<0.01	<0.05
Dilution exceeded 98% of time	84:1	0.002	0.08	1.2	0.001	0.04	1.4	0.0001	0.0006
Dilution exceeded 10% of time	713:1	0.0004	0.01	0.1	0.0001	0.005	0.2	0.00001	0.0001
2011-12 undiluted wastewater average value		0.4	4.1	79	0.09	3.6	109	<0.01	<0.05
Dilution exceeded 98% of time	81:1	0.005	0.05	1.0	0.001	0.04	1.3	0.0001	0.0006
Dilution exceeded 10% of time	818:1	0.0005	0.005	0.1	0.0001	0.004	0.1	0.00001	0.00006
2010-11 undiluted wastewater average value		0.4	5.3	96	0.2	3.6	130	<0.01	<0.05
Dilution exceeded 98% of time	73:1	0.006	0.07	1.3	0.003	0.05	1.8	0.0001	0.0007
Dilution exceeded 10% of time	595:1	0.0006	0.009	0.2	0.0003	0.006	0.2	0.00002	0.00008
2009-10 undiluted wastewater average value		0.4	6.2	99	0.2	4.6	122	<0.01	<0.05
Dilution exceeded 98% of time	68:1	0.006	0.09	1.4	0.003	0.07	1.8	0.0001	0.0007
Dilution exceeded 10% of time	798:1	0.0005	0.008	0.1	0.0003	0.006	0.2	0.00001	0.00006
2008-09 undiluted wastewater average value		0.4	5.8	96	0.1	4.9	121	<0.01	<0.05
Dilution exceeded 98% of time	82:1	0.005	0.07	1.2	0.001	0.06	1.5	0.0001	0.0006
Dilution exceeded 10% of time	774:1	0.0005	0.007	0.1	0.0001	0.006	0.2	0.00001	0.00006

Table 9-2 Comparison of modelled chemical concentrations near the deepwater ocean outfalls for (financial years) to ANZECC (2000) guideline values for Bondi

Bondi		Chemical concentration (µg/L)							
		cadmium	chromium	Copper	mercury	lead	zinc	endosulphan	chlorpyrifos
Guideline 95th %ile for protection of marine species		5.5	27.4	1.3	0.4	4.4	15	0.01	0.009
2019-20 undiluted wastewater average value		<0.1	1.6	118	0.02	2.9	101	<0.01	<0.05
Dilution exceeded 98% of time	105:1	0.001	0.02	1.1	0.0002	0.03	1.0	0.0001	0.0005
Dilution exceeded 10% of time	978:1	0.0001	0.002	0.1	0.00002	0.003	0.1	0.00001	0.00005
2018-19 undiluted wastewater average value		0.1	1.58	152	0.03	3.0	113	<0.01	<0.05
Dilution exceeded 98% of time	93:1	0.001	0.02	1.6	0.0004	0.03	1.2	0.0001	0.0005
Dilution exceeded 10% of time	1007:1	0.0001	0.002	0.2	0.00003	0.003	0.1	0.00001	0.00005
2017-18 undiluted wastewater average value		0.1	1.83	148	0.05	3.98	109	<0.01	<0.05
Dilution exceeded 98% of time	114:1	0.0009	0.02	1.3	0.0004	0.03	1.0	0.0001	0.0004
Dilution exceeded 10% of time	1711:1	0.00006	0.001	0.1	0.00003	0.002	0.06	0.00001	0.00003
2016-17 undiluted wastewater average value		<0.1	2.4	130	0.04	3.1	105	<0.01	<0.05
Dilution exceeded 98% of time	89:1	0.001	0.03	1.5	0.0004	0.03	1.2	0.0001	0.001
Dilution exceeded 10% of time	1018:1	0.0001	0.002	0.1	0.00004	0.003	0.1	0.00001	0.00005
2015-16 undiluted wastewater average value		0.1	2.3	152	0.03	4.1	108	<0.01	<0.05
Dilution exceeded 98% of time	92:1	0.001	0.02	1.6	0.0004	0.04	1.2	0.0001	0.0005
Dilution exceeded 10% of time	623:1	0.0002	0.004	0.2	0.00005	0.007	0.2	0.00002	0.00008
2014-15 undiluted wastewater average value		0.2	1.5	121	0.1	3.6	108	<0.01	<0.05
Dilution exceeded 98% of time	111:1	0.001	0.01	1.1	0.001	0.03	1.0	0.00009	0.0005
Dilution exceeded 10% of time	1522:1	0.0001	0.001	0.08	0.00007	0.002	0.07	0.000007	0.00003
2013-14 undiluted wastewater average value		0.1	1.1	120	0.07	3.6	106	<0.01	<0.05
Dilution exceeded 98% of time	89:1	0.001	0.01	1.3	0.001	0.04	1.2	0.0001	0.0006
Dilution exceeded 10% of time	943:1	0.0001	0.001	0.1	0.0001	0.004	0.1	0.00001	0.00005

Bondi		Chemical concentration (µg/L)							
		cadmium	chromium	Copper	mercury	lead	zinc	endosulphan	chlorpyrifos
Guideline 95th %ile for protection of marine species		5.5	27.4	1.3	0.4	4.4	15	0.01	0.009
2012-13 undiluted wastewater average value		0.3	2.3	125	0.09	5.4	123	<0.01	<0.05
Dilution exceeded 98% of time	102:1	0.003	0.02	1.2	0.001	0.05	1.2	0.0001	0.0005
Dilution exceeded 10% of time	1033:1	0.0003	0.002	0.1	0.0001	0.005	0.1	0.00001	0.0001
2011-12 undiluted wastewater average value		0.2	1.6	110	0.06	5.1	102	<0.01	<0.05
Dilution exceeded 98% of time	104:1	0.002	0.02	1.1	0.001	0.05	1.0	0.0001	0.0005
Dilution exceeded 10% of time	1353:1	0.0001	0.001	0.08	0.00004	0.004	0.08	0.00001	0.00004
2010-11 undiluted wastewater average value		0.1	1.8	113	<0.1	3.5	104	<0.01	<0.05
Dilution exceeded 98% of time	93:1	0.001	0.02	1.2	0.001	0.04	1.1	0.0001	0.0005
Dilution exceeded 10% of time	917:1	0.0001	0.002	0.1	0.0001	0.004	0.1	0.00001	0.00005
2009-10 undiluted wastewater average value		0.2	1.8	110	<0.1	4.4	102	<0.01	<0.05
Dilution exceeded 98% of time	86:1	0.002	0.02	1.3	0.001	0.05	1.2	0.0001	0.0006
Dilution exceeded 10% of time	1233:1	0.0002	0.001	0.1	0.00008	0.004	0.08	0.000008	0.00004
2008-09 undiluted wastewater average value		0.1	2.3	118	<0.1	4.7	106	<0.01	<0.05
Dilution exceeded 98% of time	108:1	0.001	0.02	1.1	0.001	0.04	1.0	0.0001	0.0005
Dilution exceeded 10% of time	1271:1	0.00008	0.002	0.09	0.00008	0.004	0.08	0.000008	0.00004

Table 9-3 Comparison of modelled chemical concentrations near the deepwater ocean outfalls for (financial years) to ANZECC (2000) guideline values for Malabar

Malabar		Chemical concentration (µg/L)							
		cadmium	chromium	copper	mercury	lead	zinc	endosulphan	Chlorpyrifos
Guideline 95th %ile for protection of marine species		5.5	27.4	1.3	0.4	4.4	15	0.01	0.009
2019-20 undiluted wastewater average value		0.2	7.4	100	0.02	3.6	116	<0.01	<0.05
Dilution exceeded 98% of time	70	0.003	0.11	1.4	0.0003	0.05	1.7	0.0001	0.0007
Dilution exceeded 10% of time	426	0.0005	0.017	0.2	0.00005	0.008	0.3	0.00002	0.00012
2018-19 undiluted wastewater average value		0.1	9.1	98	0.2	2.7	99	<0.01	<0.05
Dilution exceeded 98% of time	64:1	0.002	0.1	1.5	0.003	0.04	1.6	0.0002	0.0008
Dilution exceeded 10% of time	470:1	0.0002	0.02	0.2	0.0003	0.006	0.2	0.00002	0.0001
2017-18 undiluted wastewater average value		0.2	9.0	105	0.05	3.9	111	<0.01	<0.05
Dilution exceeded 98% of time	68:1	0.003	0.1	1.5	0.0007	0.06	1.6	0.0001	0.0007
Dilution exceeded 10% of time	824:1	0.0002	0.01	0.1	0.00006	0.005	0.1	0.00001	0.00006
2016-17 undiluted wastewater average value		0.3	8.1	103	0.04	4.0	118	<0.01	0.124
Dilution exceeded 98% of time	56:1	0.004	0.1	1.8	0.0008	0.07	2.1	0.0002	0.002
Dilution exceeded 10% of time	515:1	0.0005	0.02	0.2	0.0001	0.008	0.2	0.00002	0.0002
2015-16 undiluted wastewater average value		0.2	6.8	91	0.13	4.8	92	<0.01	<0.05
Dilution exceeded 98% of time	55:1	0.004	0.1	1.7	0.002	0.09	1.7	0.0002	0.0009
Dilution exceeded 10% of time	244:1	0.0009	0.03	0.4	0.0005	0.02	0.4	0.00004	0.0002
2014-15 undiluted wastewater average value		0.1	6.5	78	0.03	3.3	94	<0.01	<0.05
Dilution exceeded 98% of time	70:1	0.002	0.09	1.1	0.0004	0.05	1.3	0.0001	0.0007
Dilution exceeded 10% of time	665:1	0.0002	0.01	0.1	0.00005	0.005	0.1	0.00002	0.00008
2013-14 undiluted wastewater average value		0.2	9.3	80	0.05	3.3	102	<0.01	<0.05
Dilution exceeded 98% of time	56:1	0.004	0.17	1.4	0.001	0.06	1.8	0.0002	0.0009
Dilution exceeded 10% of time	478:1	0.0004	0.02	0.2	0.0001	0.01	0.2	0.00002	0.0001

Malabar		Chemical concentration (µg/L)							
		cadmium	chromium	copper	mercury	lead	zinc	endosulphan	Chlorpyrifos
Guideline 95th %ile for protection of marine species		5.5	27.4	1.3	0.4	4.4	15	0.01	0.009
2012-13 undiluted wastewater average value		0.2	6.0	74	0.07	4.3	97	<0.01	<0.05
Dilution exceeded 98% of time	65:1	0.003	0.09	1.1	0.001	0.07	1.5	0.0002	0.0008
Dilution exceeded 10% of time	507:1	0.0003	0.01	0.1	0.0001	0.01	0.2	0.00002	0.0001
2011-12 undiluted wastewater average value		0.2	7.8	74	0.06	4.2	107	<0.01	<0.05
Dilution exceeded 98% of time	68:1	0.003	0.11	1.1	0.001	0.06	1.6	0.0001	0.0007
Dilution exceeded 10% of time	578:1	0.0003	0.01	0.1	0.0001	0.007	0.2	0.00002	0.00009
2010-11 undiluted wastewater average value		0.1	7.8	59	<0.1	2.7	86	<0.01	<0.05
Dilution exceeded 98% of time	55:1	0.002	0.14	1.1	0.002	0.05	1.6	0.0002	0.0009
Dilution exceeded 10% of time	448:1	0.0002	0.02	0.1	0.0002	0.006	0.2	0.00002	0.0001
2009-10 undiluted wastewater average value		0.3	10.2	67	<0.1	13.3	86	<0.01	<0.05
Dilution exceeded 98% of time	55:1	0.005	0.19	1.2	0.002	0.24	1.6	0.0002	0.0009
Dilution exceeded 10% of time	551:1	0.0005	0.02	0.1	0.0002	0.02	0.2	0.00002	0.00009
2008-09 undiluted wastewater average value		0.2	7.0	68	<0.1	4.1	90	<0.01	<0.05
Dilution exceeded 98% of time	67:1	0.003	0.10	1.0	0.001	0.06	1.3	0.0001	0.0007
Dilution exceeded 10% of time	550:1	0.0004	0.01	0.1	0.0002	0.007	0.2	0.00002	0.00009

9.3 Appendix C Comparison of ocean sediment program sediment quality data of each assessment year with available sediment quality guideline values

N/A = no level set to date

Results that exceed ANZECC (2000) low level thresholds but below upper level thresholds are shaded grey

Results that exceed ANZECC (2000) upper level thresholds are shaded blue

Revised guidelines were introduced for silver, total PAHs, total PCBs and Organochlorine pesticides (Simpson and Batley, 2016)

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		Long Reef							
		2002	2005	2008	2011	2014	2016	2020	
TOC	%	0.08-4.41	0.09-1.92	0.07-0.36	0.1-0.52	0.11-0.6	0.08-0.38	0.05-1.41	N/A
metals									
aluminium	mg/kg	1660-3450	2270-5290	865-1770	1320-3750	1150-2280	1290-2520	1100-4300	N/A
cadmium	mg/kg	0.04-0.20	0.03-0.19	0.03-0.08	0.03-0.12	0.02-0.05	0.03-0.1	0.02-0.18	1.5-10
chromium	mg/kg	7.34-18.0	12.2-22.2	9.71-17.1	11.9-17.2	8.89-14.2	8.1-19.5	6.3-18.0	80-370
copper	mg/kg	1.10-3.92	1.6-4.8	0.81-3.09	1.28-4.47	1.24-3.27	1.48-3.74	0.9-5.0	65-270
iron	mg/kg	4330-13100	7000-12200	5020-9060	6720-11000	5010-8520	4870-15600	4000-13000	N/A
lead	mg/kg	3.60-9.96	4.97-11.5	2.53-7.62	5.19-11.3	3.34-9.5	3.44-8.74	1.8-12.0	50-220
mercury	mg/kg	0.03-0.18	0.04-0.11	0.02-0.09	0.02-0.13	0.03-0.41	0.03-0.12	0.02-0.16	0.15-1.0
nickel	mg/kg	2.59-6.04	3.88-5.75	2.27-4.26	2.83-5.34	2.12-5.35	2.32-5.85	1.8-5.9	21-52
selenium	mg/kg	0.01-0.11	0.07-0.18	0.03-0.07	0.08-0.18	0.06-0.13	0.04-0.12	0.04-0.22	N/A
silver	mg/kg	0.02-0.06	0.01-0.07	0.01-0.03	0.02-0.05	0.01-0.02	0.01-0.03	0.01-0.05	1.0-4.0 (prev. 1-3.7)
zinc	mg/kg	8.4-20.0	9.9-21.3	6.40-16.4	11.4-22.0	8.7-18.6	9.7-19.7	5.3-23.0	200-410
metalloid									
arsenic	mg/kg	5.74-22.7	5.06-27.6	4.22-17.3	4.91-16.5	4.06-7.49	5.21-24.8	4.6-23.0	20-70
organics									
naphthalene	µg/kg	<10-25	<10-24	<10	<10-66	<5	<5	<5	160-2100
M-cresol	µg/kg	<10	<10	<10	<10-20	<10	<10	<10	N/A
others									
mud	%	0.86-2.93	1.8-5.8	1.42-3.13	1.86 – 4.92	1.61-4.58	1.43-2.97	1.6-6.7	N/A
sand	%	58.2-98.5	89.9-98.2	66.6-97.2	76.0 – 96.8	82.2-98	61.05-97.9	60-95.5	N/A
gravel	%	0.00-41.0	<0.1-7.1	0.71-27.9	0.00 – 19.8	0.15-14.7	<0.1-37.3	0.25-34.8	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		North Head							
		2002	2005	2008	2011	2014	2016	2020	
TOC	%	0.20-1.88	0.1-0.39	0.19-0.59	0.11-3.49	0.23-0.59	0.09-0.43	0.2-0.76	N/A
metals									
aluminium	mg/kg	2750-5150	2010-4430	1800-3320	2480-3690	2280-3710	2010-3560	2100-4400	N/A
cadmium	mg/kg	0.10-0.19	0.05-0.11	0.08-0.13	0.07-0.15	0.08-0.13	0.06-0.13	0.07-0.12	1.5-10
chromium	mg/kg	15.2-33.2	16.7-28.6	13.2-22.7	17.5-34.5	14.7-29.3	14.1-34.5	13.0-36.0	80-370
copper	mg/kg	2.89-4.64	2.43-5.59	2.63-5.69	2.93-6.90	2.81-7.07	2.19-6.07	2.3-7.1	65-270
iron	mg/kg	10400-23700	10500-18900	10100-17300	10800-20200	10400-22600	10500-25900	9900-30000	N/A
lead	mg/kg	11.6-22.3	8.09-24.3	8.06-13.3	9.33-17.3	9.52-18.8	8.56-13.8	6.7-18.0	50-220
mercury	mg/kg	0.07-0.93	0.03-0.21	0.05-0.24	0.05-0.17	0.08-3.65	0.04-0.43	0.06-0.48	0.15-1.0
nickel	mg/kg	5.92-9.73	3.83-8.04	3.34-6.50	4.56-8.01	4.28-7.81	3.53-9.33	3.4-9.6	21-52
selenium	mg/kg	0.03-0.06	0.27-0.53	0.06-0.15	0.13-0.27	0.11-0.24	0.1-0.18	0.08-0.23	N/A
silver	mg/kg	0.03-0.09	0.02-0.07	0.02-0.08	0.03-0.07	0.02-0.05	0.02-0.05	0.01-0.04	1.0-4.0 (prev. 1-3.7)
zinc	mg/kg	15.5-25.4	14.5-50.5	15.3-26.0	18.6-28.7	17.4-28.8	17.6-29.8	15-31	200-410
metalloid									
arsenic	mg/kg	10.0-57.4	12.8-32.9	5.87-32.2	6.47-38.7	10.6-43.2	9.07-57.7	9.6-59	20-70
organics									
total PAHs	µg/kg	101-28000	231-2740	389-2680	75-2290	944-2490	64-3640	46-3030	10,000-50,000 (prev. 4000-45000)
acenaphthene	µg/kg	<10-115	<10	<10-10	<10	<10	<10	<10	16-500
acenaphthylene	µg/kg	<10-200	<10	<10-41	<10-31	<10-87	<10-43	<10-48	44-640
anthracene	µg/kg	<10-1000	<10-23	<10-79	<10-37	<10-50	<10-68	<10-74	85-1100
benzo(a)anthracene	µg/kg	13-2360	23-323	39-304	13-156	132-258	<10-331	11-315	261-1600
benzo(a)pyrene	µg/kg	14-2380	<10-293	58-343	13-226	111-291	<10-320	<10-233	430-1600
benzo(b)fluoranthene	µg/kg	10-1880	18-187	38-196	14-218	120-321	19-652	12-290	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		North Head							
		2002	2005	2008	2011	2014	2016	2020	
benzo(e)pyrene	µg/kg	<10-1230	23-153	<10-200	<10-109	46-145	<10-82	<10-136	N/A
benzo(ghi)perylene	µg/kg	<10-656	<10-58	29-172	<10-227	32-111	<10-178	<10-122	N/A
benzo(k)fluoranthene	µg/kg	10-1710	15-203	23-116	<10-99	28-89	<10-130	<10-67	N/A
chrysene	µg/kg	13-2190	24-329	<10-307	<10-155	46-127	<10-229	<10-165	384-2800
dibenzo(a,h)anthracene	µg/kg	<10-463	<10-28	<10-51	<10-12	<10-33	<10-30	<10-16	63-260
fluoranthene	µg/kg	19-4280	43-367	55-444	18-273	131-301	16-515	12-528	600-5100
fluorene	µg/kg	<10-176	<10	<10-24	<10-15	<10-14	<10-18	<10-43	19-540
indeno-123-CD-pyrene	µg/kg	<10-2140	13-136	27-166	<10-263	92-236	<10-234	<10-193	N/A
naphthalene	µg/kg	<10-19	<10-17	<10-17	<10-23	<10-30	<10-17	<10-26	160-2100
perylene	µg/kg	<10-510	<10-48	14-79	<10-69	18-52	<10-74	<10-59	N/A
phenanthrene	µg/kg	<10-2650	20-122	18-219	<10-136	23-135	13-202	<10-266	240-1500
pyrene	µg/kg	22-4280	41-564	88-479	17-260	126-303	16-525	11-457	665-2600
coronene	µg/kg	<10	<10	<10-29	<10-73	39-140	<10-13	30-696	N/A
M-cresol	µg/kg	<10	<10	<10	<10-10	<10	<10	<10-50	N/A
O-cresol	µg/kg	<10	<10	<10	<10	<10	<10	<10-70	N/A
2-Chlorophenol	µg/kg	<10	<10	<10	<10	<10	<10	<10	N/A
total PCBs	µg/kg	<10	<25	<25	<25	<25	<25	<25	34-280 (prev. 23- -)
Organochlorine Pesticides	µg/kg	All <0.5	All <0.5	All <0.5	All <0.5	All <0.5	All <0.5	All <0.5	0.09-60 (prev. 0.02-46)
others									
mud	%	1.09-3.19	1.4-3	1.71-9.60	1.91 – 6.67	2.27-4.67	1.25-5.86	2.32-10.8	N/A
sand	%	74.3-96.4	54.8-98.3	75.2-95.8	81.9 – 96.3	79.3-97.5	66.7-96.1	73.8-97.4	N/A
gravel	%	1.48-24.1	<0.1-43	0.48-15.2	0.62 – 13.2	0.21-17.6	1.33-30.2	0.33-22.2	N/A
TKN	mg/kg	292-556	251-429	312-650	279-524	298-527	223-433	214-605	N/A
phosphorus	mg/kg	617-1200	492-1110	432-785	523-945	468-1070	536-1180	510-1300	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		Bondi							
		2002	2005	2008	2011	2014	2016	2020	
TOC	%	0.07-0.50	0.10-0.46	0.09-0.91	0.18-0.56	0.3-0.46	0.09-0.52	0.12-0.73	N/A
metals									
aluminium	mg/kg	2300-6460	826-5070	803-2480	1400-3140	1770-2690	743-2520	500-4100	N/A
cadmium	mg/kg	0.07-0.11	0.01-0.05	0.03-0.06	0.03-0.07	0.04-0.07	0.03-0.07	0.02-0.06	1.5-10
chromium	mg/kg	8.61-15.8	5.82-17.8	5.95-14.1	8.33-17.2	10.6-13.7	7.74-17.7	4.5-17	80-370
copper	mg/kg	2.39-5.13	1.26-7.25	1.55-4.91	2.96-6.59	3.13-5.1	1.47-6.73	0.73-8.1	65-270
iron	mg/kg	5060-10500	3150-8900	3970-7020	6170-9480	6090-9470	3510-9230	3500-9400	N/A
lead	mg/kg	6.05-14.3	4.9-12.9	4.21-9.27	5.99-12.8	6.53-14.5	2.86-13	5.4-10	50-220
mercury	mg/kg	0.07-1.2	0.03-0.15	0.03-0.10	0.06-0.16	0.06-0.11	0.03-0.25	0.02-0.14	0.15-1.0
nickel	mg/kg	4.13-7.63	1.08-5.44	1.17-4.14	1.88-5.11	2.62-4.26	1.59-5.54	0.71-5.3	21-52
selenium	mg/kg	0.02-0.06	0.11-0.31	0.05-0.10	0.11-0.21	0.09-0.17	0.04-0.27	0.05-0.22	N/A
silver	mg/kg	0.03-0.14	0.02-0.11	0.02-0.05	0.04-0.09	0.03-0.05	0.01-0.24	0.01-0.06	1.0-4.0 (prev. 1-3.7)
zinc	mg/kg	11.4-23.4	7.7-24.4	8.20-19.8	10.4-28.8	16.3-22.8	7.2-28.2	5.3-24	200-410
metalloid									
arsenic	mg/kg	4.26-7.40	3.19-6.81	4.53-6.30	3.52-6.29	5.18-10.8	3.61-7.09	4.5-8.6	20-70
organics									
naphthalene	µg/kg	<10-15	<10-63	<10	<10-20	<5	<5	<5	160-2100
M-cresol	µg/kg	<10	<10	<10	<10-10	<10	<10	<10	N/A
others									
mud	%	1.97-4.28	1.4-4.4	1.65-5.34	3.03–5.59	2.46-8.04	0.64-5.44	2.08-12.4	N/A
sand	%	84.2-97.7	92.2-98.6	87.6-97.9	80.0–96.4	89-97.3	93.5-99.1	86.5-97.1	N/A
gravel	%	0.00-13.1	<0.1-4.3	<0.1-10.7	0.13–16.97	<0.1-2.94	0.18-3.16	0.15-1.49	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		Malabar 0 km							
		2002	2005	2008	2011	2014	2016	2020	
TOC	%	0.08-0.58	0.21-0.6	0.30-0.60	0.21-0.64	0.33-0.66	0.28-1.25	0.28-0.72	N/A
metals									
aluminium	mg/kg	1850-6240	2770-6600	2250-4240	1570-4850	1740-4480	1430-3950	2300-4200	N/A
cadmium	mg/kg	0.02-0.13	<0.01-0.07	0.06-0.10	0.05-0.07	0.03-0.07	0.04-0.07	0.05-0.08	1.5-10
chromium	mg/kg	8.01-15.2	12.3-22.4	9.77-18.8	8.64-19.2	9.8-17.5	7.4-18.8	12-18	80-370
copper	mg/kg	1.05-5.62	2.91-7.39	2.97-7.36	2.65-6.75	2.73-7.46	3.74-9.5	4.1-8.2	65-270
iron	mg/kg	5080-8940	6120-8850	5520-8170	4850-10500	5440-8580	4290-8980	6000-9200	N/A
lead	mg/kg	4.84-10.6	4.9-9.6	4.43-9.14	4.20-9.67	4.12-8.15	4.54-7.62	4.8-7.3	50-220
mercury	mg/kg	0.03-0.14	0.04-0.12	0.05-0.11	0.05-0.12	0.04-0.13	0.05-0.14	0.02-0.08	0.15-1.0
nickel	mg/kg	2.07-7.02	3.74-7.26	3.18-6.80	2.88-7.27	2.81-6.5	2.81-6.49	4-7.1	21-52
selenium	mg/kg	0.02-0.08	0.1-0.27	0.12-0.20	0.13-0.24	0.11-0.33	0.16-0.28	0.24-0.42	N/A
silver	mg/kg	0.02-0.13	0.05-0.14	0.04-0.11	0.03-0.08	0.03-0.09	0.02-0.07	0.03-0.08	1.0-4.0 (prev. 1-3.7)
zinc	mg/kg	9.0-23.2	15.6-28.7	15.5-28.8	14.4-28.0	12.8-27.9	13.3-29.8	19-32	200-410
metalloid									
arsenic	mg/kg	4.23-6.09	4.4-5.32	3.16-4.62	3.07-5.41	4-5.25	4.05-5.46	4.2-6.1	20-70
organics									
total PAHs	µg/kg	<10-269	60-260	31-297	<10-353	97-871	14-658	10-493	10,000-50,000 (prev. 4000-45000)
acenaphthene	µg/kg	<10	<10	<10	<10	<10	<10	<10	16-500
acenaphthylene	µg/kg	<10	<10	<10	<10	<10-14	<10	<10	44-640
anthracene	µg/kg	<10	<10	<10	<10	<10-15	<10	<10-11	85-1100
benzo(a)anthracene	µg/kg	<10-21	<10-24	<10-30	<10-31	18-107	<10-53	<10-70	261-1600
benzo(a)pyrene	µg/kg	<10-22	<10-22	<10-29	<10-35	14-89	<10-47	<10-22	430-1600
benzo(b)fluoranthene	µg/kg	<10-20	<10-21	<10-25	<10-40	14-104	14-123	<10-48	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		Malabar 0 km							
		2002	2005	2008	2011	2014	2016	2020	
benzo(e)pyrene	µg/kg	<10-15	<10-17	<10-20	<10-19	<10-38	<10-15	<10-19	N/A
benzo(ghi)perylene	µg/kg	<10-15	<10	<10-17	<10-19	<10-34	<10-36	<10-14	N/A
benzo(k)fluoranthene	µg/kg	<10-19	<10-14	<10-12	<10-20	<10-25	<10-20	<10	N/A
chrysene	µg/kg	<10-21	<10-25	<10-18	<10-24	<10-36	<10-41	<10-27	384-2800
dibenzo(a,h)anthracene	µg/kg	<10	<10	<10	<10	<10	<10	<10	63-260
fluoranthene	µg/kg	<10-44	<10-38	16-59	<10-52	14-116	<10-113	<10-105	600-5100
fluorene	µg/kg	<10-14	<10	<10	<10	<10	<10	<10	19-540
indeno-123-CD-pyrene	µg/kg	<10-14	<10-17	<10-17	<10-27	12-87	<10-41	<10-17	N/A
naphthalene	µg/kg	<10-15	22-64	<10-27	<10-26	10-38	<10-19	<10-25	160-2100
perylene	µg/kg	<10	<10	<10	<10	<10-15	<10-17	<10	N/A
phenanthrene	µg/kg	<10-24	11-35	<10-31	<10-26	10-52	<10-55	<10-53	240-1500
pyrene	µg/kg	<10-39	<10-42	15-48	<10-44	15-102	<10-85	<10-82	665-2600
coronene	µg/kg	<10	<10	<10	<10	<10-41	<10-11	<10	N/A
M-cresol	µg/kg	<10	<10	<10	<10	<10	<10	<10	N/A
O-cresol	µg/kg	<10	<10	<10	<10	<10	<10	<10	N/A
2-Chlorophenol	µg/kg	<10	<10	<10	<10	<10	<10	<10	N/A
total PCBs	µg/kg	<10	<25	<25	<25	<25	<25	<25	34-280 (prev. 23- -)
Organochlorine Pesticides	µg/kg	All <0.5	All <0.5	All <0.5	All <0.05	All <0.5	All <0.5	All <0.5	0.09-60 (prev. 0.02-46)
others									
mud	%	1.83-10.1	3.5-10.6	2.02-12.6	2.97-9.96	3.4-12.3	3.57-14	3.95-9.08	N/A
sand	%	89.9-98.2	89.4-96.5	87.4-98.0	89.9-96.2	87.2-95.4	85.5-91.6	88.2-94.4	N/A
gravel	%	0	<0.1	<0.1	0.15-1.63	0.48-1.68	0.2-7.54	0.35-2.74	N/A
TKN	mg/kg	168-622	337-756	393-782	283-696	277-1010	272-1020	484-1640	N/A
phosphorus	mg/kg	262-474	260-365	263-355	231-475	269-368	217-386	250-410	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		Malabar 3 km							
		2002	2005	2008	2011	2014	2016	2020	
TOC	%	0.61-0.80	0.37-0.87	0.36-1.00	0.93-0.93	0.64-0.76	0.62-0.76	0.75-0.96	N/A
metals									
aluminium	mg/kg	5400-7580	4050-8170	1340-3430	4680-5740	3800-5810	3240-3730	5300-6600	N/A
cadmium	mg/kg	0.09-0.12	0.03-0.1	0.05-0.17	0.09-0.11	0.08-0.11	0.08-0.1	0.09-0.12	1.5-10
chromium	mg/kg	18.3-21.6	15.3-24.8	9.9-23.0	18.9-21.4	18.2-21.9	18.7-22.3	19-24	80-370
copper	mg/kg	6.28-9.54	5.2-8.82	3.11-9.02	7.48-8.45	6.75-8.41	6.63-8.87	7.9-11	65-270
iron	mg/kg	9040-10300	7300-10300	4530-9160	9760-10900	8990-10800	8680-10100	9800-11000	N/A
lead	mg/kg	11.7-13.6	7.85-12.5	5.27-10.8	9.68-10.7	8.78-11.6	8.08-10.7	9-12	50-220
mercury	mg/kg	0.11-0.18	0.06-0.13	0.11-0.17	0.14-0.17	0.14-0.18	0.13-0.18	0.12-0.14	0.15-1.0
nickel	mg/kg	7.43-10.3	5.42-9.25	3.05-8.15	7.63-8.72	6.87-8.56	7.41-9.3	7.9-9.8	21-52
selenium	mg/kg	0.08-0.14	0.22-0.36	0.09-0.33	0.27-0.33	0.23-0.36	0.33-1.11	0.27-0.32	N/A
silver	mg/kg	0.12-0.20	0.06-0.18	0.05-0.14	0.10-0.12	0.07-0.11	0.07-0.12	0.07-0.1	1.0-4.0 (prev. 1-3.7)
zinc	mg/kg	25.7-36.7	22.1-32.5	12.7-33.0.	31.1-34.5	28.5-35.5	30.2-36.2	28-35	200-410
metalloid									
arsenic	mg/kg	5.75-6.84	4.42-5.89	2.57-3.46	3.30-5.62	4.91-6.4	5.49-6.49	5.2-7.3	20-70
organics									
naphthalene	µg/kg	<10-20	15-36	11-33	18-38	<5	<5	<5	160-2100
M-cresol	µg/kg	<10	<1.0	<10	<10	<10	<10	<10	N/A
others									
mud	%	10.4-13.6	5.5-14.3	4.14-11.8	10.8-13.8	8.41-14.2	6.09-15.8	5.05-15.2	N/A
sand	%	86.4-89.6	85.7-64.5	88.2-95.9	85.3-88.9	85.4-91.4	84.1-93.8	84.3-94.5	N/A
gravel	%	0	<0.1-1.2	<0.1	<0.1-1.27	<0.1-0.58	<0.1-2.4	0.13-0.65	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		Malabar 5 km							
		2002	2005	2008	2011	2014	2016	2020	
TOC	%	0.39-0.71	0.09-0.95	0.36-0.70	0.70-0.92	0.52-0.67	0.39-0.83	0.5-1.85	N/A
metals									
aluminium	mg/kg	4170-7620	1620-7890	1710-2680	4200-4680	2840-5830	2670-5460	3500-5100	N/A
cadmium	mg/kg	0.06-0.12	0.02-0.09	0.05-0.09	0.06-0.07	0.05-0.07	0.05-0.06	0.06-0.08	1.5-10
chromium	mg/kg	14.3-18.4	5.33-22.5	11.5-18.7	16.8-18.2	13.5-18.9	13.8-32.7	15-21	80-370
copper	mg/kg	4.82-6.11	1.32-7.36	4.12-7.08	6.22-7.19	4.86-6.49	4.17-7.01	5-8.6	65-270
iron	mg/kg	6670-8290	2960-9490	4490-7080	8980-9860	6780-9860	6230-9070	7700-9500	N/A
lead	mg/kg	8.81-11.6	3.36-10.6	6.47-9.03	8.52-9.56	6.47-9.5	6.03-8.08	6.4-9.4	50-220
mercury	mg/kg	0.08-0.15	0.03-0.1	0.06-0.13	0.11-0.14	0.11-0.13	0.10-0.15	0.08-0.17	0.15-1.0
nickel	mg/kg	5.95-8.53	1.37-10.8	3.80-6.60	6.60-7.27	4.92-7.29	4.93-9.3	5.7-8.5	21-52
selenium	mg/kg	0.06-0.09	0.07-0.29	0.10-0.24	0.24-0.30	0.17-0.28	0.18-0.28	0.2-0.3	N/A
silver	mg/kg	0.09-0.13	0.02-0.14	0.07-0.11	0.07-0.09	0.06-0.08	0.05-0.07	0.04-0.1	1.0-4.0 (prev. 1-3.7)
zinc	mg/kg	22.2-27.7	6-28.5	17.0-26.3	25.7-34.4	21.8-28.3	18.8-29.4	21-30	200-410
metalloid									
arsenic	mg/kg	4.26-7.43	3.19-5.58	2.15-3.41	3.70-4.31	3.89-6.33	4.64-5.3	4.6-6.4	20-70
organics									
naphthalene	µg/kg	19-78	<10-127	<10-38	25-35	<5	<5	<5	160-2100
M-cresol	µg/kg	<10	<10	<10	<10-160	<10	<10	<10	N/A
others									
mud	%	6.20-11.6	1.6-11.7	6.79-11.3	10-12.3	7.97-11.8	6.52-12.7	7.6-13.1	N/A
sand	%	88.1-93.8	88.3-96.5	88.7-93.2	85.6-89.8	88-91.8	87.0-93.0	86.4-92.3	N/A
gravel	%	0.00-1.20	<0.1-1.9	<0.1	2.04-0.17	0.12-0.57	0.16-0.78	0.1-0.51	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		Malabar 7 km							
		2002	2005	2008	2011	2014	2016	2020	
TOC	%	0.42-0.63	0.17-0.89	0.39-0.79	0.70-1.11	0.66-0.88	0.72-0.9	0.66-1.22	N/A
metals									
aluminium	mg/kg	3280-6700	3090-6990	1550-4580	2760-5120	3020-5970	3240-5730	3500-5200	N/A
cadmium	mg/kg	0.06-0.10	0.03-0.09	0.01-0.01	0.05-0.08	0.05-0.07	0.04-0.08	0.06-0.12	1.5-10
chromium	mg/kg	8.81-12.7	9.42-18.3	5.73-17.8	10.6-18.0	11.7-19.6	12.2-21.5	13-21	80-370
copper	mg/kg	2.93-4.80	2.32-5.63	2.27-6.90	4.19-7.68	5.52-7.74	6.66-10.3	5.3-9.3	65-270
iron	mg/kg	3880-7360	5650-8870	3090-9340	6090-9180	6240-8660	5540-10200	5500-9700	N/A
lead	mg/kg	6.02-10.0	6.4-10.9	3.55-8.36	6.56-10.0	6.54-9.84	6.71-11.6	6.6-11	50-220
mercury	mg/kg	0.06-0.09	0.04-0.10	0.04-0.11	0.07-0.12	0.08-0.13	0.09-0.17	0.08-0.13	0.15-1.0
nickel	mg/kg	4.86-7.63	3.53-6.87	1.96-8.94	4.41-7.44	4.69-7.9	4.94-8.6	4.9-8.7	21-52
selenium	mg/kg	0.05-0.13	0.11-0.22	0.09-0.19	0.18-0.30	0.19-0.31	0.24-0.34	0.21-0.33	N/A
silver	mg/kg	0.04-0.09	0.03-0.13	0.02-0.12	0.05-0.08	0.04-0.07	0.04-0.08	0.06-0.08	1.0-4.0 (prev. 1-3.7)
zinc	mg/kg	12.8-20.1	10.6-21.2	8.20-26.6	19.6-27.5	18.5-27.7	19.9-31.8	17-32	200-410
metalloid									
arsenic	mg/kg	2.45-4.42	5.11-7.16	2.27-5.27	2.05-4.74	4.15-5.87	3.13-5.82	3.5-5.7	20-70
organics									
naphthalene	µg/kg	44-101	<10-100	<10-33	19-47	<5	<5	<5	160-2100
M-cresol	µg/kg	<10	<10	<10	<10	<10	<10	<10	N/A
others									
mud	%	4.20-7.04	3.2-15.2	5.36-14.6	8.06-14.4	7.87-15.6	11.6-21.4	6.35-16.4	N/A
sand	%	88.5-95.8	84.8-95.7	85.4-94.6	85.6-91.4	84.1-91.7	78.1-88.1	82.3-93.2	N/A
gravel	%	0.00-4.92	<0.1-1.1	<0.1	<0.1-0.52	<0.1-3.38	<0.1-0.75	0.14-1.71	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		Port Hacking							
		2002	2005	2008	2011	2014	2016	2020	
TOC	%	0.44-0.70	0.41-0.66	0.47-0.64	0.48-0.76	0.41-0.64	0.48-0.69	0.51-0.71	N/A
metals									
aluminium	mg/kg	4070-7060	4310-7050	2400-3280	3080-5050	3400-4650	4180-5520	3400-4900	N/A
cadmium	mg/kg	0.05-0.11	0.05-0.07	0.01-0.07	0.05-0.1	0.05-0.09	0.06-0.09	0.06-0.08	1.5-10
chromium	mg/kg	11.2-15.9	15.8-19.7	13.0-15.4	13.2-19.0	14-19.8	16-20.6	13-19	80-370
copper	mg/kg	3.84-5.61	4.75-5.69	3.67-5.00	4.0-5.94	4.39-6	4.74-6.74	4.3-6.2	65-270
iron	mg/kg	6650-9590	7070-9990	7360-9030	6960-10100	7360-10400	7710-9790	6600-9200	N/A
lead	mg/kg	6.33-9.52	7.27-11.7	5.60-7.10	6.03-8.72	6.32-8.96	6.42-12.9	5.7-7.6	50-220
mercury	mg/kg	0.06-0.15	0.05-0.09	0.07-0.09	0.06-0.12	0.06-0.11	0.07-0.14	0.06-0.13	0.15-1.0
nickel	mg/kg	5.79-8.35	6.03-7.75	4.98-5.91	5.12-7.51	5.58-8.32	6.45-8.54	5.5-7.7	21-52
selenium	mg/kg	0.06-0.11	0.18-0.32	0.13-0.17	0.14-0.29	0.18-0.24	0.2-0.27	0.18-0.24	N/A
silver	mg/kg	0.06-0.09	0.05-0.07	0.04-0.08	0.03-0.07	0.04-0.05	0.04-0.05	0.03-0.06	1.0-4.0 (prev. 1-3.7)
zinc	mg/kg	22.5-31.0	19.7-26.0	18.3-22.0	18.8-27.9	21.5-29.4	22.7-31.7	18-26	200-410
metalloid									
arsenic	mg/kg	4.58-5.52	3.74-5.80	2.56-4.09	3.74-5.39	4.3-5.27	4.49-5.45	4.4-5.3	20-70
organics									
naphthalene	µg/kg	25-107	59-100	15-129	21-43	<5	<5	<5	160-2100
M-cresol	µg/kg	<10	<10	<10	<10	<10	<10	<10	N/A
others									
mud	%	5.91-11.0	6.7-10.8	5.94-11.5	9.4-14.1	6.08-10.6	9.77-14.3	2.91-15.3	N/A
sand	%	89.0-94.1	88.7-92..4	88.5-94.1	85.6-90.5	89.2-93.6	85.1-90.0	84.5-96.8	N/A
gravel	%	0.00	<0.1-1.6	<0.1	<0.1-0.72	<0.1-0.75	0.14-0.61	0.12-1.27	N/A

Variable	Units	Range (minimum and maximum) of results for each location							ANZECC (2013) ISQC low-high
		Marley Beach							
		2002	2005	2008	2011	2014	2016	2020	
TOC	%	0.43-0.58	0.39-0.55	0.48-0.65	0.58-0.85	0.43-0.58	0.49-0.72	0.5-0.65	N/A
metals									
aluminium	mg/kg	4220-7250	5000-10100	541-3060	4010-5890	3700-6780	4600-5840	4400-4900	N/A
cadmium	mg/kg	0.06-0.15	0.04-0.06	0.01-0.01	0.06-0.08	0.06-0.09	0.06-0.08	0.07-0.08	1.5-10
chromium	mg/kg	12.9-18.6	15.0-19.9	7.09-14.0	14.5-19.3	14.9-18.2	17.7-21.5	15-17	80-370
copper	mg/kg	3.90-5.27	4.14-5.36	0.38-4.56	4.21-7.15	4.22-6.38	5.59-6.81	4.7-5.4	65-270
iron	mg/kg	7360-9240	7730-10200	4570-7780	8590-11000	7590-10700	8640-10300	8500-9200	N/A
lead	mg/kg	6.84-9.73	6.75-8.94	1.45-6.65	6.32-10.3	6.25-8.68	7.3-8.79	6.2-7	50-220
mercury	mg/kg	0.05-0.08	0.05-0.08	0.01-0.06	0.06-0.10	0.05-0.08	0.07-0.11	0.06-0.07	0.15-1.0
nickel	mg/kg	5.61-9.21	6.07-7.85	0.89-5.95	6.30-8.80	6.25-8.15	7.3-8.86	6.9-7.5	21-52
selenium	mg/kg	0.04-0.09	0.20-0.34	0.05-0.15	0.18-0.32	0.21-0.28	0.21-0.3	0.21-0.23	N/A
silver	mg/kg	0.04-0.06	0.04-0.06	0.01-0.05	0.02-0.05	0.02-0.04	0.03-0.05	0.03-0.04	1.0-4.0 (prev. 1-3.7)
zinc	mg/kg	20.7-26.3	19.8-25.3	2.90-22.2	21.0-31.9	22-31.1	25.4-37.9	22-25	200-410
metalloid									
arsenic	mg/kg	4.25-5.70	4.29-5.00	2.75-4.88	2.48-3.83	4.51-5.62	4.53-5.08	4.5-5.2	20-70
organics									
naphthalene	µg/kg	44-75	61-295	23-43	16-52	<5	<5	<5	160-2100
M-cresol	µg/kg	<10	<10	<10	<10	<10	<10	<10	N/A
others									
mud	%	2.95-15.0	8.1-12.3	8.57-13.0	11.1-19.7	10.8-15.6	12.9-17.8	11-15.6	N/A
sand	%	88.2-97.0	87.7-91.9	87.0-91.4	79.5-87.8	62-88.8	81.8-86.9	84.3-88.3	N/A
gravel	%	0.00-0.54	<0.1-1.3	<0.1	0.37-1.27	0.24-0.63	0.23-1.01	0.14-1.01	N/A

9.1 Appendix D Analysis of covariance

60 m locations

Aluminium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	7.8546E+06	7.8546E+06	14.626	0.001	9839
Location	2	1.1101E+07	5.5506E+06	10.336	0.0007	9952
FinesxLocation	2	1.9056E+06	9.5278E+05	1.7742	0.189	9960
Res	24	1.2889E+07	5.3703E+05			
Total	29	3.375E+07				

Groups	t	P(perm)	perms
LR, NH	3.2021	0.0054	9840
LR, B	1.6398	0.1157	9811
NH, B	4.0979	0.0011	9841

Average Distance between/within groups

	LR	NH	B
LR	977.78		
NH	1122	740	
B	1185	1507	1451.3

Arsenic

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	86.856	86.856	0.62738	0.4271	9835
Location	2	2003.9	1001.9	7.2372	0.0032	9960
FinesxLocation	2	100.03	50.015	0.36127	0.6759	9947
Res	24	3322.6	138.44			
Total	29	5513.4				

Groups	t	P(perm)	perms
LR, NH	2.3639	0.0325	9825
LR, B	1.8384	0.0747	9878
NH, B	3.034	0.0031	9847

Average Distance between/within groups

	LR	NH	B
LR	6.2089		
NH	17.484	20.813	
B	4.226	19.15	1.1933

Cadmium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.0016451	0.0016451	1.6092	0.2022	9816
Location	2	0.017287	0.0086435	8.4548	0.0012	9962
FinesxLocation	2	0.0010125	0.00050627	0.49522	0.5677	9957
Res	24	0.024535	0.0010223			
Total	29	0.04448				

Groups	t	P(perm)	perms
LR, NH	0.43642	0.6644	9854
LR, B	0.48594	0.6426	9816
NH, B	5.1104	0.0001	9829

Average Distance between/within groups

	LR	NH	B
LR	0.056		
NH	0.051	0.025111	
B	0.0396	0.056	0.014444

Chromium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	9.2598	9.2598	0.29873	0.5839	9848
Location	2	685.36	342.68	11.055	0.0004	9944
FinesxLocation	2	94.072	47.036	1.5174	0.2387	9959
Res	24	743.95	30.998			
Total	29	1532.6				

Groups	t	P(perm)	perms
LR, NH	3.2605	0.0039	9841
LR, B	1.0609	0.3043	9833
NH, B	3.6133	0.0005	9855

Average Distance between/within groups

	LR	NH	B
LR	4.0978		
NH	9.64	9.1556	
B	4.14	10.68	4.7378

Copper

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	34.634	34.634	17.545	0.0006	9832
Location	2	12.979	6.4896	3.2875	0.0478	9949
FinesxLocation	2	0.93224	0.46612	0.23612	0.76	9954
Res	24	47.377	1.974			
Total	29	95.923				

Groups	t	P(perm)	perms
LR, NH	3.4577	0.0038	9829
LR, B	1.6037	0.1243	9876
NH, B	0.6645	0.5373	9849

Average Distance between/within groups

	LR	NH	B
LR	1.4089		
NH	1.932	1.9756	
B	2.106	2.132	2.5911

Iron

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	19816	19816	0.0009567	0.9784	9852
Location	2	6.007E+08	3.0035E+08	14.501	0.0001	9949
FinesxLocation	2	4.1023E+07	2.0511E+07	0.9903	0.3723	9943
Res	24	4.971E+08	2.0712E+07			
Total	29	1.1388E+09				

Groups	t	P(perm)	perms
LR, NH	3.5006	0.002	9852
LR, B	1.9058	0.0741	9836
NH, B	4.2393	0.0002	9851

Average Distance between/within groups

	LR	NH	B
LR	3195.6		
NH	8616	7664.4	
B	2946	10140	2517.8

Lead

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	19.404	19.404	3.2391	0.088	9831
Location	2	176.95	88.477	14.769	0.0001	9948
FinesxLocation	2	26.446	13.223	2.2073	0.1376	9964
Res	24	143.77	5.9906			
Total	29	366.58				

Groups	t	P(perm)	perms
LR, NH	4.2267	0.0008	9829
LR, B	0.1892	0.8574	9843
NH, B	4.4008	0.0006	9831

Average Distance between/within groups

	LR	NH	B
LR	3.7711		
NH	5.49	3.5	
B	2.8	4.99	2.0756

Mercury

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.01254	0.01254	1.8951	0.1624	9801
Location	2	0.041012	0.020506	3.0989	0.0409	9956
FinesxLocation	2	0.0021174	0.0010587	0.16	0.7977	9940
Res	24	0.15881	0.0066172			
Total	29	0.21448				

Groups	t	P(perm)	perms
LR, NH	1.5213	0.1483	9868
LR, B	1.3562	0.1793	9829
NH, B	2.001	0.0442	9903

Average Distance between/within groups

	LR	NH	B
LR	0.055778		
NH	0.09072	0.12278	
B	0.05236	0.09734	0.051756

Nickel

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	2.9442	2.9442	1.301	0.2696	9860
Location	2	53.936	26.968	11.916	0.0001	9947
FinesxLocation	2	9.7179	4.859	2.1471	0.141	9942
Res	24	54.314	2.2631			
Total	29	120.91				

Groups	t	P(perm)	perms
LR, NH	3.1786	0.0064	9832
LR, B	1.7738	0.0995	9821
NH, B	4.0904	0.0006	9860

Average Distance between/within groups

	LR	NH	B
LR	1.4333		
NH	2.56	2.2689	
B	1.642	3.232	1.8711

Selenium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.026489	0.026489	20.941	0.0006	9819
Location	2	0.014563	0.0072816	5.7564	0.0098	9936
FinesxLocation	2	0.00040531	0.00020265	0.16021	0.8521	9954
Res	24	0.030359	0.001265			
Total	29	0.071817				

Groups	t	P(perm)	perms
LR, NH	1.083	0.3009	9857
LR, B	1.9831	0.0659	9839
NH, B	4.703	0.0004	9813

Average Distance between/within groups

	LR	NH	B
LR	0.062444		
NH	0.052	0.045778	
B	0.0608	0.0634	0.054222

Silver

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.0024578	0.0024578	22.639	0.0001	9827
Location	2	7.4714E-05	3.7357E-05	0.34409	0.7059	9948
FinesxLocation	2	0.00015852	7.926E-05	0.73006	0.5011	9946
Res	24	0.0026056	0.00010857			
Total	29	0.0052967				

Zinc

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	126.82	126.82	5.8295	0.0209	9842
Location	2	533.51	266.75	12.262	0.0004	9959
FinesxLocation	2	134.32	67.162	3.0872	0.0594	9947
Res	24	522.13	21.755			
Total	29	1316.8				

80 m locations

Aluminium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	5.5725E+06	5.5725E+06	24.613	0.0001	9846
Location	2	2.4625E+06	1.2313E+06	5.4383	0.0102	9957
FinesxLocation	2	3.8489E+05	1.9245E+05	0.85	0.4475	9962
Res	24	5.4337E+06	2.2641E+05			
Total	29	1.3854E+07				

Groups	t	P(perm)	perms
M0, PH	2.6169	0.0195	9835
M0, MB	1.0409	0.3179	9841
PH, MB	0.76626	0.4583	9838

Average Distance between/within groups

	M0	PH	MB
M0	746.67		
PH	992	575.56	
MB	1180	420	186.67

Arsenic

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.47289	0.47289	2.4191	0.134	9836
Location	2	1.9756	0.98782	5.0533	0.0134	9949
FinesxLocation	2	0.089578	0.044789	0.22912	0.7889	9953
Res	24	4.6916	0.19548			
Total	29	7.2297				

Groups	t	P(perm)	perms
M0, PH	2.626	0.0203	9835
M0, MB	0.97924	0.3343	9819
PH, MB	0.065869	0.945	9833

Average Distance between/within groups

	M0	PH	MB
M0	0.75333		
PH	0.816	0.31111	
MB	0.738	0.286	0.24889

Cadmium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.00087703	0.00087703	16.937	0.0002	9834
Location	2	4.5471E-05	2.2735E-05	0.43906	0.6517	9961
FinesxLocation	2	0.00010474	5.2369E-05	1.0113	0.3811	9952
Res	24	0.0012428	5.1782E-05			
Total	29	0.00227				

Chromium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	10.305	10.305	3.4261	0.0763	9860
Location	2	10.326	5.163	1.7165	0.2022	9956
FinesxLocation	2	3.0475	1.5238	0.50659	0.6086	9944
Res	24	72.188	3.0078			
Total	29	95.867				

Copper

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	3.1886	3.1886	4.7991	0.0384	9868
Location	2	11.405	5.7026	8.583	0.0017	9960
FinesxLocation	2	2.2389	1.1195	1.6849	0.1992	9952
Res	24	15.946	0.66441			
Total	29	32.779				

Groups	t	P(perm)	perms
M0, PH	3.0488	0.0079	9831
M0, MB	3.2963	0.0054	9844
PH, MB	1.4137	0.1794	9847

Average Distance between/within groups

	M0	PH	MB
M0	1.4889		
PH	1.562	0.82444	
MB	1.728	0.656	0.28222

Iron

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	5.1698E+06	5.1698E+06	7.8044	0.0121	9839
Location	2	7.249E+05	3.6245E+05	0.54715	0.5842	9952
FinesxLocation	2	8.6166E+05	4.3083E+05	0.65038	0.529	9952
Res	24	1.5898E+07	6.6243E+05			
Total	29	2.2655E+07				

Lead

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	4.0334	4.0334	9.7111	0.0045	9829
Location	2	3.8836	1.9418	4.6752	0.0192	9940
FinesxLocation	2	0.035038	0.017519	0.042181	0.9556	9946
Res	24	9.968	0.41533			
Total	29	17.92				

Groups	t	P(perm)	perms
M0, PH	2.4376	0.0247	9812
M0, MB	0.91692	0.3824	9849
PH, MB	1.0063	0.3402	9836

Average Distance between/within groups

	M0	PH	MB
M0	0.81778		
PH	1.256	0.88	
MB	1.104	0.692	0.26667

Mercury

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.0017104	0.0017104	7.3866	0.0103	9829
Location	2	0.0044263	0.0022131	9.5579	0.0005	9951
FinesxLocation	2	0.00016557	8.2785E-05	0.35752	0.6962	9950
Res	24	0.0055572	0.00023155			
Total	29	0.011859				

Groups	t	P(perm)	perms
M0, PH	2.6829	0.0175	9828
M0, MB	0.43972	0.6739	9841
PH, MB	2.9089	0.0104	9829

Average Distance between/within groups

	M0	PH	MB
M0	0.017933		
PH	0.0342	0.025244	
MB	0.01848	0.02056	0.0048667

Nickel

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	9.798	9.798	17.149	0.0004	9833
Location	2	3.948	1.974	3.455	0.0479	9944
FinesxLocation	2	0.81561	0.4078	0.71377	0.5028	9966
Res	24	13.712	0.57134			
Total	29	28.274				

Groups	t	P(perm)	perms
M0, PH	2.0681	0.0545	9837
M0, MB	0.79969	0.4434	9856
PH, MB	0.45119	0.662	9850

Average Distance between/within groups

	M0	PH	MB
M0	1.1844		
PH	1.408	0.92667	
MB	1.526	0.672	0.24667

Selenium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.022426	0.022426	17.702	0.0004	9818
Location	2	0.065432	0.032716	25.824	0.0001	9962
FinesxLocation	2	0.0010735	0.00053674	0.42368	0.6481	9952
Res	24	0.030405	0.0012669			
Total	29	0.11934				

Groups	t	P(perm)	perms
M0, PH	5.7956	0.0001	9855
M0, MB	3.33	0.0034	9843
PH, MB	0.13925	0.8861	9824

Average Distance between/within groups

	M0	PH	MB
M0	0.067111		
PH	0.118	0.026667	
MB	0.109	0.0188	0.0055556

Silver

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.00070277	0.00070277	6.425	0.0192	9826
Location	2	0.00077459	0.00038729	3.5408	0.0435	9945
FinesxLocation	2	9.7501E-05	4.8751E-05	0.4457	0.6405	9958
Res	24	0.0026251	0.00010938			
Total	29	0.0042				

Groups	t	P(perm)	perms
M0, PH	1.2157	0.2506	9842
M0, MB	2.14	0.0487	9843
PH, MB	3.0159	0.0083	9865

Average Distance between/within groups

	M0	PH	MB
M0	0.017778		
PH	0.013	0.006	
MB	0.0174	0.0102	0.002

Zinc

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.0042159	0.0042159	0.00045516	0.9833	9838
Location	2	25.657	12.828	1.385	0.2696	9950
FinesxLocation	2	0.74381	0.3719	0.040152	0.9578	9952
Res	24	222.3	9.2623			
Total	29	248.7				

Gradient study locations

Aluminium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	7.3639E+06	7.3639E+06	38.731	0.0001	9821
Location	3	2.1812E+07	7.2706E+06	38.241	0.0001	9950
FinesxLocation	3	2.154E+06	7.1799E+05	3.7764	0.0194	9954
Res	32	6.084E+06	1.9013E+05			
Total	39	3.7414E+07				

Source	df	SS	MS	Pseudo-F	P(perm)	perms
TOC	1	8.8261E+06	8.8261E+06	31.587	0.0001	9836
Location	3	1.9181E+07	6.3937E+06	22.881	0.0001	9954
TOCxLocation	3	4.6505E+05	1.5502E+05	0.55477	0.6528	9947
Res	32	8.9416E+06	2.7943E+05			
Total	39	3.7414E+07				

Groups	t	P(perm)	perms
M0, M3	3.9389	0.0013	9830
M0, M5	2.3852	0.0338	9846
M0, M7	1.4938	0.1519	9847
M3, M5	6.6074	0.0001	9833
M3, M7	5.7327	0.0001	9867
M5, M7	1.1027	0.291	9848

Average Distance between/within groups

	M0	M3	M5	M7
M0	746.67			
M3	2310	402.22		
M5	924	1470	653.33	
M7	1206	1150	652	560

Arsenic

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.097324	0.097324	0.24922	0.6218	9845
Location	3	14.489	4.8298	12.368	0.0001	9946
FinesxLocation	3	1.0445	0.34818	0.89161	0.4686	9945
Res	32	12.496	0.39051			
Total	39	28.128				

Groups	t	P(perm)	perms
M0, M3	2.0417	0.0546	9836
M0, M5	0.8566	0.399	9812
M0, M7	2.6775	0.0164	9820
M3, M5	3.1296	0.007	9850
M3, M7	5.4187	0.0002	9829
M5, M7	4.2017	0.0009	9840

Average Distance between/within groups

	M0	M3	M5	M7
M0	0.75333			
M3	0.928	0.72444		
M5	0.666	0.896	0.66444	
M7	1.036	1.634	1.012	0.89556

Cadmium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.00078567	0.00078567	5.8249	0.0237	9834
Location	3	0.0074433	0.0024811	18.395	0.0001	9946
FinesxLocation	3	3.2356E-05	1.0785E-05	0.079962	0.9657	9957
Res	32	0.0043162	0.00013488			
Total	39	0.012578				

Groups	t	P(perm)	perms
M0, M3	7.5441	0.0001	9838
M0, M5	0.92531	0.3632	9824
M0, M7	1.3251	0.1912	9841
M3, M5	8.6121	0.0001	9838
M3, M7	3.358	0.0047	9830
M5, M7	1.0276	0.3275	9839

Average Distance between/within groups

	M0	M3	M5	M7
M0	0.010889			
M3	0.038	0.006		
M5	0.0108	0.031	0.0093333	
M7	0.0178	0.0258	0.0134	0.017111

Chromium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	49.758	49.758	16.963	0.0002	9867
Location	3	188.08	62.694	21.373	0.0001	9953
FinesxLocation	3	7.791	2.597	0.88533	0.4501	9961
Res	32	93.868	2.9334			
Total	39	339.5				

Groups	t	P(perm)	perms
M0, M3	5.0795	0.0002	9837
M0, M5	0.26618	0.7969	9822
M0, M7	1.0306	0.3191	9840
M3, M5	6.9977	0.0001	9829
M3, M7	6.6272	0.0001	9856
M5, M7	2.1993	0.0425	9830

Average Distance between/within groups

	M0	M3	M5	M7
M0	2.5111			
M3	6	1.5778		
M5	2.48	4.3	2.0667	
M7	2.72	4.5	2.24	2.6889

Copper

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	11.079	11.079	12.7	0.0012	9826
Location	3	39.906	13.302	15.248	0.0001	9950
FinesxLocation	3	8.3575	2.7858	3.1933	0.0312	9966
Res	32	27.917	0.8724			
Total	39	87.26				

Source	df	SS	MS	Pseudo-F	P(perm)	perms
TOC	1	13.827	13.827	12.009	0.0011	9812
Location	3	31.45	10.483	9.1048	0.0002	9955
TOCxLocation	3	5.1366	1.7122	1.487	0.234	9960
Res	32	36.845	1.1514			
Total	39	87.26				

Groups	t	P(perm)	perms
M0, M3	0.43072	0.6714	9801
M0, M5	1.0503	0.3086	9847
M0, M7	1.1378	0.2713	9835
M3, M5	5.0339	0.0001	9831
M3, M7	3.9971	0.0005	9837
M5, M7	1.408	0.1799	9843

Average Distance between/within groups

	M0	M3	M5	M7
M0	1.4889			
M3	2.348	0.91556		
M5	1.424	2.58	1.4689	
M7	1.392	1.752	1.558	1.32

Iron

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	5.2315E+06	5.2315E+06	7.6621	0.0089	9838
Location	3	3.8437E+07	1.2812E+07	18.765	0.0001	9954
FinesxLocation	3	1.8413E+06	6.1378E+05	0.89894	0.4441	9963
Res	32	2.1849E+07	6.8278E+05			
Total	39	6.7359E+07				

Groups	t	P(perm)	perms
M0, M3	4.7977	0.0004	9815
M0, M5	0.33595	0.7597	9851
M0, M7	1.0221	0.3202	9846
M3, M5	9.5442	0.0001	9823
M3, M7	5.5683	0.0001	9856
M5, M7	2.3523	0.0314	9851

Average Distance between/within groups

	M0	M3	M5	M7
M0	1262.2			
M3	2550	588.89		
M5	1086	1780	717.78	
M7	1238	2170	988	1315.6

Lead

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	47.947	47.947	70.724	0.0001	9803
Location	3	65.919	21.973	32.411	0.0001	9954
FinesxLocation	3	1.9354	0.64512	0.95157	0.4106	9951
Res	32	21.694	0.67795			
Total	39	137.5				

Groups	t	P(perm)	perms
M0, M3	8.4809	0.0001	9844
M0, M5	2.187	0.0429	9824
M0, M7	2.4292	0.028	9833
M3, M5	7.6198	0.0001	9824
M3, M7	4.4155	0.0006	9816
M5, M7	0.39788	0.6902	9833

Average Distance between/within groups

	M0	M3	M5	M7
M0	0.81778			
M3	4.4	1.1156		
M5	1.98	2.478	1.1689	
M7	2.914	1.736	1.438	1.3867

Mercury

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.015747	0.015747	60.442	0.0001	9827
Location	3	0.019403	0.0064676	24.825	0.0001	9960
FinesxLocation	3	0.001326	0.000442	1.6966	0.1921	9963
Res	32	0.0083367	0.00026052			
Total	39	0.044812				

Groups	t	P(perm)	perms
M0, M3	10.71	0.0001	9860
M0, M5	2.4696	0.0266	9856
M0, M7	3.8559	0.0011	9837
M3, M5	2.9012	0.0072	9847
M3, M7	5.2482	0.0001	9836
M5, M7	0.97643	0.3396	9829

Average Distance between/within groups

	M0	M3	M5	M7
M0	0.017933			
M3	0.077	0.0087778		
M5	0.0546	0.03266	0.032156	
M7	0.0572	0.02028	0.02474	0.0154

Nickel

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	13.106	13.106	22.231	0.0001	9835
Location	3	39.002	13.001	22.051	0.0001	9959
FinesxLocation	3	2.1646	0.72154	1.2238	0.3176	9951
Res	32	18.866	0.58957			
Total	39	73.139				

Groups	t	P(perm)	perms
M0, M3	5.7451	0.0001	9841
M0, M5	0.26065	0.7977	9848
M0, M7	0.5923	0.5593	9829
M3, M5	8.1531	0.0001	9823
M3, M7	6.2342	0.0001	9840
M5, M7	1.7056	0.1141	9844

Average Distance between/within groups

	M0	M3	M5	M7
M0	1.1844			
M3	2.88	0.60667		
M5	1.226	1.966	1.02	
M7	1.382	1.928	1.074	1.2644

Selenium

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.0015184	0.0015184	1.2934	0.2661	9824
Location	3	0.054864	0.018288	15.578	0.0001	9961
FinesxLocation	3	0.0037606	0.0012535	1.0678	0.3645	9958
Res	32	0.037567	0.001174			
Total	39	0.09771				

Groups	t	P(perm)	perms
M0, M3	2.0482	0.0571	9857
M0, M5	5.0913	0.0001	9838
M0, M7	3.201	0.0046	9858
M3, M5	7.2616	0.0001	9830
M3, M7	3.5356	0.0026	9806
M5, M7	0.26922	0.7918	9842

Average Distance between/within groups

	M0	M3	M5	M7
M0	0.067111			
M3	0.0544	0.021778		
M5	0.0956	0.0586	0.037778	
M7	0.0748	0.038	0.0424	0.036

Silver

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	0.0021172	0.0021172	11.698	0.0022	9831
Location	3	0.0045584	0.0015195	8.3951	0.0001	9930
FinesxLocation	3	0.00031012	0.00010337	0.57115	0.6167	9957
Res	32	0.0057918	0.00018099			
Total	39	0.012778				

Groups	t	P(perm)	perms
M0, M3	3.9454	0.001	9831
M0, M5	0.25151	0.8039	9826
M0, M7	0.94071	0.3534	9819
M3, M5	3.0685	0.0064	9832
M3, M7	5.9062	0.0001	9834
M5, M7	0.61619	0.5428	9835

Average Distance between/within groups

	M0	M3	M5	M7
M0	0.017778			
M3	0.0344	0.010222		
M5	0.0218	0.0248	0.022444	
M7	0.0192	0.0184	0.0166	0.0066667

Zinc

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Fines	1	20.784	20.784	2.2494	0.1432	9832
Location	3	328.18	109.39	11.84	0.0002	9947
FinesxLocation	3	28.138	9.3793	1.0151	0.3984	9954
Res	32	295.67	9.2397			
Total	39	672.78				

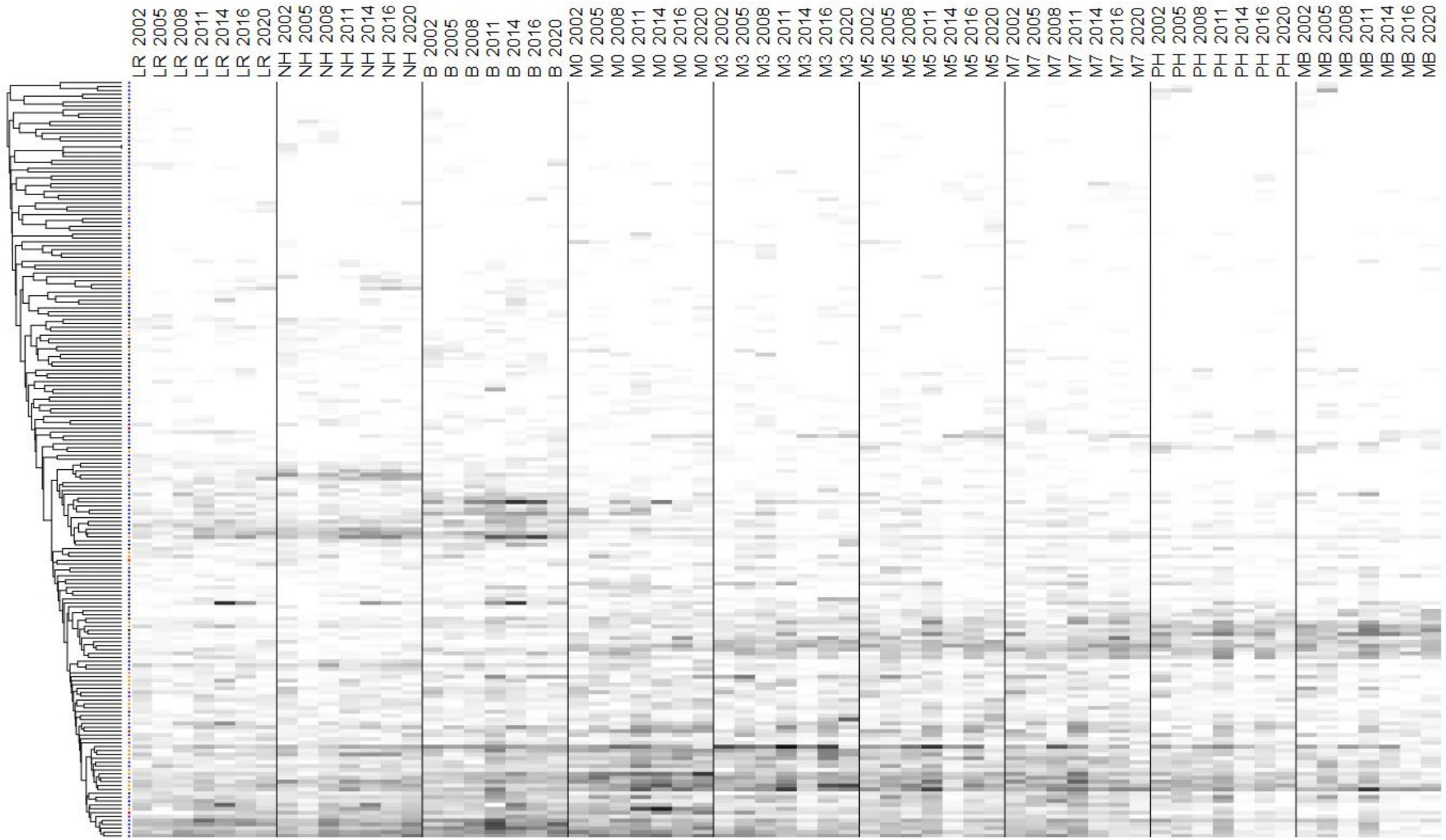
Groups	t	P(perm)	perms
M0, M3	2.9222	0.0092	9857
M0, M5	1.4176	0.176	9847
M0, M7	1.7527	0.0993	9842
M3, M5	6.9628	0.0002	9849
M3, M7	5.4839	0.0001	9833
M5, M7	1.7086	0.1115	9845

Average Distance between/within groups

	M0	M3	M5	M7
M0	4.7333			
M3	6.16	2.2444		
M5	3.68	6.4	3.0222	
M7	4.26	6.72	3.48	4.5111

9.2 Appendix E Shade plot of 195 taxa in the infauna dataset of the seven assessment years collected from the nine study locations

NB this page is designed to be printed on A3 paper. Locations are displayed in a north to south (left to right on page) order.



Shade plot based on the full set of 195 family level taxa for site by assessment year with family level taxa serially reordered from classification based on a data matrix raised with Whittaker's (1952) Index of Association resemblance measure. Locations codes: LR = Long Reef reference; NH = North Head outfall; B = Bondi outfall; M0 = Malabar outfall; M3 = Malabar 3 km; M5 = Malabar 5 km; M7 = Malabar 7 km; PH = Port Hacking reference; MB = Marley reference. White spaces represent absence of family while depth of grey scale is linearly proportional to dispersion weighted, square root transformed and averged by site-year abundance counts; blue triangle = Crustacean; red square = Echinodermata; black downward triangle = Mollusca; orange circle = Polychaeta

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9.3 Appendix F Ocean Sediment Program Oceanographic Report from WQ Data Pty Ltd for Oceanographic Field Services Pty Ltd

Ocean Sediment Program
Oceanographic Report

Prepared by WQ Data Pty Ltd for Oceanographic Field Services Pty Ltd

August 2020

Report No. WQD202003a

Author: D.J. Tate

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Contents

1. Introduction

This report forms part of Sydney Water's Ocean Sediment Program. It contains the oceanographic components including wastewater plume movement and dilution, the settlement of particulate matter from the wastewater plumes and the possibility of resuspension of settled material.

1.1. Overview

Wastewater from Sydney's three deepwater ocean outfalls contains particulate matter to which contaminants may be attached. It is not uncommon that environmental conditions arise under which negatively buoyant particles settle in the sediments, leading to a possible accumulation of contaminants therein. Sufficiently large ocean currents and waves will re-suspend the sediments thereby potentially releasing contaminants to the water column and their distribution may become more widespread.

The work described in this section assesses deepwater ocean outfall plume characteristics and examines the likelihood of sediment re-suspension in the months of December 2019, January 2020, and February 2020. This includes the ocean sediment sampling period, February 2020. An assessment is also made of the wave data between 2014 and 2020 to determine whether environmental conditions during 2020 were fundamentally different from those in the previous decade. Unless explicitly noted, analyses were undertaken using data averaged into daily bins.

2. Data processing

Inevitably, there are some gaps in the data. Gaps were filled using spectral techniques described in Tate et al (2019). Patching of the data was undertaken on less than 5% of the total length of the record and is unlikely to result in substantial errors in the analyses undertaken here.

Plots of the daily maximum wave height (Hmax), daily average significant wave height (Hsig) and corresponding significant wave period (Tsig) from the beginning of 2014 until the end of February 2020 are presented in

Figure 1. Superimposed on these plots are the times during which the sediment sampling was undertaken (i.e. February of each year).

Daily maximum wave heights are generally in the range 2-6 metres, although wave heights in excess of 10 m are observed in some years. Significant wave height is generally less than 4 m. Significant wave period is generally in the range 7-10 sec, with excursions as great as 12 sec observed in some years.

2.1. Interannular variability of waves

An analysis of variance (ANOVA) was undertaken to compare wave data collected during the December-January-February period of each year. To apply ANOVA, three conditions should be met: data are independent, data exhibit homogeneity of variance and data are drawn from a normal distribution (e.g. Sahai and Ageel, 2000). ANOVA is a robust technique and is able to cope with departures from the last two conditions (Sahai and Ageel, 2000).

2.1.1. Independence

Independence of the data is a critical condition for the application of ANOVA. A lagged correlation assessment was undertaken to check that the data used in the analysis are not linearly correlated. The first “turning point” in the correlation versus lag plot indicates that the data are uncorrelated. This occurs at a lag of less than fourteen days for the wave heights. Based on this lack of correlation, wave data more than two weeks apart are regarded as independent. Commencing on the 1st January 2014, wave data from every fourteenth day were selected for the ANOVA. Data commencing on other days were similarly selected with no substantial difference in the results. Independence was confirmed using the serial independence test described in Sokal and Rohlf (1995).

2.1.2. Homogeneity of variance

Bartlett’s test was used to validate the assumption that the wave data from each year originates from populations of equal variances. At the 5 % level of significance, each of the calculated chi-squared values were smaller than the critical chi-squared value, suggesting that the data variances were homogeneous. We conclude that the data variances originate from populations of variances which are close enough to perform ANOVA and the analysis is continued.

2.1.3. Normal distribution

A one-parameter Box-Cox transformation was performed to identify a transformation under which the data were normally distributed. The Box-Cox process determined that the logarithm of each of the three statistics under consideration was approximately normally distributed. This was confirmed by performing a chi-squared test on the transformed data. We therefore conclude that the transformed data are sufficiently close to being normally distributed that we may proceed to apply ANOVA to this set. Taking the logarithm of each data set does not impact the independence or homogeneity of variance conditions satisfied previously.

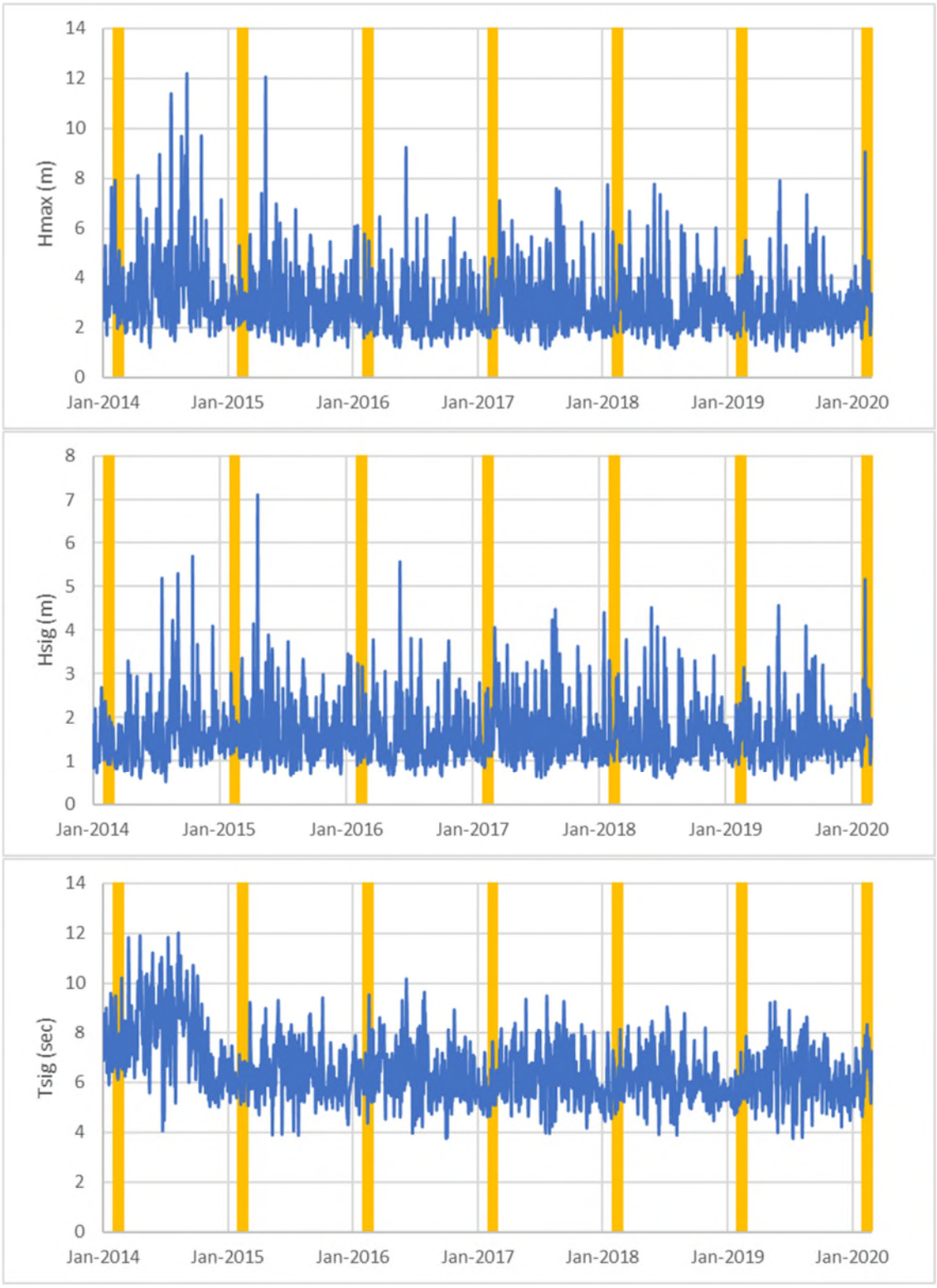

Figure 1 Daily maximum wave height, significant wave height and significant wave period from 1 January 2014 to 29 February 2020. Data obtained from the Ocean Reference Station. Vertical yellow bars indicate February of each year – the month during which sediment sampling was undertaken.

2.2. Historical wave data analysis

Results from the ANOVA are presented in Tables 1-3 for maximum wave height, significant wave height and significant wave period, respectively. A group of black cells in one row of one of these tables indicates a set of years between which ANOVA found no statistical difference (at the 5% level). For each statistic, the ANOVA process found no significant difference between the data from 2019-20 and at least two of the previous five December-January-February periods. When considering significant wave height and period this grew to five and four, respectively. Statistical power generally exceeds 0.6. We conclude that the data collected in 2019-20 are consistent with those recorded in the months preceding the previous five collection periods.

Hmax (m)	2017-18	2015-16	2016-17	2018-19	2014-15	2019-20
Mean	3.03	3.07	3.13	3.31	4.11	4.18

Hsig (m)	2018-19	2017-18	2016-17	2015-16	2019-20	2014-15
Mean	1.32	1.35	1.35	1.4	1.67	1.82

Tsig (s)	2016-17	2018-19	2017-18	2015-16	2019-20	2014-15
Mean	6.82	7.22	7.38	8.02	8.10	8.19

Tables 1-3 ANOVA results for significant wave height, maximum wave height and significant wave period in December, January and February. The Mean refers to the geometric mean of the untransformed data used to perform the ANOVA. The black cells in each row indicate a set of years for which ANOVA found no significant difference in Mean.

3. Sediment movement

3.1. Wave and current motion

Soulsby (1997) suggested that if,

$$h < 0.1\, g\, T^2 \text{ or } h < 10\, H_{sig}\ ,$$

where

- h denotes water depth,
- g is the gravitational constant,
- T is the wave period,
- H_{sig} is the significant wave height,

then wave-driven oscillatory flow at the seabed may be important to sediment mobility. Based on these formulae, if the water depth is 65 m, wave action may be important for sediment mobility when the wave period exceeds 8.1 sec, or the significant wave height exceeds 6.5 m. At 80 m water depth, these values are 9.0 sec and 8.0 m, respectively. From

Figure 1, it appears unlikely that wave height alone is sufficient to induce substantial sediment mobility. However, the wave period occasionally exceeds 10 sec indicating that the relatively long wave periods observed at the ORS site may induce sediment mobility at both the 65 m and 80 m sites.

Shear stress at the seabed is usually used to determine whether currents (including those induced by waves) are of sufficient strength to initiate sediment movement. There are many ways to determine the critical shear stress required to initiate sediment movement. A review by Rowinski, Aberle and Mazurczyk (2005) assesses methods for determining bed shear stress. One such method uses the Shields parameter. Both Blake et al. (2004) and Camenen and Lason (2005) use various forms of the "Shields parameter approach" to estimate sediment movement. The former approach is used here.

From Blake *et al* (2004), the shear stress, τ, (related to the Shield's parameter) from flow due to currents can be expressed as

$$\tau = \rho \left(\frac{\kappa \mu}{\ln h - \ln 2z_0} \right)^2 \ ,$$

where

- ρ is the density of the sea water,
- κ is von Karman's constant,
- z_0 is the effective bottom roughness (approximated using the median grain diameter),
- h is the water depth,
- μ is the average current speed.

The shear stress due to waves can be estimated by:

$$\tau = \frac{\rho\mu^2}{2}\exp\left[5.213\left(\frac{2500d_0}{H}\right)^{0.194} - 5.9777\right],$$

where

- d_0 is the median grain size,
- H is the wave height,
- μ is the orbital current speed from the (deepwater) wave-induced motion.

The orbital current speed parameter μ is given by the following equation.

$$\text{Speed } (\mu) = \frac{3.14\,H}{T}\exp\left[\frac{2.01z}{T^2}\right],$$

where

- H is the wave height,
- T is the wave period,
- z is the water depth (measured such that it is negative).

Knowing the median grain size, the bed shear stress from both wave-induced currents and the bulk water currents can be estimated.

3.2. Critical shear stress

The critical shear stress to initiate sediment motion is a complex, non-linear function. From Blake *et al* (2004), for particles larger than 0.2 mm, the critical shear stress, τ (N/m^2), to initiate sediment movement is given by the following equations.

$\tau = 0.024\frac{(\rho_s-1)gd}{d^*}$ for $1 < d^* \leq 4$,

$\tau = 0.014\frac{(\rho_s-1)gd}{(d^*)^{0.64}}$ for $4 < d^* \leq 10$,

$\tau = 0.004\frac{(\rho_s-1)gd}{(d^*)^{0.1}}$ for $10 < d^* \leq 20$,

$\tau = 0.0013(d^*)^{0.29}(\rho_s - 1)gd$ for $20 < d^* \leq 150$,

$\tau = 0.0055(\rho_s - 1)gd$ for $d^* > 150$,

where

- ρ_s is the specific density of the particles,
- $g = 9.81$ m/s^2,
- d is the median particle diameter,
- ν is the kinematic viscosity of the water,
- d^* is given by the following equation.

$$d^* = d\left[(\rho_s - 1)\frac{g}{\upsilon^2}\right]^{1/3}.$$

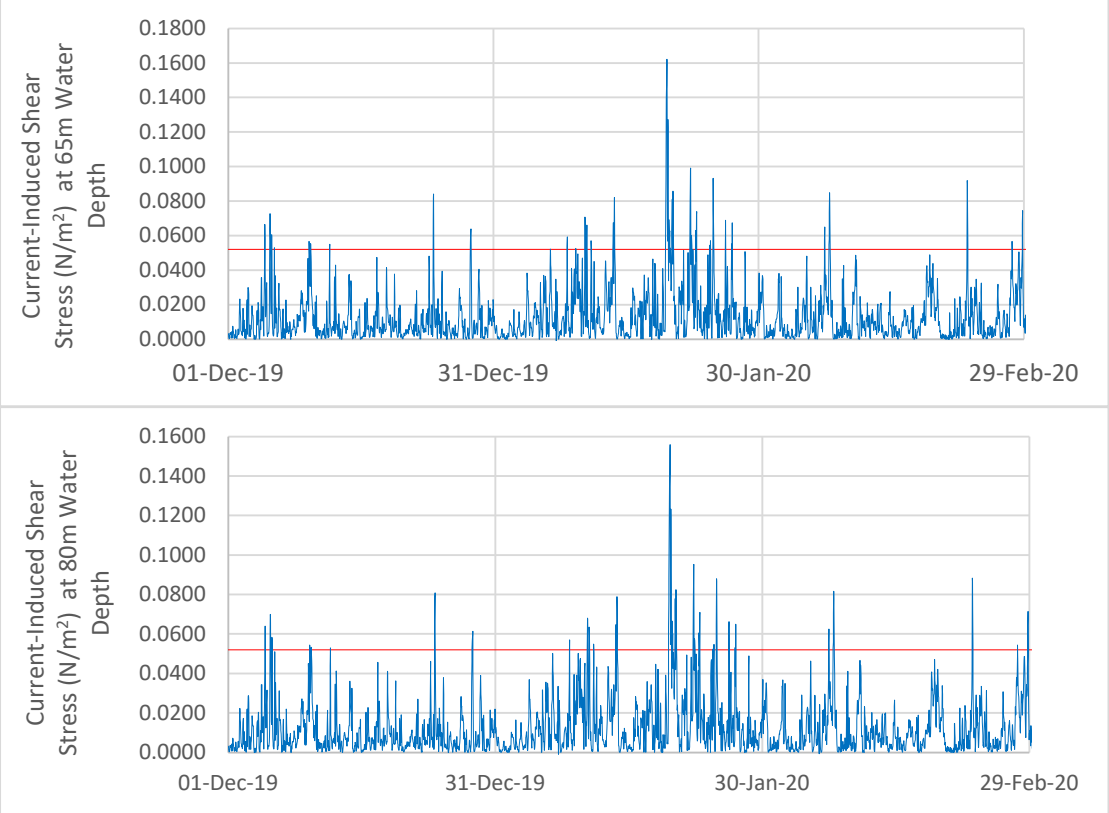

Figure 2 Current-induced shear stress at 65m and 80m water depth. The red line indicates the critical shear stress required to initiate sediment movement.

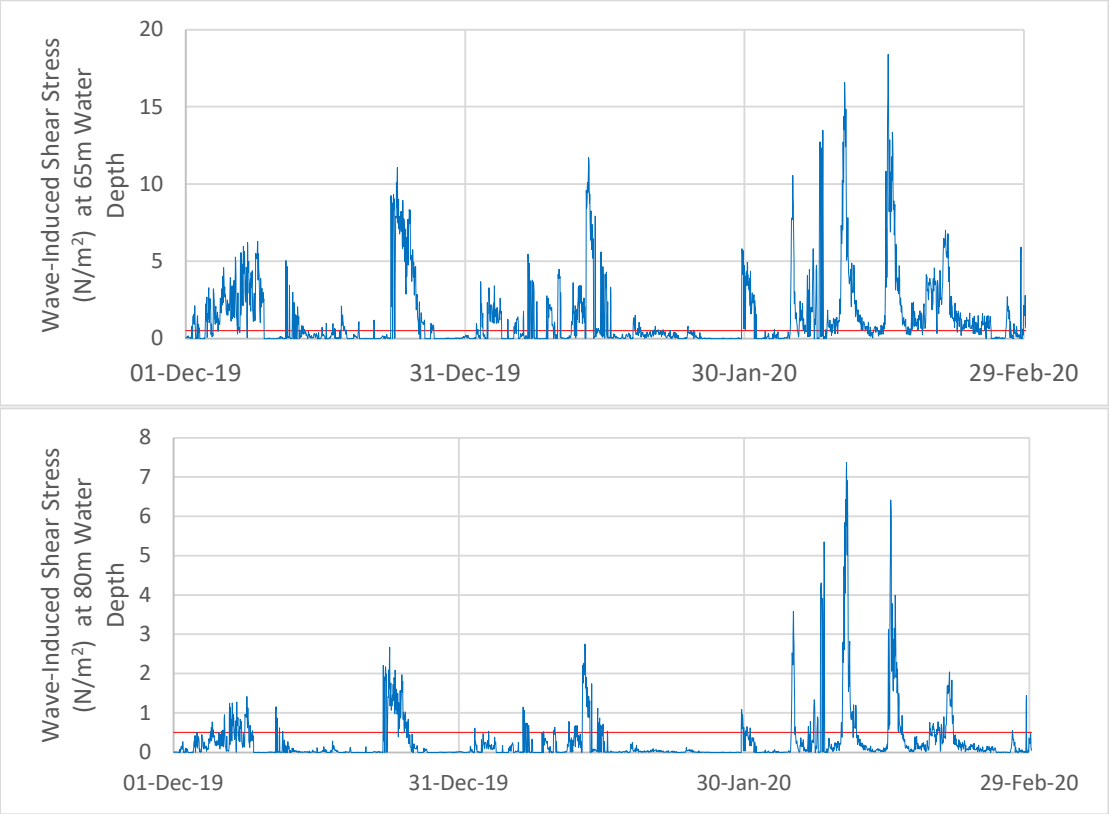

Figure 3 Wave-induced shear stress at 65m and 80m water depth. The red line indicates the critical shear stress required to initiate sediment movement.

3.3. Sediment resuspension

Comparing the critical shear stress required to initiate sediment movement with the current- and wave-induced shear stress provides estimates of when sediment movement is likely to occur. Based on this model current-induced sediment movement is likely to occur at isolated times in early December 2019 and late February 2020, as well as on a more regular basis in the second half of January 2020 (see Figure 2). Current-induced shear stress exhibits a similar pattern at both the 65m and 80m depths. At both the 65m and 80m depths this high shear stress is particularly pronounced in the periods 3-9 and 20-26 December 2019 as well as throughout February of 2020. There is a high likelihood of wave-induced sediment movement at these times. At the 65m depth wave-induced shear stress is also likely to generate sediment movement throughout the first half of January 2020. Evidence of this is borne out in Figure 3.

Therefore, in the two months preceding the February 2020 sediment-sampling period, either waves or currents are likely to have caused substantial sediment movement. Such an active seabed environment will mask any potential accumulation of contaminants in the sediments, making it difficult to interpret results obtained from such studies.

4. Plume distribution

4.1. Near-field model: PLOOM3

The near-field plume model described in Tate and Middleton (2000, 2004) is used in conjunction with data from the North Head, Bondi and Malabar wastewater treatment plants and oceanographic data from the Ocean Reference Station to estimate the position and dilution of the plumes from each of the three deepwater ocean outfalls. The period covered is from 1st December 2019 to 29th February 2020. These results are presented in Figure 4, Figure 5 and Figure 6 for the North Head, Bondi and Malabar outfalls, respectively.

In general, the information contained in these figures suggests the height of plume rise lies in the range 10-30 m. Plume dilutions during this period are highly variable, lying between (approximately) 100:1 and 1000:1. Dilutions are greatest for the Bondi outfall, thence for the North Head outfall. At both locations dilutions routinely entered the thousands. The lowest dilution values were modelled for the Malabar outfall where it was not uncommon for dilutions to drop below 100:1.

4.2. Particulate matter in the plume

Negatively buoyant particles originally within the wastewater plume will likely fall out of suspension and reside in or on the sediments that form the sea floor. Using the wastewater characterisation data outlined in Baker *et al* (1995) and assuming that the current speed and direction data at the Ocean Reference Station are representative of the region, the model proposed by Cheng (quoted in Blake *et al*, 2004) can be used to estimate the intersection of such negatively buoyant particles with the seabed. A fundamental assumption is that all particles remain within the effluent plume until the plume has reached its level of neutral buoyancy (or the sea surface).

Estimates of the location at which negatively buoyant particles reach the sea floor are presented in Figure 4, Figure 5 and Figure 6 for the North Head, Bondi and Malabar outfalls respectively, for the period 1st December 2019 to 29th February 2020. Using Cheng's model, heavy particulate matter discharged from the deepwater outfalls reaches the seabed within approximately 10 km of the outfall. The spatial distribution of such negatively buoyant particles around each outfall is approximately aligned with the bottom bathymetry.

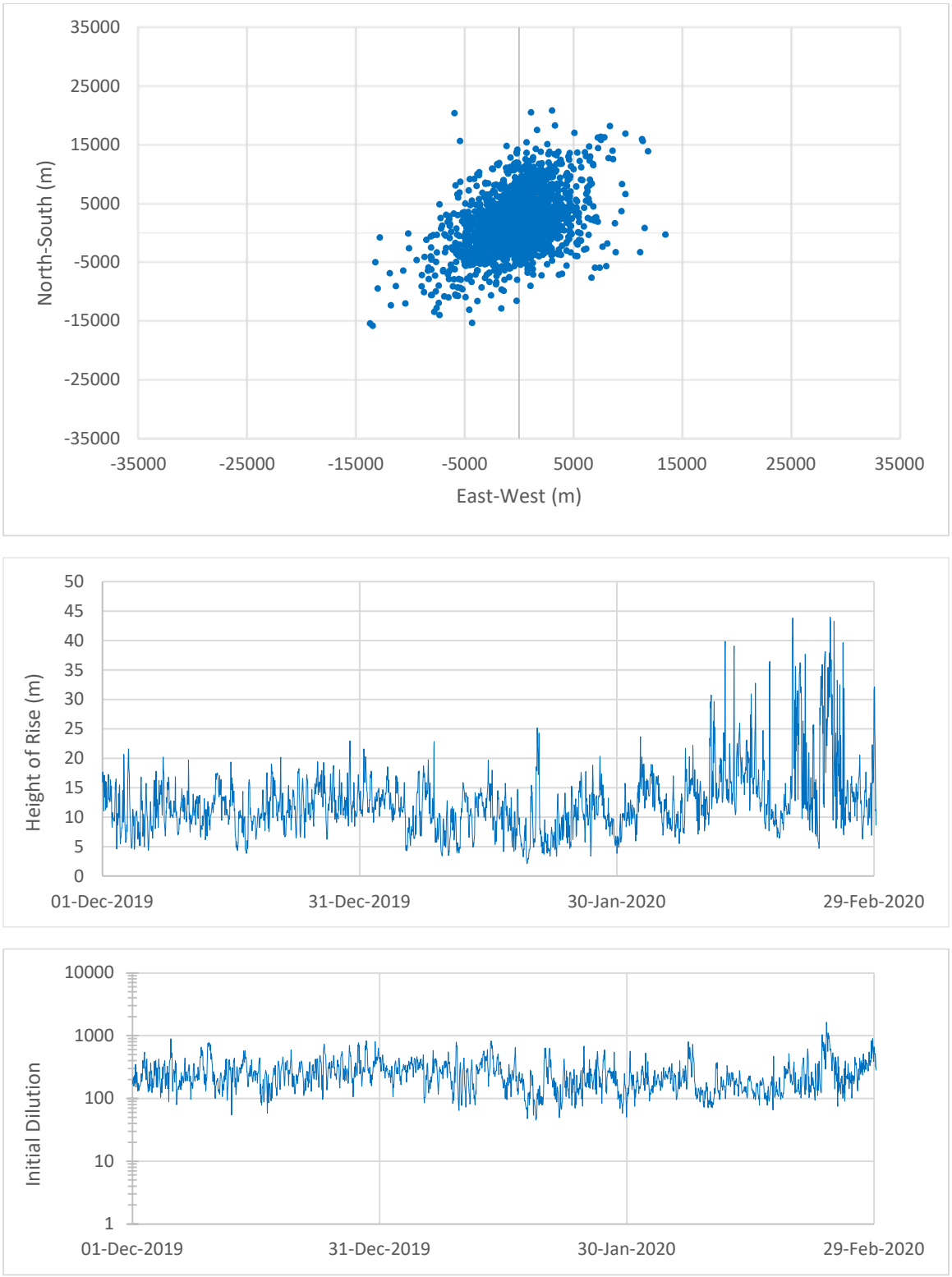

Figure 4 North Head outfall. Estimates of the location of heavy particles reaching the sea floor (top), height of plume rise (middle) and initial dilution (bottom) between 1st December 2019 and 29th February 2020.

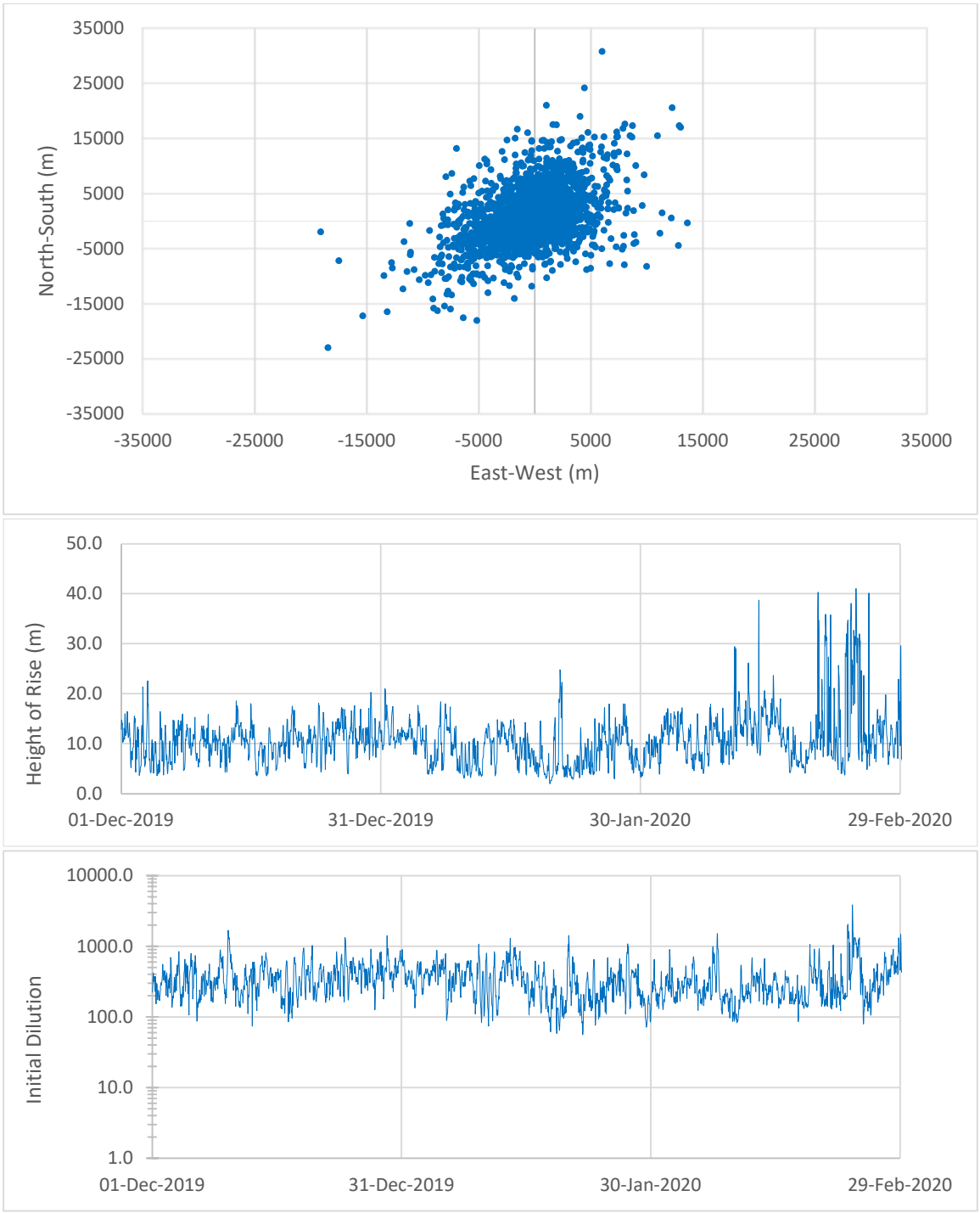

Figure 5 Bondi outfall. Estimates of the location of heavy particles reaching the sea floor (top), height of plume rise (middle) and initial dilution (bottom) between 1st December 2019 and 29th February 2020.

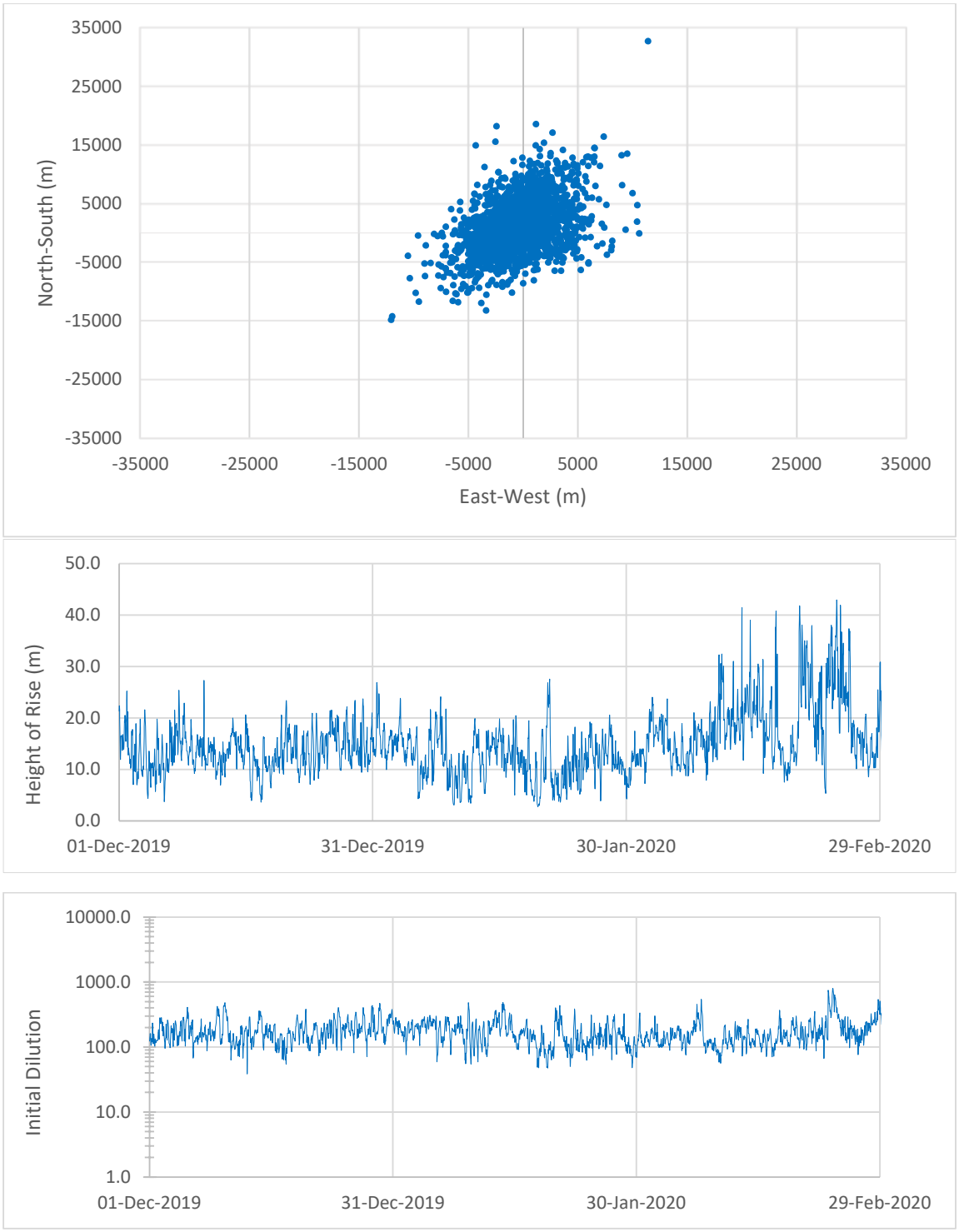

Figure 6 Malabar outfall. Estimates of the location of heavy particles reaching the sea floor (top), height of plume rise (middle) and initial dilution (bottom) between 1st December 2019 and 29th February 2020.

5. References

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10 Glossary and bibliography

10.1 Glossary

Abbreviation	Description
ANCOVA	analysis of covariance
CAP	Canonical analysis of principal coordinates
DISTLM	Distance-based linear models
Fines	Ambient sediment particles < 0.063 mm
MERMQ	mean Effects Range Median quotient scheme
mMDS	Metric Multidimensional Scaling
nMDS	Non-metric Multidimensional Scaling
OC	organochlorine compounds
ordered-ANOSIM	Ordered Analysis of Similarities
PAH	polycyclic aromatic hydrocarbons
PERMANOVA	Permutational Analysis of Variance
PCA	Principal Components Analysis
PCO	Principal Coordinates analysis
TOC	Total Organic Carbon

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