Integrated hazard, risk and impact assessment of tropical marine sediments from Tema Harbour (Ghana)

Article in Chemosphere · February 2017
DOI: 10.1016/j.chemosphere.2017.02.138

7 authors, including:

Benjamin Botwe
University of Ghana
18 PUBLICATIONS 89 CITATIONS
SEE PROFILE

Cor A Schipper
Deltas
56 PUBLICATIONS 671 CITATIONS
SEE PROFILE

Johannes Teuchies
University of Antwerp
20 PUBLICATIONS 230 CITATIONS
SEE PROFILE

Ronny Blust
University of Antwerp
568 PUBLICATIONS 14,614 CITATIONS
SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Biofilm Reactor Technology and Design View project

Constructed WetRoof v.Helvoirt Groenprojecten View project

All content following this page was uploaded by Cor A Schipper on 07 March 2017.
The user has requested enhancement of the downloaded file.
Integrated hazard, risk and impact assessment of tropical marine sediments from Tema Harbour (Ghana)

Benjamin O. Botwe a, c, *, Kristine De Schamphelaere b, c, Cor A. Schipper d, Johannes Teuchies b, Ronny Blust b, Elvis Nyarko e, Piet N.L. Lens a

a UNESCO-IHE Institute for Water Education, PO Box 3015, 2601 DA Delft, The Netherlands
b Department of Biology, Systemic Physiological and Ecotoxicological Research, University of Antwerp, Groenenborgerlaan 171, 2020 Antwerp, Belgium
c Department of Biology, Ecosystem Management Research Group, University of Antwerp, Universiteitsplein 1, B-2610 Wilrijk, Belgium
d Deltares, PO Box 177, 2600 MH Delft, The Netherlands
e University of Ghana, Department of Marine and Fisheries Sciences, PO Box LG 99, Legon, Accra, Ghana

HIGHLIGHTS
- Whole-sediment bioassays indicated severe toxicity in Tema Harbour sediments.
- C. volutator exhibited greater sensitivity to the sediment toxicity than H. diversicolor.
- A logarithmic correlation was observed between sediment Cd concentration and C. volutator mortality.
- A linear correlation was observed between sediment Cu concentration and H. diversicolor mortality.
- Tema Harbour sediments are not suitable for disposal at sea without remediation.

ARTICLE INFO
Article history:
Received 20 December 2016
Received in revised form
17 February 2017
Accepted 27 February 2017
Available online 28 February 2017
Handling Editor: Jim Lazorchak

Keywords:
Bioaccumulation
Corophium volutator
Hediste diversicolor
Impact assessment
Metals
Whole-sediment bioassay

ABSTRACT
The potential ecological hazard, risk and impact of tropical marine sediments from the Tema Harbour (Greater Accra, Ghana) was investigated by integrating Corophium volutator and Hediste diversicolor whole-sediment toxicity bioassays with data on the metals (Cd, Pb, Cr, Ni, Cu, Zn and As) concentrations of the sediments. The whole-sediment toxicity bioassay results showed that sediments of the Tema Harbour are potentially hazardous to marine benthic invertebrates. C. volutator exhibited a higher vulnerability to the sediment toxicity than H. diversicolor, although the latter showed higher biota-sediment accumulation factors for the investigated metals. Statistically significant correlations were observed between C. volutator mortality and sediment Cd concentration ($r = 0.84, p < 0.05; n = 6$) and between H. diversicolor mortality and sediment Cu concentration ($r = 0.94, p < 0.05; n = 5$). Comparison of metal concentrations with international action levels for contaminated sediment disposal indicates that the Tema Harbour sediments contain potentially hazardous concentrations of Cu and Zn. This study shows that sediments from the Tema Harbour are not suitable for disposal at sea without remediation. There is, therefore, a need to improve environmental management and regulate the disposal of dredged material originating from the Tema Harbour.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Contaminated sediments can be a source of hazardous contaminants to aquatic organisms, particularly benthic species (Burgess et al., 2007; Birch and Hutson, 2009). These benthic organisms play important roles in the functioning of aquatic ecosystems, such as biogeochemical cycling (Durou et al., 2007) and as a source of food for other species in the aquatic food chain (Burton Jr, 2002; Birch and Hutson, 2009; Carvalho et al., 2011; Gaion et al., 2014). The impact of contaminated sediments on benthic organisms can thus have serious consequences for the entire food chain (Burton Jr, 2002; Gaion et al., 2014) and the proper functioning of aquatic ecosystems. Consequently, sediment contamination is a major issue and information on the associated potential adverse
ecological impact is of great interest to environmental regulators (Birch and Hutson, 2009; Schipper et al., 2010). Several biological effect-based sediment quality guidelines (SQGs) have been developed as predictive tools for assessing the potential of contaminated sediments to cause adverse biological effects (Burton Jr, 2002; Long et al., 2006; Schipper et al., 2013).

The abilities of SQGs to predict adverse biological effects associated with contaminated sediments are, however, limited, since SQGs do not account for: (1) contaminant bioavailability (Schipper et al., 2010); (2) synergistic or antagonistic effects of contaminant mixtures present in sediments under natural conditions (Ciarelli et al., 1998; Forrester et al., 2003; Eisenraeger et al., 2004; Schipper et al., 2010); (3) multiple effects that may be exhibited by a single contaminant (Eggen et al., 2004); (4) chronic effects that may result from long-term exposure to low concentrations of contaminants present in sediments (Eggen et al., 2004) and (5) contaminants present in sediments without being measured or identified as toxic or hazardous substances (Eisenraeger et al., 2004; Burgess et al., 2007). Consequently, whole-sediment toxicity bioassays have been recommended for the ecotoxicological characterisation of contaminated sediments to overcome the limitations of the SQG approach (Annicchiarico et al., 2007; Re et al., 2009; Schipper et al., 2010). Whole-sediment toxicity bioassays involve the exposure of pollution-sensitive benthic invertebrates to contaminated sediments under laboratory conditions (Forrester et al., 2003). Integrating whole-sediment bioassays with the SQG approach can provide valuable insight into contaminants potentially contributing to sediment toxicity.

Marine benthic invertebrates such as C. volutator (Stronkhorst et al., 2003; Scarlett et al., 2007; van den Heuvel-Greve et al., 2007; Mayor et al., 2008) and H. diversicolor (Moreira et al., 2006; Mayor et al., 2008) are often employed as bio-indicators of pollution in marine and estuarine whole-sediment toxicity bioassays. Preference for C. volutator is due to its ease of collection and maintenance under laboratory conditions, availability in the field throughout the year, and tolerance to a wide range of salinities, sediment grain sizes and organic carbon contents (Ciarelli et al., 1998; Roddie and Thain, 2002; Scaps, 2002; Bat, 2005). H. diversicolor commonly occurs in intertidal areas, is able to survive in hypoxic and contaminated environments and exhibits tolerance to wide fluctuations in salinity and temperature (Scaps, 2002; Philippe et al., 2008). Both C. volutator and H. diversicolor have wide geographic distributions across polar, temperate and tropical marine regions (Bat, 2005; Moreira et al., 2006; Uwadiae, 2010; Carvalho et al., 2011). However, standard whole-sediment toxicity bioassay protocols have been developed mainly with temperate C. volutator (Roddie and Thain, 2002; Schipper et al., 2006) and H. diversicolor (Hannewijk et al., 2004) with mortality as toxic response (endpoint), whereas whole-sediment toxicity bioassays with tropical species are not well developed (Adams and Stauber, 2010). Therefore, studies on the use of C. volutator and H. diversicolor bioassays to assess the toxicity of sediments from tropical marine environments are scarce. With over 50% of the world’s population living in coastal zones (Petrosillo et al., 2009), the coastal marine environment is characterised by intense anthropogenic activities such as waste disposal, crude oil extraction and oil spills, shipping, fishing, agriculture and industrialisation (Petrosillo et al., 2009; Lepland et al., 2010; Schipper et al., 2010). This is also the case for the tropical marine Tema Harbour in Greater Accra (Ghana). Anthropogenic activities are a source of a wide range of hazardous substances, which adversely impact organisms inhabiting the coastal marine environment (Petrosillo et al., 2009; Lepland et al., 2010; Schipper et al., 2010); previous studies have shown that sediments of the Tema Harbour are contaminated by polycyclic aromatic hydrocarbons and organochlorine pesticide residues (Botwe et al., 2017) and metals (Nyarko et al., 2014; Botwe et al., unpublished results). Since Tema Harbour sediments are dredged periodically with subsequent disposal/storage under seawater, assessment of sediment quality is required to guide sediment management decisions at Tema Harbour and minimise adverse ecological impact. Therefore, the objectives of this study were to investigate: (1) the overall potential toxicity (hazard) of Tema Harbour sediments, (2) the potential risk (toxicity and bioavailability) of metal contamination in the sediments and (3) the potential impact (bioaccumulation) of metal contamination in the Tema Harbour sediments on benthic invertebrates by integrating whole-sediment toxicity bioassays with metal contamination data.

2. Materials and methods

2.1. Study area

The Tema Harbour in Greater Accra (Ghana) is a semi-enclosed coastal marine harbour with a water area of approximately 2 km², which forms part of the Gulf of Guinea (Fig. 1). The salinity of the Tema Harbour water ranges from 30 to 35‰. The Tema Harbour is complemented into a Main Harbour, an Inner Fishing Harbour, an Outer Fishing Harbour and a Canoe Basin, which are bound to experience different anthropogenic impacts. The Main Harbour, the Inner Fishing Harbour and the Canoe Basin have been in operation since 1962, while the Outer Fishing Harbour was constructed in 1965. Various ships including oil tankers, bulk carriers, general cargo ships and container ships call at the Main Harbour. The Fishing Harbour provides handling facilities for semi-industrial and industrial fishing vessels such as trawlers, tuna vessels, and deep-sea carriers, while the Canoe Basin is a dedicated artisanal canoe fishing landing site. To ensure safe navigation, the Main Harbour is subject to dredging since 1998, whereas the Canoe Basin was dredged in May 2013. No dredging has yet been conducted in the Fishing Harbour. Located within an industrial setting, the Tema Harbour is subject to contamination not only from maritime operations (e.g. bunkering and refuelling, maintenance and repairs of vessels), but also from industrial activities (e.g. wastewater discharges into the harbour).

2.2. Sediment sampling

Grab sediment samples were collected from thirty stations (1–30) within the Tema Harbour (Fig. 1) in January 2016 using a stainless steel 3.5 L Ekman grab. The grab samples were composited to obtain five samples for analysis. In the Main Harbour, grabs 1–6 were composited to form sample MH1, while grabs 7–12 formed sample MH2. All grabs from the Outer Fishing Harbour (13–18) were composited into sample OFH, grabs from the Inner Fishing Harbour (19–24) formed sample IFH, while grabs from the Canoe Basin (25–30) formed sample CB (Fig. 1). All composite samples were mixed thoroughly with a plastic shovel in acid-washed plastic bowls before taking about 3.5 L portions into 3.78 L FoodSaver® zipper bags. All the samples were sealed air-tight using a hand-held vacuum pump and kept on ice in an ice-cool box in the field and during transportation to the Marine and Fisheries Department laboratory at the University of Ghana (Accra, Ghana), where they were stored overnight in a refrigerator at 4 ºC. The samples were kept chilled in an ice-cool box and transported by air to the Systemic Physiological and Ecotoxicological Research laboratory (SPHERE) at the University of Antwerp (Belgium). The samples were kept there in a cold room at 4 ºC until the bioassay experiments were conducted within 2 weeks of sample collection (Roddie and Thain, 2002).
2.3. Sampling of test organisms

The test organisms, C. volutator and H. diversicolor, were collected from the Eastern Scheldt estuary located in the south-western part of the Netherlands, which is used as a non-contaminated control site for conducting whole-sediment bioassays (Kater et al., 2006; van den Heuvel-Greve et al., 2007). The field collection of C. volutator followed standard guidelines used around the world (Roddie and Thain, 2002). C. volutator were collected at low tide, when the shore was exposed, by carefully removing the upper 5 cm layer of sediments with a small stainless steel shovel into 10 L plastic buckets. The sediments were subsequently sieved over a 0.5 mm mesh with seawater from the same area (salinity of 30–31‰) into a separate 10 L plastic bucket while the C. volutator retained on the sieve were carefully transferred into another 10 L plastic bucket containing seawater. The sieved sediment (about 2 kg) was mixed thoroughly and kept as control sediment for the C. volutator bioassay.

H. diversicolor was carefully collected by hand along the banks of the Eastern Scheldt estuary, together with some of their associated sediments, and placed in a 10 L plastic bucket. The sediment was then covered by a layer of about 20 cm estuarine water. About 3 kg of sediment was also collected from the same area and sieved over a 0.5 mm mesh with some estuarine water from the same area into a 10 L plastic bucket to serve as control sediment for the H. diversicolor bioassay.

During sampling, care was taken to ensure that the C. volutator and H. diversicolor were not damaged. The collected samples were transported to the SPHERE laboratory, where the C. volutator and H. diversicolor aquaria were kept under continuous aeration at 15 °C in a climate-controlled room for 7 d for organisms to acclimatise prior to the whole-sediment bioassays. The water salinity in the aquaria was monitored with a conductivity meter (HACH, USA) during the acclimatisation period and kept at 30% by the addition of deionised water.

2.4. Laboratory bioassay experiments

The standard acute 10-day C. volutator whole-sediment bioassay as described by Roddie and Thain (2002) and Schipper et al. (2006) was adopted. The Ci volutator used were of similar sizes (typically 4–5 mm long). The bioassays were conducted on sediments from the Tema Harbour and the reference site (control) in acid-washed 1.5 L wide-mouth glass bottles. Each set-up contained 200 mL homogenised sediment sample (about 3 cm thick), 600 mL well-aerated artificial seawater (about 12 cm depth of overlying seawater) of 30% salinity and 20 active individuals of C. volutator. Five (5) replicates were prepared for the control and the Tema Harbour sediment bioassays, except for the MH1 (n = 4) and OFH (n = 3) bioassays, due to loss of sample during transport.

The standard chronic 28-day H. diversicolor whole-sediment bioassay as described by Hannewijk et al. (2004) was adopted. H. diversicolor of similar mass (typically 0.2–0.3 g fresh weight) were used. The bioassays were conducted on sediments from the Tema Harbour and the reference site (control) in acid-washed 0.5 L wide-mouth glass bottles. Each set-up contained 100 mL homogenised sediment samples (about 3 cm thick), 120 mL artificially prepared seawater (about 6 cm depth of overlying seawater) and one active H. diversicolor. Fifteen (15) replicates were prepared for the control bioassay, while the number of bioassay replicates prepared per type of Tema Harbour sediment varied from 10 to 13, due to limited quantity of sediment sample. No CB sediment sample was available to conduct the H. diversicolor bioassay.

Prior to the introduction of C. volutator and H. diversicolor, the overlying seawater in each bottle was aerated continuously for 48 h to ensure adequate supply of oxygen, while avoiding sediment resuspension. Moreover, care was taken to ensure that the organisms were not damaged while being introduced into the bottles. All bioassays were conducted at a temperature of 15 ± 1 °C and under a light regime of 16 h light and 8 h darkness. Periodic measurements of pH, salinity and dissolved oxygen (DO) levels of the overlying seawater were conducted from the start till the end of the exposure period using a pH meter, conductivity meter and DO meter (HACH, USA), respectively, and adjustments to the initial salinity were made when necessary. H. diversicolor were fed 3 times per week with 30 mg of ground fish food (TetraMin® XL Flakes) (Hannewijk et al., 2004), while their overlying seawater was renewed weekly to minimise the potential build-up of ammonia and hydrogen sulphide (Ferretti et al., 2000). At the end of their exposure periods, C. volutator were gently sieved over a 0.5 mm mesh, while H. diversicolor were gently removed with a pair of forceps. The organisms were then rinsed with artificial seawater to remove adhering particles and the numbers of living organisms were counted to determine mortalities.

2.5. Analyses of metal, sediment grain size and TOC contents

Upon completion of the bioassays, the organisms and sediment samples were freeze-dried prior to analyses of their metal contents. Metal analysis in C. volutator and H. diversicolor was based on whole-body tissues. H. diversicolor were analysed individually for metals. In the case of C. volutator, five composite samples were obtained from each replicate by pooling four individuals together and subsequently analysing their metal content. The freeze-dried C. volutator and H. diversicolor samples, together with 0.2 g portions of a mussel-based standard reference material (SRM 2976) from the National Institute of Standards and Technology (NIST, Luxembourg, Belgium) and procedural blanks were subjected to microwave-assisted digestion using 2 mL HNO3 (for H. diversicolor) or 0.5 mL HNO3 (for C. volutator).

About 0.2 g portions of freeze-dried homogenised sediment samples, a sediment certified reference material (BCR-701) and procedural blanks were analysed for total metal concentrations and metal fractionation by adopting the harmonised Community Bureau of Reference (BCR) 3-step sequential extraction and aqua regia extraction techniques, respectively, following Pueyo et al. (2001). The metal concentrations were measured using ICP-MS (Varian, Australia). The dry sediments were also analysed for their grain-size distribution by the Malvern laser diffraction method (Blott et al., 2004), while total organic carbon (TOC) was analysed by the Walkley-Black wet oxidation method following Botwe et al. (2017). The mean metal recoveries in the standard BCR-701 samples ranged between 77 and 116% with relative standard deviation (RSD) of 1.3–11.8%, while the mean metal recoveries in the NIST SRM 2976 varied between 86 and 102% with RSD of 0.6–5.3%, depending on the metal measured. Metal concentrations in the biota and sediment samples were corrected for recovery, using their respective mean recoveries in the certified reference materials.

2.6. Data analysis

One-way analysis of variance (ANOVA) and Holm-Sidak multiple comparison tests or Kruskal-Walliss one-way ANOVA on ranks (where normality test failed) were used to test for significant differences in C. volutator and H. diversicolor mortalities as well as metal concentrations in sediments across sites by using the statistical software SigmaPlot (version 11.0). Using the same software, normality and equal variance tests were performed with the Shapiro-Wilk and Levene’s mean tests, respectively. Two-tailed
Pearson correlations (using SPSS, version 16.0) among metal bio-accumulation factor, metal concentration in sediment, mortality and TOC content in sediment were determined separately for *C. volutator* (*n* = 6) and *H. diversicolor* (*n* = 5).

Regression plots were made to determine linear associations between measured parameters of interest using MS Excel 2007. To characterise the potential ecological impact of metal contamination in Tema Harbour sediments, biota-sediment accumulation factors...
(BSAFs) were estimated by dividing the metal concentrations in whole-body tissues of C. volutator and H. diversicolor by the corresponding concentrations in the sediment (Aydin-Onen et al., 2015). A BSAF >1.0 is indicative that metal bioaccumulation has occurred, and the greater the BSAF, the greater the bioaccumulation efficiency (Aydin-Onen et al., 2015). When necessary, raw metal concentrations were normalised to the <63 μm fraction of sediments as follows (Horowitz, 1985):

\[
\text{[Metal]n} = \frac{100}{\text{<63 μm fraction of sediment(%)}} \times \text{[metal]r}
\]

(1)

where [Metal]n is the normalised metal concentration and [metal]r is the raw metal concentration.

3. Results

3.1. C. volutator and H. diversicolor mortalities in the whole-sediment bioassays

The mean C. volutator mortalities in the MH1, MH2, OFH, IFH, CB and control bioassays were 29, 38, 77, 98 and 7%, respectively (Fig. 2). One-way ANOVA (p < 0.001; n = 6) followed by the Holm-Sidak multiple comparison test (p < 0.05; n = 6) showed that the mortalities of C. volutator in the Tema Harbour sediment bioassays were significantly higher than those of the control bioassays with the following mortality trend across the Tema Harbour sediments: MH1 < MH2 < OFH < IFH < CB. The H. diversicolor mortalities in the MH1, MH2, OFH and IFH bioassays were 46, 15, 10 and 92%, respectively, while the control mortality was 7% (Fig. 3). As in the case of C. volutator, the highest H. diversicolor mortality was associated with the IFH sediments. However, Fig. 3 shows that the trend in H. diversicolor mortality across the Tema Harbour sediments was OFH < MH2 < MH1 < IFH, which contrasted with the trend in C. volutator mortality (Fig. 2): the MH2 and OFH sediments caused low H. diversicolor mortalities (10–15%) but high C. volutator mortalities (38–77%).

3.2. Physicochemical conditions of water and sediments from the Tema Harbour and control bioassays

The physicochemical conditions of water and sediments from the Tema Harbour and control bioassays are summarised in Table 1. The salinity, pH and dissolved oxygen (DO) levels of the overlying water during the bioassay experiments varied between 28 and 34‰, 7.7–8.5 and 7.4–8.7 mgL⁻¹, respectively. There were marked differences in the grain size distributions of the Tema Harbour and control sediments: whereas sand (63–500 μm fraction) dominated the control sediment (62–90%), a predominance (63–88%) of silt (4–63 μm fraction) was present in the Tema Harbour sediments. However, the control sediments had a relatively higher TOC content (5.2–5.9%) than the Tema Harbour sediments (2.9–4.2%). Neither sediment grain size nor TOC content correlated significantly with both C. volutator mortality and H. diversicolor mortality.

3.3. Total metal concentrations and metal fractionation in the analysed sediments

The mean total metal concentrations in the Tema Harbour sediments (mg.kg⁻¹ dw) ranged from 0.07 to 1.16 for Cd, 24.9–102 for Pb, 50.1–80.3 for Cr, 17.4–277 for Ni, 33.4–210 for Cu, 98–730 for Zn, and 7.9–14.2 for As (Table 2). One-way ANOVA (p < 0.001) followed by the Holm-Sidak multiple comparison test revealed significant differences (p < 0.05; n = 6) in the total concentrations of Pb and Zn (i.e., CB > IFH > OFH > MH1 > MH2), Cr (i.e., IFH > OFH > MH1 > CB > MH2) and Ni (i.e., OFH > IFH > MH1 > CB > MH2) across the Tema Harbour sediments. Kruskal-Wallis one-way ANOVA on ranks also revealed significant differences in the sediment concentrations of Cd (p < 0.003), Cu (p < 0.004) and As (p < 0.004) across the Tema Harbour bottom. The CB sediments had the highest Cd concentration, whereas the IFH sediments had the highest Cu and As concentrations. The mean concentrations for each metal for the Tema Harbour sediments were greater than the means for the Eastern Scheldt (control) sediments, except for Cd. A statistically significant correlation was observed between sediment Cd concentration and C. volutator mortality (r = 0.84, p < 0.05; n = 6), with a high coefficient of determination (r² = 0.85) (Fig. 4). In the case of H. diversicolor, a statistically significant correlation was observed between mortality and sediment Cu concentration (r = 0.94, p < 0.05; n = 5), with a high coefficient of determination (r² = 0.89) (Fig. 4).

The fractionation of metals among exchangeable, reducible, oxidisable, and residual phases in the Tema Harbour sediments is shown in Table 3. Zn was present in appreciable amounts in all four fractions. The sediments contained considerable fractions of exchangeable metals only for Cd (15.7–46.8%) and Zn (8.6–32.6%), Cd: (96.1–95.7%), Pb: (81.3–95.9%), Cu: (54.1–90.5%) and Zn: (72.2–96.5%) were mainly present in the labile (i.e., the exchangeable, reducible and oxidisable) fractions rather than in the residual fraction. In contrast, Cr, Ni and As were predominantly present in the residual fraction, except for the IFH and CB sediments.

3.4. Metal bioaccumulation in C. volutator and H. diversicolor

Table 4 presents the mean concentrations of metals in whole-body tissues of C. volutator and H. diversicolor as well as their corresponding biota-sediment accumulation factors (BSAFs). The mean tissue Cd, Pb, Cr, Ni, Cu, Zn and As concentrations of C. volutator exposed to the Tema Harbour sediments were, respectively, 1–5, 4–17, 1–5, 2–5, 2–12, 2–7 and 1–5 times those of the controls. Similarly, the mean tissue Cd, Pb, Cr, Ni, Cu, Zn and As concentrations of H. diversicolor exposed to the Tema Harbour sediments were, respectively, 0–13, 4–10, 1–6, 1–3, 3–5, 3–4 and 2–4 times those of the controls. Generally, the metal BSAFs for H. diversicolor were markedly higher than those of C. volutator (except in some cases of Cd). In the tissues of C. volutator, Zn and Cu were found in the highest concentrations relative to the other metals, while Zn was found in the highest concentrations in H. diversicolor. However, for both C. volutator and H. diversicolor, the BSAFs of As were relatively higher than those of the other metals investigated. For all the metals investigated, no statistically significant correlations (p > 0.05) were observed between the sediment and tissue concentrations in C. volutator and H. diversicolor.

4. Discussion

4.1. Hazard potential of Tema Harbour sediments

This study showed that the mean C. volutator mortalities in the Tema Harbour sediment bioassays exceeded the mean control mortality by >20% (Fig. 2), indicating that all the Tema Harbour sediments were toxic or hazardous to C. volutator (EFSA, 1998). According to the International Council for the Exploration of the Sea based on C. volutator whole-sediment bioassays (ICES, 2009), sediment toxicity is classified as “elevated” or “high concern” if the C. volutator mortality exceeds that of the control by >30% and >60%, respectively. Thus, the MH2 sediments had elevated toxicity, whereas the toxicities of the OFH, IFH and CB sediments were of
high concern. During the exposure period, no burrowing activity was observed in the IFH and CB sediments as most of the C. volutator avoided these sediments and kept swimming in the water column. This behaviour, which was not observed in the control and the remaining sediments, is an indication that C. volutator avoided the highly toxic sediments (Bat and Raffaelli, 1998; Bat, 2005).

Higher mortalities of H. diversicolor were observed in the MH1 (46%) and IFH (92%) sediment bioassays than in the control (7%), indicating that the MH1 and IFH sediments were also hazardous to H. diversicolor. However, the mortalities of H. diversicolor in the MH2 (15%) and the OFH (10%) were within the acceptable mortality of 10–15% (Thain and Bifield, 2002; ICES, 2008). As in the case of C. volutator, no burrowing activity of H. diversicolor was observed in the IFH sediments, possibly due to the high toxicity of the sediment (Bat and Raffaelli, 1998).

C. volutator and H. diversicolor exhibited strikingly different vulnerabilities towards the toxicities of the MH2 and OFH sediments, which underscores the importance of using a battery of species in whole-sediment toxicity bioassays (Bat and Raffaelli, 1998; DelValls et al., 2004; Eisenraeger et al., 2004; Annicchiarico et al., 2007; Schipper et al., 2010). Figs. 2 and 3 show that the MH2 and OFH sediments caused higher mortalities of C. volutator (38 and 77%, respectively) than H. diversicolor (15 and 10%, respectively). This observation supports previous findings that amphipods such as C. volutator are more sensitive to sediment toxicity than polychaetes such as H. diversicolor (Long et al., 2006). Moreover, sediments are often contaminated by a range of toxicants (Burton Jr. 2002; Forrester et al., 2003; Long et al., 2006), which may potentially impose different toxic responses on C. volutator and H. diversicolor. For example, Bat and Raffaelli (1998) have shown that C. volutator and the marine polychaete Arenicola sp. have different sensitivities to Cu, Cd and Zn. They observed that lethal concentrations (LC50) of Cu, Cd and Zn differed for C. volutator (37, 14 and 32 mg kg⁻¹ dw, respectively) and Arenicola sp. (20, 35 and 50 mg kg⁻¹ dw, respectively). This indicates that C. volutator is more sensitive to Cd and Zn, but less sensitive to Cu, than Arenicola sp.

The lower sensitivity of C. volutator to Cu compared to H. diversicolor has also been observed by Mayor et al. (2008), who reported LC50 values of 193 and 75 mg kg⁻¹, respectively. The levels of Cd in the Tema Harbour sediments were much lower than the LC50 value of Cd for C. volutator, reported by Mayor et al. (2008). The levels of Cu (except for the MH2 sediments) and Zn in the Tema Harbour sediments exceeded their corresponding LC50 values reported for C. volutator (Bat and Raffaelli, 1998). This suggests that Cu and Zn may play a significant role in the toxicity of the Tema Harbour sediments. Bat and Raffaelli (1998) also observed that the mortality of C. volutator increased with increasing sediment Cu, Cd and Zn concentrations. In this study, statistically significant correlations were observed between C. volutator mortality and sediment Cd concentration and between H. diversicolor mortality and sediment Cu concentration. Scatter plots show that the former correlation is logarithmic with a high regression coefficient (R²) of 0.85, whereas the latter correlation is linear with a high R² of 0.88 (Fig. 4a and b). The variation in sediment Cd and Cu concentrations could explain the variation in C. volutator and H. diversicolor mortalities, respectively. In the Main Harbour, for example, the Cu level in the MH1 sediment was higher than that of the MH2 sediment, the former resulting in a correspondingly higher H. diversicolor mortality. Although the level of Cu in the MH2 sediment was lower than that of the OFH sediment, the latter resulted in a lower H. diversicolor mortality. Clearly, other factors apart from the measured metals may play a role in the sediment toxicity to H. diversicolor. A potential source of the Cu contamination in the harbour sediments is the use of Cu-based antifouling paints on marine crafts to mitigate biofouling (Mukherjee et al., 2009).

Despite their markedly different vulnerabilities to the toxicities of the MH2 and OFH sediments, both C. volutator and H. diversicolor clearly distinguished the IFH sediments as being highly toxic or hazardous. The high toxicity of the CB sediments indicated by the associated high C. volutator mortality (98%) could not be confirmed by using H. diversicolor, due to limited sediment quantity. The high toxicities of sediments from the IFH, OFH and the CB are a clear indication that these areas are the most polluted within the Tema Harbour, which may be due to intense anthropogenic activities. The IFH and the OFH sustain a productive fishing industry through the provision of handling facilities for semi-industrial and industrial fishing vessels as well as a storage facility for petroleum products, while the CB is a dedicated artisanal canoe landing site. Daily, an average of 125 vessels operate from the IFH and the OFH, while the CB is normally overcrowded.

Fishing-related activities such as refuelling, painting of vessels
Table 1
Physicochemical conditions of water and sediments in bioassays of bottom sediments from Tema Harbour, Ghana and Eastern Scheldt, The Netherlands (reference controls).

<table>
<thead>
<tr>
<th>Sediment sample</th>
<th>Salinity (%)</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>Sediment grain size distribution (%)</th>
<th>TOC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;4 μm</td>
<td>4–63 μm</td>
</tr>
<tr>
<td><code>MH1</code></td>
<td>30–32</td>
<td>8.0–8.4</td>
<td>7.9–8.4</td>
<td>10</td>
<td>79</td>
</tr>
<tr>
<td><code>MH2</code></td>
<td>30–32</td>
<td>7.8–8.3</td>
<td>8.2–8.5</td>
<td>8</td>
<td>63</td>
</tr>
<tr>
<td><code>OFH</code></td>
<td>30–33</td>
<td>7.7–8.4</td>
<td>7.9–8.1</td>
<td>12</td>
<td>85</td>
</tr>
<tr>
<td><code>IFH</code></td>
<td>30–32</td>
<td>7.8–8.5</td>
<td>7.4–7.8</td>
<td>12</td>
<td>88</td>
</tr>
<tr>
<td><code>CB</code></td>
<td>30–32</td>
<td>8.1–8.5</td>
<td>8.0–8.5</td>
<td>10</td>
<td>86</td>
</tr>
<tr>
<td><code>RC</code></td>
<td>30–34</td>
<td>8.2–8.5</td>
<td>8.1–8.5</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td><code>RH</code></td>
<td>28–31</td>
<td>8.0–8.4</td>
<td>7.9–8.7</td>
<td>4</td>
<td>34</td>
</tr>
</tbody>
</table>

a Sediments from Tema Harbour.
b Reference sediment from C. volutator site.
c Reference sediment from H. diversicolor site.

Table 2
Mean (n = 3) concentrations of selected metals in sediments from Tema Harbour, Ghana and Eastern Scheldt, The Netherlands reference sites, and sediment quality guidelines (mg kg⁻¹ dw⁻¹).

<table>
<thead>
<tr>
<th>Sediment sample</th>
<th>Cd</th>
<th>Pb</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>MH1</code></td>
<td>0.12 ± 0.00</td>
<td>39.7 ± 1.4</td>
<td>63.6 ± 1.6</td>
<td>24.2 ± 0.5</td>
<td>100 ± 0.4</td>
<td>190 ± 7</td>
<td>7.9 ± 0.2</td>
</tr>
<tr>
<td><code>MH2</code></td>
<td>0.07 ± 0.00</td>
<td>24.9 ± 0.9</td>
<td>50.1 ± 0.8</td>
<td>17.4 ± 0.5</td>
<td>33.4 ± 0.5</td>
<td>98.0 ± 14</td>
<td>8.5 ± 0.2</td>
</tr>
<tr>
<td><code>OFH</code></td>
<td>0.19 ± 0.00</td>
<td>50.6 ± 0.6</td>
<td>78.0 ± 0.2</td>
<td>27.7 ± 1.2</td>
<td>78.0 ± 2.1</td>
<td>244 ± 3</td>
<td>13.0 ± 0.2</td>
</tr>
<tr>
<td><code>IFH</code></td>
<td>0.43 ± 0.03</td>
<td>84.3 ± 0.9</td>
<td>80.3 ± 0.3</td>
<td>260 ± 1.0</td>
<td>210 ± 7</td>
<td>415 ± 4</td>
<td>14.2 ± 0.5</td>
</tr>
<tr>
<td><code>CB</code></td>
<td>1.16 ± 0.05</td>
<td>102 ± 2</td>
<td>61.2 ± 0.9</td>
<td>233 ± 0.5</td>
<td>195 ± 1</td>
<td>730 ± 5</td>
<td>12.6 ± 0.3</td>
</tr>
<tr>
<td><code>RC</code></td>
<td>0.04 ± 0.01</td>
<td>46.2 ± 0.2</td>
<td>15.1 ± 0.5</td>
<td>3.0 ± 0.1</td>
<td>3.0 ± 0.2</td>
<td>147 ± 0.4</td>
<td>3.6 ± 0.1</td>
</tr>
<tr>
<td><code>RH</code></td>
<td>0.21 ± 0.02</td>
<td>11.1 ± 0.7</td>
<td>20.4 ± 0.8</td>
<td>6.5 ± 0.6</td>
<td>6.5 ± 0.6</td>
<td>47.8 ± 4.4</td>
<td>5.7 ± 0.5</td>
</tr>
<tr>
<td><code>ERL</code></td>
<td>1.2</td>
<td>46.7</td>
<td>81</td>
<td>20.9</td>
<td>34</td>
<td>150</td>
<td>8.2</td>
</tr>
<tr>
<td><code>ERM</code></td>
<td>9.6</td>
<td>218</td>
<td>370</td>
<td>51.6</td>
<td>270</td>
<td>410</td>
<td>70</td>
</tr>
</tbody>
</table>

a Same definition as in Table 1.
b Sediment quality guidelines (DelValls et al., 2004); ERL represents a metal concentration associated with rare occurrence of harmful biological effects, the ERL-ERM interval represents a range of metal concentrations likely to cause harmful biological effects occasionally, while the ERM represents a metal concentration likely to cause harmful biological effects frequently (Long et al., 1995).
significant role in the toxicity of the Tema Harbour sediments, and identifies the IFH and the CB as priority areas for management and remediation attention in the Tema Harbour. The levels of Ni and Cu (except for the MH2 sediment, where they may pose low potential risks), as well as As (except for the MH1 sediment, where the potential risk is low) pose moderate potential ecotoxicological risks.

The levels of Pb in sediments from the IFH, OFH and the CB were associated with moderate potential ecotoxicological risks, while those of the MH1 and the MH2 sediments were associated with low potential ecotoxicological risks.

Table 3

<table>
<thead>
<tr>
<th>Sediment sample</th>
<th>Sediment phase</th>
<th>Fraction of metals (%) associated with the different sediment phases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cd</td>
<td>Pb</td>
</tr>
<tr>
<td>MH1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exchangeable</td>
<td>46.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Reducible</td>
<td>30.7</td>
<td>79.6</td>
</tr>
<tr>
<td>Oxidisable</td>
<td>19.6</td>
<td>6.3</td>
</tr>
<tr>
<td>Residual</td>
<td>2.9</td>
<td>11.2</td>
</tr>
<tr>
<td>Labile</td>
<td>97.1</td>
<td>88.8</td>
</tr>
<tr>
<td>MH2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exchangeable</td>
<td>23.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Reducible</td>
<td>39.3</td>
<td>74.2</td>
</tr>
<tr>
<td>Oxidisable</td>
<td>33.5</td>
<td>10.6</td>
</tr>
<tr>
<td>Residual</td>
<td>3.9</td>
<td>13.7</td>
</tr>
<tr>
<td>Labile</td>
<td>96.1</td>
<td>86.3</td>
</tr>
<tr>
<td>OFH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exchangeable</td>
<td>36.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Reducible</td>
<td>46.8</td>
<td>78.8</td>
</tr>
<tr>
<td>Oxidisable</td>
<td>14.7</td>
<td>7.5</td>
</tr>
<tr>
<td>Residual</td>
<td>2.6</td>
<td>12.5</td>
</tr>
<tr>
<td>Labile</td>
<td>97.4</td>
<td>87.5</td>
</tr>
<tr>
<td>IFH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exchangeable</td>
<td>32.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Reducible</td>
<td>53.5</td>
<td>74.0</td>
</tr>
<tr>
<td>Oxidisable</td>
<td>13.9</td>
<td>17.0</td>
</tr>
<tr>
<td>Residual</td>
<td>0.6</td>
<td>8.2</td>
</tr>
<tr>
<td>Labile</td>
<td>99.4</td>
<td>91.8</td>
</tr>
<tr>
<td>CB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exchangeable</td>
<td>15.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Reducible</td>
<td>70.5</td>
<td>76.2</td>
</tr>
<tr>
<td>Oxidisable</td>
<td>13.4</td>
<td>18.6</td>
</tr>
<tr>
<td>Residual</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>Labile</td>
<td>99.7</td>
<td>95.0</td>
</tr>
</tbody>
</table>

Risk assessment code (RAC) based on the percentage of sediment-associated metal in the exchangeable phase is as follows (Jain, 2004): no risk (<1%), low risk (1–10%), medium risk (11–30%), high risk (31–50) and very high risk (>50%).

Metals fractionate over different phases in sediment: the exchangeable (carbonate-bound), reducible (iron/manganese oxide-bound), oxidisable (organic/sulphide-bound) and residual/refractory (silicate/mineral-bound) phases. Metals in the exchangeable phase are the most weakly bound and represent the potentially bioavailable fraction (Jain, 2004; Iqbal et al., 2013). Based on the percentage of metal in the exchangeable phase, also known as the risk assessment code (RAC), the potential risks were characterised as follows (Jain, 2004): no risk (<1%), low risk (1–10%), medium risk (11–30%), high risk (31–50) and very high risk (>50%). Thus, the measured metal concentrations in the Tema Harbour sediments pose the following potential ecological risks: medium-high risk for Cd; low to high risk for Zn; low risk for As; no to low risk for Pb, Ni and Cu; and no risk for Cr (Table 3).

The relatively higher exchangeable fractions of Cd (15.7–46.8%) and Zn (8.6–32.6%) (Table 3) indicate that Cd and Zn had the highest potential of entering the food chain (Jain, 2004; Iqbal et al., 2013). The predominance of Cd, Pb, Cu and Zn in the labile phase, rather than the residual phase, suggests that these metals are derived predominantly from anthropogenic sources (Jain, 2004). Ni was predominantly in the residual phase, suggesting that it is mainly of natural origin. With regards to Cr and As, a predominance of the labile phase was observed in sediments from the IFH and the CB, suggesting greater anthropogenic influences in these areas of the Tema Harbour.

4.3. Potential ecological impact of sediment-associated metal in Tema Harbour

Benthic organisms can accumulate sediment-associated contaminants e.g. through direct ingestion of sediments (Burton Jr, 2002) and impact other organisms and humans via food chain transfer of the accumulated metals (Marsden and Rainbow, 2004). Table 4 shows that in most cases, the metal BSAFs for H. diversicolor exceeded 1.0, indicating a significant bioaccumulation of the investigated metals by H. diversicolor (Aydin-Onen et al., 2015). The metal BSAFs for H. diversicolor were higher than those for C. volutator, which may be attributed to the longer exposure periods for H. diversicolor (28 d) than C. volutator (10 d) and potential variability in metal bioaccumulation by different species (Marsden and Rainbow, 2004) due to e.g. potential differences in the ability to store or eliminate the metals (Adams et al., 2011). For both C. volutator and H. diversicolor, the BSAFs of As were higher than those of...
biota-sediment accumulation factors (BSAFs).

Thus, the Tema Harbour sediments can be regulated by both non-burrowing organisms (those exposed to the IFH and CB bioassays) and burrowing organisms to regulate metal uptake (Adams et al., 2011). Burrowing behaviour appeared to influence metal bioaccumulation as the non-burrowing organisms (those exposed to the IFH and CB bioassays) tend to have lower metal bioaccumulation factors. This is expected as burrowing results in increased exposure of organisms to contaminants in sediments (Bat, 2005).

4.4. Dredged material management implications for Tema Harbour

The practice of harbour dredging with subsequent disposal at sea poses a potential hazard to biota in the receiving site as dredged materials are often found to contain hazardous concentrations of chemical contaminants (Marsden and Rainbow, 2004; Schipper et al., 2010). To guide the management and disposal of dredged materials, countries such as the Netherlands and Spain have developed sediment quality guidelines or action levels, which represent potentially hazardous concentrations of chemical pollutants (DelValls et al., 2004; Casado-Martinez et al., 2006; Kelderman, 2012; Schipper et al., 2013).

Currently, no regulatory standards have been established for dredged materials in Ghana, despite routine maintenance dredging with subsequent disposal or storage at sea. Thus, in addition to the bioassay tests, the Spanish action levels (action levels 1 and 2) for dredged materials (DelValls et al., 2004; Casado-Martinez et al., 2006) were compared to the data for this study. These Spanish action levels are based on the probability of their associated chemical concentrations to cause adverse effects in marine biota (Casado-Martinez et al., 2006) and are presented in Table 6. Based on these action levels, dredged materials may be classified into three categories, which can then influence decisions about their management and disposal. Category I dredged materials have pollutant concentrations below action level 1 (AL1) and their disposal at sea is allowed, whereas category II dredged materials have pollutant concentrations between AL1 and action level 2 (AL2) and thus, would require further assessments to determine their suitability for disposal at sea. Category III dredged materials have pollutant concentrations above AL2 and, therefore, would require isolation or disposal in a confined area (DelValls et al., 2004). Since the AL1 and AL2 are based on the <63 µm fraction of sediments tables.

The other investigated metals, suggesting that among the investigated metals, As was either most efficiently taken up or least regulated by both C. volutator and H. diversicolor.

In most cases, C. volutator and H. diversicolor exposed to the Tema Harbour sediments had higher tissue concentrations of metals than the controls. Thus, the Tema Harbour sediments can be a significant source of metal bioaccumulation for benthic organisms with potential adverse impact on the aquatic food chain. Although the degree of contamination in harbours may be evident from the contamination patterns in the sediments and from biomarkers (de Boer et al., 2001; Schipper et al., 2009), this is not always evident (Schipper et al., 2009). Contrary to findings of other studies (Bat and Raffaelli, 1998), no statistically significant correlations were found between metal bioaccumulation (or metal bioavailability) and the corresponding metal concentrations in sediment or TOC content in this study. Moreover, no statistically significant correlations were found between metal bioaccumulation and mortality for both C. volutator and H. diversicolor. This lack of correlation is possibly due to the potential of the organisms to regulate metal uptake (Adams et al., 2011). Burrowing behaviour appeared to influence metal bioaccumulation as the non-burrowing organisms (those exposed to the IFH and CB bioassays) tend to have lower metal bioaccumulation factors. This is expected as burrowing results in increased exposure of organisms to contaminants in sediments (Bat, 2005).

Table 4

<table>
<thead>
<tr>
<th>Sediment sample</th>
<th>Mean metal concentrations (BSAFs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cd</td>
</tr>
<tr>
<td>C. volutator</td>
<td></td>
</tr>
<tr>
<td>MH1</td>
<td>0.10</td>
</tr>
<tr>
<td>MH2</td>
<td>0.06</td>
</tr>
<tr>
<td>OFH</td>
<td>0.15</td>
</tr>
<tr>
<td>IFH</td>
<td>0.35</td>
</tr>
<tr>
<td>CB</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Table 5

<table>
<thead>
<tr>
<th>Sediment sample</th>
<th>Risk quotients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cd</td>
</tr>
<tr>
<td>MH1</td>
<td>0.10</td>
</tr>
<tr>
<td>MH2</td>
<td>0.06</td>
</tr>
<tr>
<td>OFH</td>
<td>0.15</td>
</tr>
<tr>
<td>IFH</td>
<td>0.35</td>
</tr>
<tr>
<td>CB</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Table 6

<table>
<thead>
<tr>
<th>Sediment sample</th>
<th>Mean metal concentrations (BSAFs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cd</td>
</tr>
<tr>
<td>MH1</td>
<td>0.10</td>
</tr>
<tr>
<td>MH2</td>
<td>0.06</td>
</tr>
<tr>
<td>OFH</td>
<td>0.15</td>
</tr>
<tr>
<td>IFH</td>
<td>0.35</td>
</tr>
<tr>
<td>CB</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Unbold – effects-range low quotients (ERLQs); ERLQs <1.0 indicate low potential ecological risk.

Bold – effects-range median quotients (ERMQs); ERMQs <1.0 indicate moderate potential ecological risk.

* ERMQ >1.0 indicating high potential ecological risk.

* Sediments from Tema Harbour.

* Reference sediment from C. volutator site.

* Reference sediment from H. diversicolor site; ND = not detected.
(DelValls et al., 2004), it was necessary to normalise the raw metal concentrations in the Tema Harbour sediments to the ~63 µm fraction as described in section 2.6.

Table 6 shows that the levels of Cd, Pb, Cr, Ni, Cu, Zn and As in sediments from the MH2 and OFH areas were below their corresponding AL1 values. Thus, in relation to the investigated metals, dredged materials from the MH2 and OFH areas may fall under category I, which can be disposed at sea. The levels of Cu in sediments from the MH1 and IFH were between the AL1 and AL2 values, which are potentially hazardous. Similarly, the levels of Cd, Cu and Zn in sediments from the CB were between their corresponding AL1 and AL2 values and are, therefore, potentially hazardous and, thus the disposal of these sediments at sea is inappropriate.

5. Conclusion

The standard 10-day C. volutator and 28-day H. diversicolor whole-sediment bioassays were combined with metal (Cd, Pb, Cr, Ni, Cu, Zn and As) concentrations to investigate the potential ecological hazard, risk and impact of contaminated sediments from the Tema Harbour. C. volutator was found to be more vulnerable than H. diversicolor to the toxicity effects the Tema Harbour sediments and underscores the importance of using different species in whole-sediment toxicity bioassays. The concentrations of Cu and Zn may play a role in the mortalities of C. volutator and H. diversicolor. A logarithmic correlation was observed between sediment Cd concentration and C. volutator mortality, while a linear correlation was observed between sediment Cu concentration and H. diversicolor mortality. Risk assessment based on sediment quality guidelines indicated that the metal contamination in the Tema Harbour sediments poses moderate to high potential ecological risks. The results indicate a need to improve environmental management and regulate the disposal of dredged materials at the Tema Harbour.

Acknowledgement

This study was conducted under the Netherlands Fellowship Programme (NFP-PhD. 12/316) and was financially supported by the Office of Research, Innovation and Development (ORID) of the University of Ghana under the Faculty Development Fund (UGFD/7/2012-2013/004). The authors are grateful to the Ghana Ports and Harbours Authority for providing logistical support. We also thank Koﬁ Ferni Anyan (Department of Marine and Fisheries Sciences, University of Ghana) for assisting in the sample collection at the Tema Harbour, Marjolein Van Ginneken (SPHERE, University of Antwerp) for assisting in the field collection of experimental organisms from the Eastern Scheldt (The Netherlands), Dr. Valentine Mubiana (SPHERE, University of Antwerp) for his technical assistance in the metal analysis and Bashara Ahmed (CERSGIS, University of Ghana) for generating the map of the study area.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.chemosphere.2017.02.138.

References

Water Res. 38, 569–578.