Does the Port 2000 harbour construction have an effect on the Seine estuary suprabenthic community?

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ABSTRACT

Using a Before/During/After protocol, the effects of Port 2000 (the Le Havre harbour extension) on the suprabenthic communities in the Northern Channel of the Seine estuary (English Channel) were examined from March 2001 to March 2009. Since the beginning of Port 2000 construction in 2002, there have been several changes in the hydrological and sedimentary characteristics in the North Channel, including changes in current velocity, bottoms salinity and sand accumulation, as well as in the benthic communities themselves, moving from mud to medium and coarse sand communities. For the suprabenthos, changes were moderate, corresponding to an increase in species richness in the upper-part of the North Channel and a decrease in species density in the dominant mysids species (i.e., mainly *Mesopodopsis slabberi*) over time. Due to hydrological changes since the beginning of the Port 2000 project (several years of low freshwater input) it has been difficult to attribute the biological changes to Port 2000 construction only. In the future, the results obtained for the suprabenthos will have to be compared to those obtained for the macrobenthos. Similarly, since the suprabenthos is known to play an important role in the estuarine trophic chain, it will also be essential to estimate the fish distribution in the North Channel and to examine their stomach contents to evaluate the probable changes since the Port 2000 project began.

1. Introduction

Estuaries are highly variable ecosystems that change continually due to the interaction of local physical, geological, chemical and biological factors. They are among the most productive aquatic systems and are an important factor in the fish and bird trophic chains. They also play an important role in the biogeochemical cycles, especially the carbon, nitrogen and phosphorus cycles, storing and transforming these elements in freshwater and marine ecosystems (McLusky and Elliott, 2004). In western industrial countries, estuaries have been affected since the middle of the XIX century by anthropogenic transformations to facilitate merchandise transport and harbour, industrial and urban development. They have also received a multitude of contaminants (i.e., urban, industrial and agricultural effluents), mainly from the freshwater watershed (McLusky et al., 1986; Chapman and Wang, 2001; Dauvin, 2008).

In the eastern part of the Channel, the Seine estuary is an apt illustration of this phenomenon: 40% of France's economic activity (industry and agriculture), 50% of its river traffic, and 30% of its population (16 million inhabitants, of which 80% live in urban areas) are concentrated inside the Seine watershed, which covers approximately 79,000 km^2 (Guézennec, 1999). As a consequence of its national importance, significant projects (i.e., dams, harbour constructions and navigation channel dredging), particularly in the lower part of the estuary, have significantly perturbed the natural environment (Dauvin, 2002; Dauvin and Desroy, 2005; Dauvin et al., 2006). The most recent development of infrastructure along the Seine estuary – part of the "Port 2000" project extended the surface of the Le Havre harbour, mainly to permit large container ships access to new extended loading platforms all day. Plans for the North Channel included (1) the construction of a 16 m deep, 350 m wide, and 2800 m long channel connected to the Le Havre harbour's navigation channel, and (2) the construction of a dam-protected basin (Dauvin et al., 2006).

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In order to assess the impact of physical disturbances on wildlife conservation, studies of the effects on habitat quality and marine fauna are important (Lewis et al., 2002). The benthos and supra-benthos were chosen as indicators of the possible ecosystem changes resulting from the development of the harbour infra-structure (Dauvin et al., 2006). However, it is often difficult to interpret the effects of disturbances in estuaries because they are complex and confusing ecosystems; dynamic physical, chemical and geologic conditions can interfere with efforts to assess the impact of anthropogenic activity on estuarine biotic integrity (Warwick, 1988; Weisberg et al., 1997; Gaston et al., 1998; Dauvin, 2007; Elliott and Quintino, 2007; Dauvin and Ruellet, 2009).

This observation was the catalyst for the 'estuarine quality paradox' applied for the first time by Dauvin (2007) to characterize such ecosystems, but more widely explored by Elliott and Quintino (2007). It seems that estuarine communities have features very similar to those found in anthropogenically-stressed areas, thus making it difficult to detect anthropogenically-induced stress in estuaries. For this reason, experimental designs that include sampling before, during and after the impact event, at several occasions and at several control sites have been recommended to achieve the necessary spatial and temporal replication needed to determine the impact of a perturbation (Underwood, 1992, 1994).

The faunistic composition, density ranges and seasonal changes of the suprabenthos in the Seine estuary are relatively well known. The first data were obtained during a 24 h survey in June 1992 while sampling a faunal drift at one site located near the mouth of the estuary (site F) (Wang and Dauvin, 1994). Then, during the first step of Seine-Aval programme (1995–2003), several studies were conducted in the Seine estuary to evaluate this biological com-partment's importance in the estuarine trophic chains from detritus to fish (Mouny et al., 1998, 2000; Zouhiri et al., 1998; Dauvin, 2002; Dauvin and Desroy, 2005). In spite of the high metallic contamination (Dauvin, 2008) and the surface reduction in the estuarine zones (Guézennec, 1999), suprabenthos appeared very rich in the navigation channel of the Seine estuary (Mouny et al., 2000) probably in relation to the megatidal regime which provoked a large dilution of the contaminants (Dauvin, 2008).

In the Seine estuary, three kinds of suprabenthic species have been distinguished (Mouny et al., 2000): (1) *neritic species*, located in marine and coastal waters in the eastern part of the Bay of Seine, such as the cumaceans *Diastylis* spp. and the mysids *Gastrosaccus* spp.; (2) *marine and euryhaline species*, living in coastal waters with estuarine-dependant juvenile development, such as the mysid *Mesopodopsis slabberi* and the shrimp *Crangon crangon*; and (3) typically *estuarine species*, living in the estuary, such as the mysid *Neomysis integer* and the shrimp *Palaemon longirostris*. Two main assemblages have been distinguished: one in the outer part of the estuary, where the supra-benthic fauna is characterized by marine species, such as *M. slabberi* and *C. crangon*, and another in the upstream part of the estuary, where the suprabenthos is dominated by estuarine species, such as *N. integer* and *P. longirostris* (Mouny et al., 2000).

As in other estuaries, mysids quantitatively dominate the suprabenthos in environments characterised by low species numbers due to great variations in salinity levels (Cattrijsse et al., 1994; Azeiteiro and Marques, 1999; Drake et al., 2002). Mees and Jones (1997), Lock and Mees (1999) and Cunha et al. (1999) have compared the suprabenthic composition and abundances in several European estuaries. In some of these estuaries, two species repre-sented more than 95% of the collected suprabenthic individuals: the mysids *Mesopodopsis slabberi* and *Neomysis integer*. In the Seine estuary, the maximum density observed for *N. integer* (216,000 ind.100 m^{-3}) is the highest reported in the literature (Mouny et al., 2000). The maximum density reported for *M. slabberi* (>34,000 ind.100 m^{-3}) is more moderate, and for example is lower

than the values observed in the Tamar estuary in the early 1990s (>100,000 ind.100 m^{-3}) (Moffat and Jones, 1992, 1993). Mysids dominate the fauna in other estuaries in the world. For example, *Metamysidopsis elongate atlantica* had densities higher than 60,000 ind.100 m^{-3} in the late 1960s and represented >99.4% of the collected fauna in the spring in the Cananeia lagoon estuarine region in the south-eastern part of the Brazil in the late 1990s (Taraman et al., 1996).

However, in the Seine estuary, these figures correspond to samples collected only in the main navigation channel that permits large ships to reach Rouen harbour, a maritime harbour at 120 km from the sea. So, the suprabenthos has never been sampled in the South or North Channel. In 2001, prior to the Port 2000 construc-tion, it was decided to sample the suprabenthos in the North Channel of the Seine estuary. As part of the compensatory actions for the Le Havre harbour, suprabenthos was sampled regularly during the construction (from October 2002 to March 2005), and three years after the end of the construction, it was again sampled in September 2008–March 2009 to evaluate the impact of the new construction on this faunal compartment. The first results of the survey were given in Dauvin et al. (2006).

Two questions are examined in this paper: (1) Do the supra-benthic fauna display the same faunal composition and abundance ranges along the whole downstream-upstream gradient?, and (2) Has the Port 2000 construction had an impact on the structure of the suprabenthic fauna (i.e., on faunal composition and density ranges)?

2. Material and methods

2.1. Sampling

Prior to the Port 2000 harbour construction, the suprabenthos was sampled at four sites (F, 17, 59 and 64) in September and December 2001 just before the construction. Later on during the construction from October 2002 to March 2005, it was sampled twice a year (during winter and beginning of autumn) at these four sites plus an additional one (F, 17, 59, 64 and 3) (Fig. 1). Three years after the completion of the last compensatory actions in July 2005, the same five sites were sampled in September 2008 and February 2009 (Table 1). The suprabenthos was sampled along the time
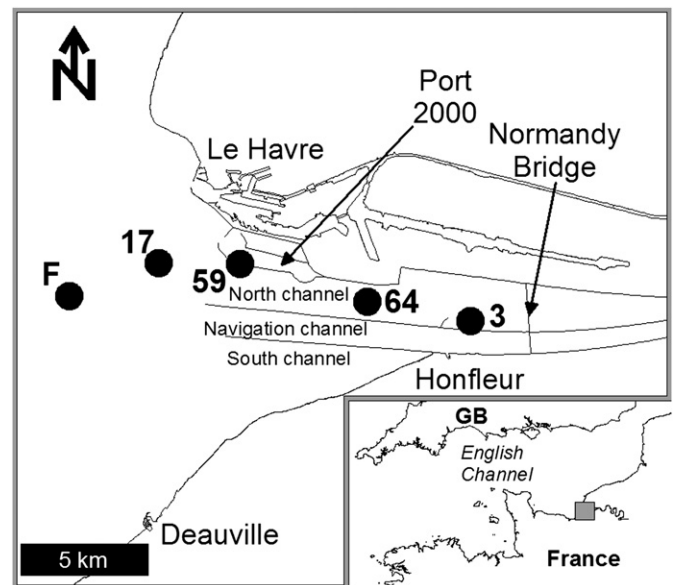

Fig. 1. Study area and location of the five sampling sites in the North Channel of the Seine estuary.

Table 1
Hydrodynamic characteristics near the sea bottom at each site during the sampling period (N.D.: no data)

Location	Site F 49°26.68 N 0°1.514 E	Site 17 49°27.440 N 0°4.403 E	Site 59 49°27.470 N 0°7.053 E	Site 64 49°26.734 N 0°11.22 E	Site 3 49°26.382 N 0°14.610 E
27 September 2001					
Temperature (°C)	16.40	16.20	16.00	15.60	N.D.
Salinity	26.62	19.69	12.72	11.63	N.D.
Seine flow ($m^3 s^{-1}$)			633		
8 December 2001					
Temperature (°C)	7.30	7.00	6.90	6.90	N.D.
Salinity	22.25	12.86	12.62	11.61	N.D.
Seine flow ($m^3 s^{-1}$)			1540		
4 October 2002					
Temperature (°C)	17.20	17.30	17.00	17.10	17.00
Salinity	26.60	20.60	15.48	17.68	16.50
Seine flow ($m^3 s^{-1}$)			220		
3 March 2003					
Temperature (°C)	7.00	6.80	6.80	6.80	6.70
Salinity	30.94	30.45	29.13	26.68	25.6
Seine flow ($m^3 s^{-1}$)			670		
24 September 2003					
Temperature (°C)	18.70	18.50	18.35	18.55	18.08
Salinity	33.03	31.18	31.84	32.21	31.32
Seine flow ($m^3 s^{-1}$)			113		
8 March 2004					
Temperature (°C)	7.12	7.06	7.25	7.24	7.13
Salinity	31.30	31.90	30.70	29.00	27.90
Seine flow ($m^3 s^{-1}$)			420		
30 September 2004					
Temperature (°C)	16.80	16.10	16.40	17.30	17.20
Salinity	22.75	12.94	13.90	15.02	16.69
Seine flow ($m^3 s^{-1}$)			269		
11 March 2005					
Temperature (°C)	5.30	5.30	5.30	5.10	5.10
Salinity	29.50	27.20	27.80	25.70	24.70
Seine flow ($m^3 s^{-1}$)			455		
28 September 2008					
Temperature (°C)	16.44	16.40	16.51	16.42	16.32
Salinity	33.40	33.20	32.80	31.50	30.70
Seine flow ($m^3 s^{-1}$)			296		
28 February 2009					
Temperature (°C)	6.65	6.77	6.76	6.68	6.64
Salinity	30.8	29.00	28.60	27.10	25.70
Seine flow ($m^3 s^{-1}$)			506		

using a new version of the Macer-GIROQ sledge (Dauvin et al., 1995). This sledge consists of four 0.18 m² boxes (0.6 × 0.3 m), which are used to filter the water column in the four layers above the sea bottom: 0.10–0.40 m (box 1), 0.45–0.75 m (box 2), 0.80–1.10 m (box 3) and 1.15–1.45 m (box 4). Each box is linked to a WP2 zooplanktonic net (0.5 mm mesh size) and includes a Tsurimi-Seiki-Kosakusho (TSK) flow meter in the centre to measure the volume of water filtered. The sampling period (i.e., the period during which the sledge was in contact with the seabed) was 5 min at a sledge speed of approximately 1.5 knots. Table 1 presents the sampling dates and the hydrological conditions at each site.

Since mysids, the dominant species in the estuary, form large swarms that fluctuate with the seasons and with the ebb and flow of the tides, the sampling procedure was designed to minimise the tide effects. In addition, mysids are good swimmers and have been known to actively avoid nets (Mauchline, 1980); although, this phenomena is probably less prevalent in the turbid zones of the estuary, such as the North Channel of the Seine, than in the open sea. Five sites were chosen for sampling, ranging from site F in the marine zone at the mouth of the estuary to site 3 in the freshwater zone in the upper section of the North Channel. The sampling was

done during the day during the flow phase of the spring tide (coefficient > 90), which allowed sufficient depth for the oceanographic vessel in the upper section of the North Channel where the water is particularly low at low tide. The sampling started between one and two hours after the beginning of the flood phase and lasted between 2.5 and 3 h.

All sampled organisms were washed, fixed with 10% neutralized formaldehyde, and then transferred to a 70% ethanol solution. All suprabenthos *sensus stricto* (see Dauvin and Vallet, 2006) (i.e., peracarids, decapods and pycnogonids) were sorted, counted and identified to the species level under a dissecting microscope. The species richness values corresponded to the total number of species found in the four nets, and the abundance values were standardised for a mean volume of 100 m³.

2.2. Statistical analysis

As the seasonal changes in suprabenthic fauna has been studied previously (see Mouny et al., 2000) and the objective of this study was to evaluate the impact of new constructions in the North Channel using a Before/During/After protocol, we assembled

practically the sampling data per year from the autumn to the next winter, because during this period there was no recruitment and the suprabenthic community was affected mainly by mortality. In other words, we put September and December 2001 as year 1, corresponding to the year before the Port 2000 construction; October 2002 and March 2003 as year 2, corresponding to the first year of construction; September 2003 and March 2004 as year 3, corresponding to the second year of the construction; September 2004 and March 2005 as year 4, corresponding to the third year of the construction; and finally September 2008 and February 2009 as year 5, corresponding to the year after the construction. Since we had five sites that were sampled all five years, except site 3 that was not sampled in 2001, there were a total of 24 sampling situations (5 sites × 5 years − 1).

Due to very low density of some species, in order to do the statistical analysis, we chose to group some species at genus level: *Apherusa*, *Caprella*, *Corophium*, *Gammarus* for the amphipods, *Cumopsis* and *Diastylis* for the cumaceans, and *Liocarcinus* and *Processa* for the decapods. Because of the difficulties in distinguishing the juveniles of the two *Schistomysis* species (*Schistomysis kervillei* and *Schistomysis ornata*), we chose to group all of the specimens in a single taxon, *S. kervillei/ornata*. All the pygnogonids were also grouped in a single taxon.

A Shapiro–Wilk normality test and a Bartlett test of homogeneity of variance were performed to verify the conditions of applications of the ANOVA. Then ANOVA were performed to assess the effect of the sampling and site location on suprabenthos species richness and species density. The Sorensen similarity coefficient was calculated for the samples and a log $(x + 1)$ transformation was used on the density matrix before calculating the Bray-Curtis similarities with Primer 6 (Clarke and Warwick, 1994). Dendrograms were created, with group averages expressed in the cluster mode.

3. Results

3.1. Environmental characteristics

Temperature and salinity characteristics near the sea bottom (Table 1) revealed seasonal and downstream-upstream gradients. Temperatures displayed great seasonal changes, ranging from lower temperatures between 5 and 7 °C in winter (December–March) to higher values between 15.6 and 18.7 °C in autumn (September–October), without any clear longitudinal pattern. There were three main salinity patterns: (1) a downstream-upstream gradient, with the highest value downstream at the marine site F and the lowest value upstream at the estuarine site 3; (2) a global variability related to the river flow, with lower values when the river flow was high (i.e., in September and December 2001) and higher values when the river flow was low (i.e., in September 2003 and September 2008); and (3) a general decreasing trend for the river flow over the sampling period (Fig. 2), with peak flows >1500 m^{-3} s^{-1} during the first three winters from 2001 to 2003 and lower values during the rest of the sampling period, especially in 2004–2005 and 2008–2009. Clearly, there was a change in the river flow during the sampling period. Two main hydrological regimes were observed: one from 2001 to 2004 characterised by a high upstream river flow and one from 2005 to the beginning of 2009 characterised by a low upstream river flow. Other than December 2001, all the samples were taken during a period of low river input (Fig. 2).

3.2. Taxonomic composition of the suprabenthic fauna

A total of 87 species were collected at the five sites (Table 2). Amphipods (41 species; 47% of the collected species), mysids (15 species, 17%) and decapods (15 species, 17%) dominated in terms of species richness, forming more than 80% of the collected species. The other groups were less diversified: cumaceans (9 species), isopods (4 species) and pycnogonids (3 species). The total species richness showed a decreasing downstream-upstream gradient, with 75 species at the site F, 57 at site 17, 50 at site 59, 49 at site 64 and finally 37 at site 3. Twenty-four species (26%) were present at all five sites; 23 species (26%) were sampled at a single site; and nine species were found at four of the five sites, with most of them being absent only at site 3.

3.3. Abundance composition of the suprabenthic fauna

Table 3 reports the maximum density for the top eleven suprabenthic species collected at the five sites. *Mesopodopsis*
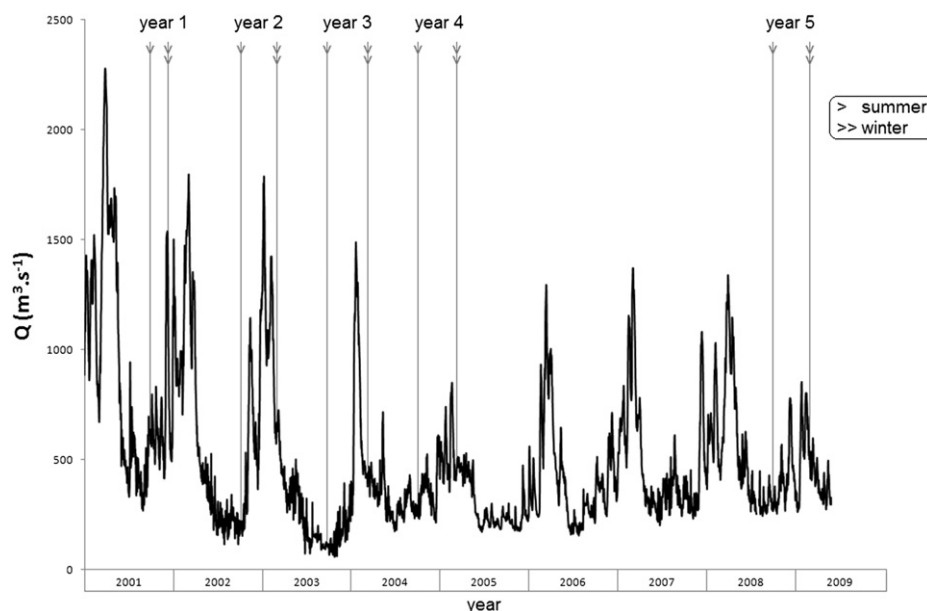

Fig. 2. Daily flow of the Seine at Poses in the upper part of the Seine estuary (Data from Hydrological dataset, C. Fisson, GIP-Seine-Aval, personal communication) with indications of the sampling dates from 2001 to 2009.

Table 2
Taxonomic composition and dominance of each species at each site (total number of individuals collected for a species in a site divided by the total number of individuals collected in this site) at the five sites in the North Channel of the Seine estuary

	F	17	59	64	3
Amphipoda					
Abludomelita obtusata (Montagu. 1813)	0.03	0.04	0.03	0.01	–
Ampelisca brevicornis (Costa. 1853)	0.04	–	–	–	–
Ampelisca diadema (Costa. 1853)	–	–	–	–	0.00
Ampelisca spinipes Boeck. 1861	–	–	0.00	–	–
Amphilochus neapolitanus Della Valle. 1893	0.02	0.02	0.01	–	–
Aoridae	0.01	0.01	0.00	0.00	–
Atylus falcatus Metzger. 1871	0.44	0.04	–	0.01	–
Atylus swammerdami (Milne-Edwards. 1830)	0.01	–	0.01	–	0.01
Atylus vedlomensis (Bate & Westwood. 1862)	–	0.00	0.00	–	–
Bathyporeia pilosa Lindström. 1855	–	0.00	–	0.02	0.03
Caprella spp.	0.18	0.22	0.08	0.01	0.01
Cheirocratus intermedius Sars. 1894	0.01	–	–	–	–
Corophium acherusicum Costa. 1851	0.00	0.00	0.00	–	–
Corophium spp.	–	0.00	–	–	–
Corophium volutator (Pallas. 1766)	0.02	0.00	0.01	0.01	0.07
Ericthonius punctatus (Bate. 1857)	0.00	0.00	0.00	0.01	–
Gammarus crinicornis Stock. 1966	0.01	0.05	1.07	0.00	0.00
Gammarus salinus Spooner. 1947	0.02	0.01	0.00	0.14	0.04
Gammarus spp.	0.25	0.49	1.31	0.49	0.18
Gammarus zaddachi Sexton. 1912	–	0.00	0.01	0.01	–
Gitana sarsi Boeck. 1871	0.00	–	0.00	0.00	–
Gitanopsis bispinosa (Boeck. 1871)	0.00	–	–	–	–
Haustorius arenarius (Slabber. 1767)	–	–	–	–	0.02
Iphimedia obesa Rathke. 1843	–	0.00	–	–	–
Ischyrocerus anguipes Krøyer. 1838	0.00	–	–	0.00	–
Jassa falcata (Montagu. 1808)	0.02	–	–	–	0.00
Leptocheirus pilosus Zaddach. 1844	–	–	–	0.00	–
Leucothoe incisa Robertson. 1892	0.02	0.02	0.01	0.01	–
Listriella picta Norman. 1889	0.00	–	0.00	–	–
Maera othonis (Milne-Edwards. 1830)	–	0.00	–	–	–
Megaluropus agilis Hoeck. 1889	0.05	0.00	–	–	0.00
Melita palmata (Montagu. 1804)	0.06	0.05	0.16	0.01	0.00
Orchomenella nana (Kroyer. 1846)	0.06	0.06	0.04	0.00	–
Pariambus typicus (Kroyer. 1844)	6.69	0.29	0.01	0.04	0.00
Perioculodes longimanus (Bate & Westwood. 1868)	0.67	0.15	0.04	–	0.00
Photis longicaudata (Bate & Westwood. 1862)	–	0.00	–	–	–
Photis reinhardi Krøyer. 1842	–	0.00	0.00	0.00	–
Phtisica marina Slabber. 1769	0.00	0.01	0.01	0.00	0.01
Pontocrates altamarinus (Bate & Westwood. 1862)	0.00	0.00	–	–	–
Stenothoe marina (Bate. 1856)	0.05	0.02	0.00	0.00	0.00
Synchelidium maculatum Stebbing. 1906	0.01	–	–	–	0.00
Tryphosella sarsi Bonnier. 1893	0.08	0.02	0.01	0.01	0.00
Urothoe pulchella (Costa. 1853)	0.00	0.00	–	–	0.00
Cumacea					
Cumopsis goodsir (Van Beneden. 1861)	–	–	–	–	0.01
Bodotria arenosa Goodsir. 1843	–	0.02	0.01	0.00	–
Cumopsis spp.	0.01	0.00	–	–	–
Cumopsis longipes (Dohrn. 1869)	0.00	0.01	–	0.01	–
Diastylis cornuta (Boeck. 1864)	0.01	–	–	–	–
Diastylis laevis Norman. 1869	5.20	3.17	0.04	0.05	0.01
Eudorella truncatula (Bate. 1856)	0.04	0.01	0.00	0.01	–
Pseudocuma longicorne (Bate. 1858)	3.47	5.44	0.11	0.13	0.01
Diastylis bradyi Norman. 1879	1.23	0.55	0.41	0.09	0.02
Vaunthompsonia cristata Bate. 1858	0.00	0.04	–	0.03	–
Mysida					
Acanthomysis longicornis (Milne-Edwards. 1837)	0.02	–	–	–	–
Anchialina agilis (G.O. Sars. 1877)	0.01	0.07	0.05	0.02	0.00
Gastrosaccus normani G.O. Sars. 1877	–	0.00	0.01	–	–
Gastrosaccus sanctus (van Beneden. 1861)	0.10	0.00	0.02	–	–
Gastrosaccus spinifer (Goës. 1864)	1.12	0.76	0.34	0.44	0.16
Hemimysis lamornae (Couch. 1856)	–	–	–	0.01	–
Leptomysis lingvura (G.O. Sars. 1866)	0.02	–	–	–	–
Mesopodopsis slabberi (van Beneden. 1861)	40.36	76.96	89.04	90.90	94.35
Mysidopsis gibbosa G.O. Sars. 1864	0.06	0.22	0.06	–	0.00
Neomysis integer (Leach. 1814)	0.04	0.01	0.09	1.85	2.36
Paramysis arenosa (G.O. Sars. 1877)	0.17	0.48	0.19	0.08	0.04
Schistomysis kervillei (G.O. Sars. 1885)	3.78	0.69	0.07	0.98	0.62
Schistomysis ornata (G.O. Sars. 1864)	32.44	8.76	6.42	3.96	1.42
Schistomysis spiritus (Norman. 1860)	0.28	0.36	0.10	0.05	0.01
Siriella jaltensis Czerniavsky. 1868	0.07	0.06	0.09	0.01	0.00
Isopoda					

Table 2 (*continued*)

	F	17	59	64	3
Cymodoce truncata Leach. 1814	–	–	–	0.00	–
Eurydice pulchra Leach. 1815	–	–	–	0.00	0.00
Idotea linearis (Linnaeus. 1766)	0.01	0.01	0.03	0.00	0.04
Lekanesphaera rugicauda (Leach. 1814)	–	–	–	0.00	–
Decapoda					
Athanas nitescens (Leach. 1814)	0.00	0.00	0.00	–	–
Carcinus maenas (Linnaeus. 1758)	–	–	0.01	–	–
Crangon crangon (Linnaeus. 1758)	1.38	0.69	0.09	0.49	0.56
Galathea intermedia Liljeborg. 1851	–	0.00	–	–	–
Hippolyte varians Leach. 1814	0.04	–	0.00	0.00	–
Liocarcinus spp.	0.01	0.01	–	–	–
Liocarcinus depurator (Linnaeus. 1758)	–	0.00	–	–	–
Liocarcinus holsatus (Fabricius. 1798)	0.00	–	–	–	–
Liocarcinus marmoreus (Leach. 1814)	0.00	–	–	–	–
Palaemon longirostris H. Milne-Edwards. 1837	0.01	–	0.01	0.01	0.01
Palaemon serratus (Pennant. 1777)	0.00	–	–	–	–
Pinnotheres pisum (Linnaeus. 1767)	0.01	0.01	0.00	0.02	–
Philocheras bispinosus (Hailstone. 1835)	1.29	0.07	0.00	0.04	0.00
Processa edulis (Risso. 1816)	0.01	–	–	–	–
Processa nouveli holthuisi Al-Adhub & Williamson. 1975	0.00	–	–	0.00	–
Thoralus cranchii (Leach. 1817)	0.00	–	0.00	–	–
Pycnogonida					
Achelia echinata Hodge. 1864	–	0.00	–	0.00	–
Anoplodactylus petiolatus (Kroyer. 1844)	0.00	0.00	–	–	–
Nymphon brevirostre Hodge. 1863	–	0.00	–	–	–
Pycnogonida unidentified	0.01	0.00	–	0.01	–
Total number of species	75	57	50	49	37
Mean abundance per 100 m^3	1531	1556	2241	2999	3722

slabberi was the single species that had a density higher than 5000 ind.100 m^{-3} at all sites, with an increasing gradient from the marine section (Site F) to the upper freshwater section of the North Channel (site 3) where the density reached about 18,000 ind.100 m^{-3}. Only two other mysids, the complex *Schistomysis kervillei/ornata* and *Neomysis integer*, exceeded 500 ind.100 m^{-3}. The first taxon showed a decreasing downstream-upstream gradient and the second one showed an inverse gradient, with maximum densities in the upstream section of the North Channel at sites 64 and 3. Except the mysid *Gastrosaccus spinifer*, which never went exceeded 100 ind.100 m^{-3}, the other seven species presented maximum densities between 106 and 359 ind.100 m^{-3}. The mean total density highlighted a gradual increase from 1531 ind.100 m^{-3} at site F to 3722 ind.100 m^{-3} at site 3 (Table 2). Similarly, the dominance of the mysid *M. slabberi* increased from 40.36% at site F to 94.35% at site 3; conversely, the mysid *S. ornata* decreased from 32.44% at site F to 1.42% at site 3 (Table 2). The mysids ranged from 88% of the total individuals at site F to 99% at site 3. Other than the mysids, three other species

Table 3
Maximum abundance (N. individuals. 100 m^{-3}) of the top eleven suprabenthic species at the five sites in the North Channel of the Seine estuary from September 2001 to March 2009

	Site F	Site 17	Site 59	Site 64	Site 3
Mesopodopsis slabberi	6696	6412	11099	13391	17890
Schistomysis kervillei/ornata	857	571	590	394	131
Neomysis integer	10	2	20	562	223
Pseudocuma longicorne	248	359	18	28	2
Crangon crangon	185	65	18	94	117
Gammarus spp.	50	113	271	78	32
Diastylis spp.	150	216	38	30	4
Pariambius typicus	301	32	3	6	3
Philocheras bispinosus neglectus	199	14	1	16	2
Schistomysis spiritus	11	106	19	16	3
Gastrosaccus spinifer	31	65	87	33	11

(*Pariambius typicus*, *Diastylis laevis* and *Pseudocuma longicorne*) formed >3% of the total density at site F, and only two species *D. laevis* and *P. longicorne* formed 8% at site 17 (Table 2).

3.4. Downstream-upstream gradient and the impact of Port 2000 construction on the suprabenthic fauna

For each situation, the abundances of the taxa had been cumulated from the more abundant to the lees abundant to reach 80% of the total abundance. All the corresponding taxa were selected in all 24 situations for the ANOVA analysis. A variance analysis (ANOVA) for one factor (one site and one year) without repetition was carried out: $F = 0.003 < Fc_{0.05} = 1.586$. This value indicates that there is no significant difference of the quantitative composition of main suprabenthic species between the samples. Then ANOVAs for two factors (years and sites) without repetition were subsequently carried out, excluding site 3, which was not sampled before the Port 2000 construction in 2001, and excluding year 1 (2001), when only four of the five sites were sampled. Species richness results show that only the site factor has a significant effect if year 1 is not considered (year, $F = 2.467 < Fc_{0.05} = 3.490$; site, $F = 3.649 > Fc_{0.05} = 3.259$). But if the year 1 (2001) is taken into account (excluding site 3, which was not sampled in 2001), both factors have an effect (year, $F = 8.996 > Fc_{0.05} = 3.259$; site, $F = 4.311 > Fc_{0.05} = 3.490$). The density results show that neither the site factor nor the year factor have a significant effect if year 1 is not considered (year, $F = 2.455 < Fc_{0.05} = 3.490$; site, $F = 1.286 < Fc_{0.05} = 3.259$). But if the year 1 (2001) is taken into account (excluding site 3, which was not sampled in 2001), the year factor has a significant effect (year, $F = 9.505 > Fc_{0.05} = 3.259$; site, $F = 1.926 > Fc_{0.05} = 3.490$).

In summary, all five sites showed different species richness values, with year 1 (2001) appearing significantly different from the others. There is no significant difference between the five sites in terms of species density, but there is a temporal change in terms of

density: the temporal effect is higher according to the longitudinal location of the sites along the downstream-upstream gradient in the North Channel.

Species composition in year 5 (2008–2009) is greatly different (60% dissimilarity) from the other years according to the Sorensen coefficient (Fig. 3a). The same analysis shows that year 1 (2001) is slightly different from the other three years (50% dissimilarity). In addition, the faunal composition of site 3 appears more variable than the others. Fig. 3b shows the temporal changes in the densities of the suprabenthic fauna [$\log_{10}(N+1)$]. Year 5 (2008–2009) appeared separated from the others (56% dissimilarity); year 1 (2001) formed a particular isolated group (69% dissimilarity) separated from the other three years, which could not be distinguished from one another.

Fig. 4 shows the square proportions to number of common taxa for the three periods (i.e., Before/During/After Port 2000 construction) for the five sites. The few taxa observed year 1 (Before) were also found during and after the construction. Both downstream sites (F and 17) showed a high number of common species during and after the construction, while the upstream sites (59 and 64) showed more changes in taxa composition between the two periods. Site 3, sampled only During and After Port 2000 construction, appears the poorest taxonomically.

There was a general decrease of the total density of the suprabenthic fauna over time from year 1 to year 5, except at site 59 during year 3 (Fig. 5). This trend was mainly due to the diminishing density of the dominant species *Mesopodopsis slabberi* along the time.
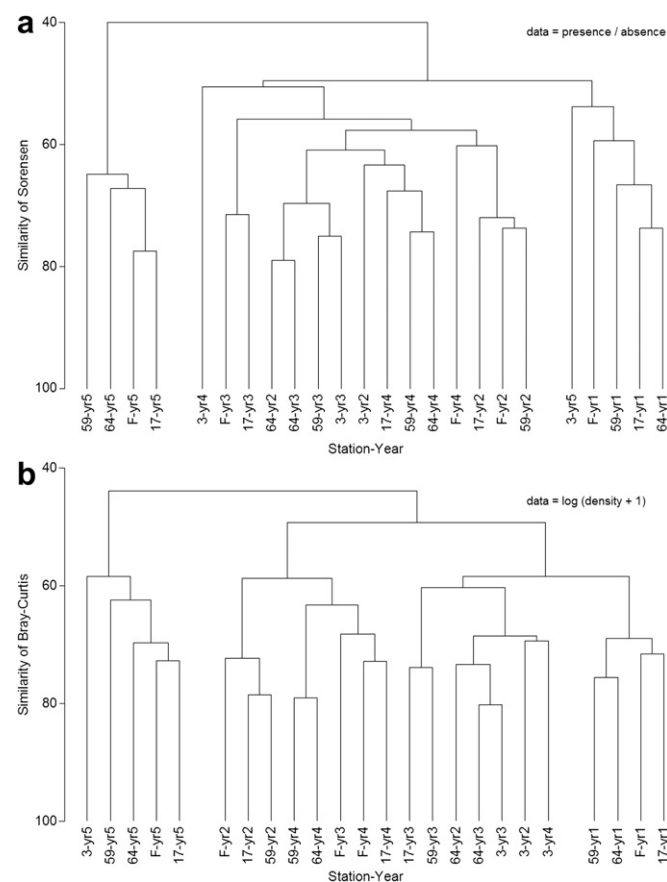

Fig. 4. Number of common taxa for the five sites for the three periods: Before/During/After Port 2000 construction.

4. Discussion

Studies on estuarine suprabenthic communities remain rare. Those that exist have focused on large European estuaries, such as the Severn estuary (Bamber and Henderson, 1994), the Ems estuary (Mees et al., 1995), the Scheldt estuary (Mees and Hamerlynck, 1992; Cattrijsse et al., 1993, 1994; Mees et al., 1993a, 1993b, 1995), the Gironde estuary (Sorbe, 1981; Mees et al., 1995), the Ria de Aveiro (Cunha et al., 1999) and the Guadalquivir estuary (Vilas et al., 2009). Amphipods and mysids are usually the dominant groups and have been found in most of the studied estuaries: *Atylus* spp., *Bathyporeia* spp., *Corophium* spp. and *Gammarus* spp. are the typical amphipods, and *Gastrosaccus* spp., *Mesopodopsis slabberi*, *Neomysis integer* and *Schistomysis* spp. are the typical mysids. Among the decapods, the shrimps *Crangon crangon*, *Palaemon longirostris* are common, occurring in all the European estuaries.

In most the estuaries, a decrease in species richness generally occurs with the decreasing salinity. This pattern is well

Fig. 3. Dendrogram, using group averages as cluster mode, showing the Bray-Curtis similarity on (a) species richness and (b) density (number of individuals per 100 m⁻³) for all five years and all five sites in the North Channel in the Seine estuary.
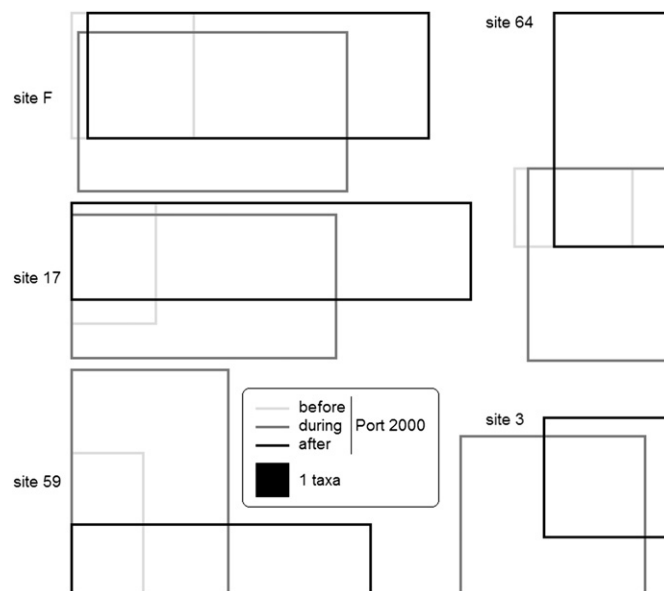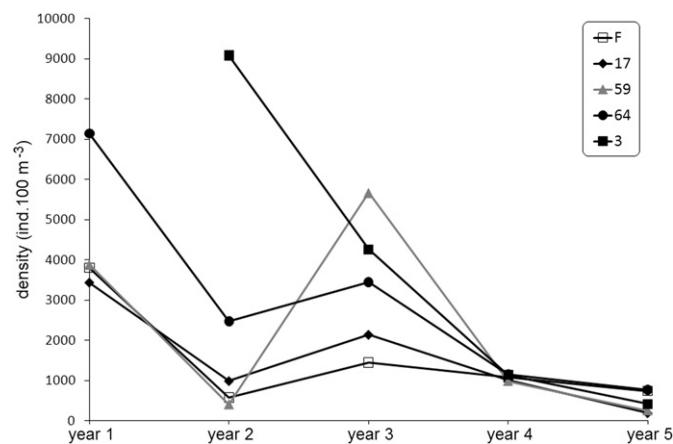

Fig. 5. Temporal changes of the total density of the suprabenthic fauna (number of individuals per 100 m⁻³) for all five years of observations at all five sites in the North Channel of the Seine estuary.

documented for mysids, which have shown a distinctive downstream-upstream gradient. The species *Gastrosaccus spinifer* and *Schistomysis spiritus* dominate the marine part of the estuaries; the euryhaline species *Mesopodopsis slabberi* is found in the mid and inner estuary, while *Neomysis integer* occurs in the inner part of estuaries (Williams and Collins, 1984; Bamber and Henderson, 1994; Zouhiri et al., 1998; Azeiteiro and Marques, 1999). Very great seasonal changes have been observed in the Severn estuary and the Bristol Channel in relation to changes in salinity and turbidity (Bamber and Henderson, 1994). Seasonal and pluri-annual (two years) mysid fluctuations have also been observed in the Westerschelde estuary (Cattrijsse et al., 1994).

The suprabenthic community found in the Seine estuary showed similar pattern than those observed in the other estuarine conditions. However, two main assemblages have been distinguished: one in the outer part of the estuary, where the suprabenthic fauna characterized by marine species, such as *Mesopodopsis slabberi* and *Crangon crangon*, and another in the upstream part of the estuary characterised by estuarine species, such as *Neomysis integer* and *Palaemon longirostris* (Mouny et al., 2000).

During this suprabenthic survey (2001–2009), it is important to notice that, since the year 2001, the hydrodological conditions of the Seine River has been dominated by a period of low freshwater input. In fact, the last consequential swelling of the Seine was in March 2001 ($>2200 \, m^3 \, s^{-1}$), and apart from two flood peaks during the winters of 2002 and 2003 ($>1500 \, m^3 \, s^{-1}$), the flow remains particularly low, especially since 2004 (Fig. 2). The estuary bottom salinities observed from 2002 to 2009 during the suprabenthic surveys (Table 1) show that the North Channel was mainly part of the polyhaline zone (salinity: >18), while in 2001 the upstream sites, respectively sites 59 and 64 in September and sites 17, 59 and 64 in December, corresponded to the mesohaline zone (salinity < 18). The highest value of temperature occurred in September 2003 after the heat wave in France and many western European countries.

Given that the river discharge has decreased since the Port 2000 construction, the rate of fine particles exported to the Bay of Seine remains low; this has caused a reduction in fine particle input from the upstream section of the estuary and an increase in the natural sand deposits in the lower section of the Seine estuary, especially in the North Channel (Cuvilliez et al., 2009). An artificial channel was opened upstream of the Normandy Bridge, which could play an important role in the flow of water coming from upstream to the North Channel. The plan was for an input of low salinity water to go through this new channel (Dauvin et al., 2006), which is located at the mesohaline zone (salinity < 18) and is inhabited by estuarine suprabenthic species, dominated by *Neomysis integer* and *Palaemon longirostris* (Mouny et al., 2000). As underlined above, there has been an inverse phenomenon with an increasing marine influence in the North Channel over time. In fact, the North Channel is now in the polyhaline zone and there is a sand progression that prevents low salinity water from circulating in the new channel.

The impact of these environmental changes was discernible both in terms of species richness and density of the suprabenthic community. First, the species composition of the marine suprabenthic community demonstrates a downstream-upstream gradient, with three groups of sites: the downstream marine sites (F and 17), where the temporal changes were minor; the intermediate sites (59 and 64), where the temporal changes were greater, and the upstream site (3, which was not sampled before the Port 2000 construction), where the temporal changes were moderate between During and After Port 2000 periods and which had the poorest species richness values (Fig. 4). Apart from site 3 in year 5 (Fig. 3a), there was an unambiguous temporal separation of the

years during the survey, with an increase in marine species after the Port 2000 construction. Second, there were also temporal changes in terms of density (Fig. 5), mainly due to the decrease in the dominant mysid species, especially *Mesopodopsis slabberi*. The densities at the five sites during year 5 were particularly low, under $1000 \, ind.100 \, m^{-3}$. Data analysis of the densities also showed an unambiguous separation of year 5 from the four previous years Before and During the Port 2000 construction.

So, there have been several changes in the hydrological and sedimentary characteristics in the North Channel, including changes in current velocity, bottoms salinity and sand accumulation, as well as in the benthic communities themselves, moving from mud to medium and coarse sand communities (Cuvilliez et al., 2009). For the suprabenthos, changes corresponded to an increase in species richness in the upper-part of the North Channel and a decrease in suprabenthic species density of the dominant mysids species (i.e., mainly *Mesopodospsis slabberi*) over time. Due to vast hydrological changes since the beginning of the Port 2000 project, it has been difficult to attribute the biological changes to Port 2000 construction.

In fact, due to the large intrusion of marine waters in the North Channel, the species that live there are typical of polyhaline waters (Dauvin et al., 2000, 2006). This composition is different than the species composition in the navigation channel, where the suprabenthos was sampled along the whole salinity gradient from euryhaline to oligohaline (Mouny et al., 1998, 2000). In this part of the Seine estuary, turbidity also influences species distribution. At the end of the 20th century, such species as the mysid *Neomysis integer* and the decapod *Palaemon longirostris*, were confined to the upstream part of the North Channel in brackish waters (salinity < 5) with high turbidity, while the mysids *Mesopodopsis slabberi*, *Gastrosaccus spinifer* and *Schistomysis ornata* were distributed downstream in marine water with low turbidity.

Acknowledgements

References

Azeiteiro, U.M.M., Marques, J.C., 1999. Temporal and spatial structure in the suprabenthic community of a shallow estuary (western Portugal: Mondego river estuary). Acta Oecologia 20, 333–342.

Bamber, R.N., Henderson, P.A., 1994. Seasonality of caridean decapod and mysid distribution and movements within the Severn Estuary and Bristol Channel. Biological Journal of the Linnean Society of London 51, 83–91.

Cattrijsse, A., Mees, J., Hamerlynck, O., 1993. The hyperbenthic Amphipoda and Isopoda of the Voordelta and the Westerschelde estuary. Cahiers de Biologie Marine 34, 187–200.

Cattrijsse, A., Makwaia, E.S., Dankwa, H.R., Hamerlynck, O., Hemminga, M.A., 1994. Nekton communities of an intertidal creek of a European estuarine brackish marsh. Marine Ecology Progress Series 109, 195–208.

Clarke, K.R., Warwick, R.M., 1994. Changes in Marine Communities: An Approach to Statistical Analysis and Interpretation. Plymouth Marine Laboratory, Plymouth.

Chapman, P.M., Wang, F., 2001. Assessing sediment contamination in estuaries. Environmental Toxicology and Chemistry 20, 3–22.

Cunha, M.R., Sorbe, J.C., Moreira, M.H., 1999. Spatial and seasonal changes of brackish peracaridan assemblages and their relation to some environmental

variables in two tidal channels of the Ria de Aveiro (NW Portugal). Marine Ecology Progress series 190, 69–87.

Cuvilliez, A., Deloffre, J., Lafite, R., Bessineton, C., 2009. Morphological responses of an estuarine intertidal mudflat to constructions since 1978 to 2005: The Seine estuary (France). Geomorphology 104, 165–174.

Dauvin, J.C., Sorbe, J.C., Lorgeré, J.C., 1995. The Benthic Boundary Layer macrofauna from the upper continental slope and the Cap-Ferret Canyon (Bay of Biscay). Oceanologica Acta 18, 113–122.

Dauvin, J.C., Vallet, C., Mouny, P., Zouhiri, S., 2000. Main characteristics of the boundary layer macrofauna in the English Channel. Hydrobiologia 426, 139–156.

Dauvin, J.C. (coord.), 2002. Patrimoine biologique et chaînes trophiques. In: Programme Scientifique Seine Aval, fascicule 7, Ifremer, Plouzané, France, 48 pp.

Dauvin, J.C., Desroy, N., 2005. The food web in the lower part of the Seine estuary: a synthesis synopsis of existing knowledge. Hydrobiologia 540, 13–27.

Dauvin, J.C., Desroy, N., Janson, A.L., Vallet, C., Duhamel, 2006. Recent changes in estuarine benthic and suprabenthic communities resulting from the development of harbour infrastructure. Marine Pollution Bulletin 53, 80–90.

Dauvin, J.C., Vallet, C., 2006. The near-bottom layer as an ecological boundary in marine ecosystems: diversity, taxonomy composition and community definitions. Hydrobiologia 555, 49–58.

Dauvin, J.C., 2007. Paradox of estuarine quality: benthic indicators and indices in estuarine environments, consensus or debate for the future. Marine Pollution Bulletin 55, 271–281.

Dauvin, J.C., 2008. Effects of heavy metal contamination on the macrobenthic fauna in estuaries: the case of the Seine estuary. Marine Pollution Bulletin 57, 160–169.

Dauvin, J.C., Ruellet, 2009. The estuarine quality paradox: is it possible to define an ecological quality status for specific modified and naturally stressed estuarine ecosystems? Marine Pollution Bulletin 59, 38–47.

Drake, P., Arias, A.M., Baldo, F., Cuesta, J.A., Rodriguez, A., Silva-Garcia, A., Sobrino, I., Garcia-Gonzalez, D., Fernadez-Delgado, 2002. Spatial and temporal variation of the nekton and hyperbenthos from a temperate European estuary with regulated freshwater inflow. Estuaries 25, 451–468.

Elliott, M., Quintino, V., 2007. The Estuarine Quality Paradox, environmental homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. Marine Pollution Bulletin 54, 640–645.

Gaston, G.R., Rakocinski, C.F., Brown, S.S., Cleveland, C.M., 1998. Trophic function in estuaries: response of macrobenthos to natural and contaminant gradients. Marine Freshwater Research 49, 833–846.

Guézennec, L. (coord.), 1999. Seine-Aval: un estuaire et ses problèmes. In: Programme Scientifique Seine Aval, fascicule 1, 30 pp.

Lewis, L.J., Davenport, J., Kelly, T.C., 2002. A study of the impact of a pipeline construction on estuarine benthic invertebrate communities. Estuarine, Coastal and Shelf Science 55, 213–221.

Lock, K., Mees, J., 1999. The winter hyperbenthos of the Ria Formosa – a lagoon in southern Portugal – and adjacent waters. Cahiers de Biologie Marine 40, 47–56.

Mauchline, J., 1980. The biology of mysids and euphausids. Advances in Marine Biology 18, 1–369.

McLusky, D.S., Bryant, V., Campbell, R., 1986. The effects of temperature and salinity on the toxicity of heavy metals to marine and estuarine invertebrates. Oceanography and Biology, an Annual Review 24, 481–520.

McLusky, D.S., Elliott, M., 2004. The Estuarine Ecosystem, Ecology, Threats and Management, third ed. Oxford University Press, UK, 224 pp.

Mees, J., Hamerlynck, O., 1992. Spatial community strusture of the winter hyperbenthos of the Shelde estuary, the Netherlands, and the adjacent coastal waters. Netherlands Journal of Sea Research 29, 357–370.

Mees, J., Cattrijsse, A., Hamerlynck, O., 1993a. Distribution and abundance of shallow-water hyperbenthic mysids (Crustacea, Mysidacea) and euphausiids (Crustacea, Euphausiacea) in the Voordelta and the Westerschelde, southwest Netherlands. Cahiers de Biologie Marine 34, 165–186.

Mees, J., Dewicke, A., Hamerlynck, O., 1993b. Seasonal composition and spatial distribution of hyperbenthic communities along estuarine gradients in the Western-Shelde. Netherlands Journal of Aquatic Ecology 27, 1–17.

Mees, J., Fockedey, N., Hamerlynck, O., 1995. Comparative study of the hyperbenthos of three European estuaries. Hydrobiologia 311, 153–174.

Mees, J., Jones, M., 1997. The hyperbenthos. Oceanography and Marine Biology: An Annual Review 35, 221–255.

Moffat, A.M., Jones, M.B., 1992. Bionomics of *Mesopodopsis slabberi* and *Neomysis integer* (Crustacea: Mysidacea) in the Tamar estuary. In: Kohn, V.J., Jones, M.B., Moffat, A. (Eds.), Taxonomy, Biology and Ecology of (Baltic) Mysids, International Expert Conference. Rostock University Press, pp. 109–119.

Moffat, A.M., Jones, M.B., 1993. Correlation of the distribution of *Mesopodopsis slabberi* (Crustacea, Mysidacea) with physico-chemical gradients in a partially-mixed estuary (Tamar, England). Netherlands Journal of Aquatic Ecology 27, 155–162.

Mouny, P., Dauvin, J.C., Bessineton, C., Elkaïm, B., Simon, S., 1998. Biological components from the Seine estuary: first results. Hydrobiologia 373/374, 333–347.

Mouny, P., Dauvin, J.C., Zouhiri, S., 2000. Benthic Boundary Layer fauna from the Seine estuary (eastern English Channel, France): spatial distribution and seasonal changes. Journal of the Marine Biological Association of the United Kingdom 80, 959–968.

Sorbe, J.C., 1981. La macrofaune vagile de l'estuaire de la Gironde. Distribution des espèces. Océanis 6, 579–592.

Taraman, A.S., Wakabara, Y., Flynn, M.N., 1996. Suprabenthic community of the Cananeia lagoon estuarine region, Southeastern Brazil. Cahiers de Biologie Marine 37, 295–308.

Underwood, A.J., 1992. Beyond BACI: the detection of environmental impact on populations in the real, but variable world. Journal of Experimental Marine Biology and Ecology 161, 145–178.

Underwood, A.J., 1994. On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecological Applications 4, 3–15.

Vilas, C., Drake, P., Pascual, E., 2009. Inter- and intra-specific differences in euryhalinity determine the spatial distribution of mysids in a temperate European estuary. Journal of Experimental Marine Biology and Ecology 369, 165–176.

Wang, X., Dauvin, J.C., 1994. The suprabenthic crustacean fauna of the infralittoral fine sand community in the Bay of seine (eastern English Channel): composition, swimming activity and diurnal variations. Cahiers de Biologie Marine 35, 135–155.

Warwick, R.M., 1988. The level of taxonomic discrimination required to detect pollution effects on marine benthic communities. Marine Pollution Bulletin 19, 259–268.

Weisberg, S.B., Ranasinghe, J.A., Dauer, D.M., Schaffner, L.C., Diaz, R.J., Frithsen, J.B., 1997. An estuary benthic index of biotic integrity (B-IBI) for Chesapeake Bay. Estuaries 20, 146–158.

Williams, R., Collins, N.R., 1984. Distribution and variability in abundance of *Schistomysis spiritus* (Crustacea: Mysidacea) in the Bristol Channel in relation to the environmental variables, with comments on other mysids. Marine Biology 80, 197–206.

Zouhiri, S., Vallet, C., Mouny, P., Dauvin, J.C., 1998. Spatial distribution and biological rhythms of suprabenthic mysids of the English Channel. Journal of the Marine Biological Association of the United Kingdom 78, 1181–1202.