Chapter 12

Eels: contaminant cocktails pinpointing environmental pollution

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Summary

There is growing concern that insufficient somatic and health conditions of silver European eels (*Anguilla anguilla)* emigrating from European waters to oceanic spawning areas might be a key causal factor in the decline of the stock. One factor that could contribute to deterioration in the status of eels is high contaminant accumulation in their body. Contaminants may affect lipid metabolism and result in lower energy stores. A high body burden of contaminants and low energy stores might be responsible for failure of migration and/or impairment of successful reproduction. During a 12-year study on a relatively small area within the river basins of IJzer, Scheldt, and Meuse (ca. 13 500 km²), 2613 eels were sampled covering a dense monitoring network of 357 stations. Eels were analysed for ca. 100 chemicals. These included PCBs, organochlorine pesticides, heavy metals, brominated flame retardants, volatile organic pollutants (VOCs), endocrine disruptors, dioxins, perfluorooctane sulphonic acids (PFOSs), metallothioneins, and polycyclic aromatic compounds. This series represents only a very small fraction (<0.5%) of the >30 000 chemicals currently marketed and used in Europe. The biomonitoring value of eels as a tool for monitoring environmental contamination is illustrated. Two major conclusions were drawn: (i) the eel is a highly suitable biomonitor for environmental contaminants, for both local and international purposes, e.g. to evaluate the chemical status for the Water Framework Directive, and (ii) dependent on the degree of pollution in their habitat, the levels of certain contaminants reported in yellow eels can be high, and might affect their potential for reproduction.

Introduction

Some recent scientific reports have posed the question whether silver eels leaving continental waters before migrating to spawning areas may be of insufficient quality[1] and that this might be a key factor explaining the overall decline of the stock (Robinet and Feunteun, 2002; Palstra *et al*., 2006). The state of eels can deteriorate through high contaminant accumulation and/or poor physiological condition (e.g. lipid weight). Contaminants are one of the elements that influence storage of energy. They may affect lipid metabolism through various mechanisms (e.g. chemical stress induces a greater energy demand, or specific contaminants can disturb thyroid function and hence fat accumulation). Poor condition and low lipid energy stores might be responsible for failed migration and/or impairment of successful reproduction. During the transoceanic migration, lipids are metabolized and the lipophilic contaminants mobilized, particularly towards the gonads where they impair the quality of gonads, compromising reproduction and normal development of the early embryonic stages. The EIFAC/ICES Working Group on Eels (WG Eel, 2006) and the Scientific, Technical and Economic Committee for Fisheries (STECF, 2006) have recommended that the Water Framework Directive (WFD; CEC, 2000) should use the eel (*Anguilla anguilla*) as a sentinel species for monitoring the chemical status of surface waters with respect to hazardous substances. The yellow eel is considered to be a good biomonitor because of its various ecological and physiological traits: eels are top carnivores, widespread, rich in lipids, resistant to pollution, and sedentary, and there is no reproduction and associated lipid metabolism in European waters.

During a 12-year study on a relatively small area within the river basins of IJzer, Scheldt, and Meuse (ca. 13 500 km²), 2613 eels were harvested over a monitoring network of 357 stations. Sampling stations were located on streams, rivers, and brooks, as well as in canals, polders, and lakes or ponds (Figure 12.1). Some 5–10 eels were sampled at each station. Each eel was analysed individually for a series of ten PCBs, nine organochlorine pesticides, and nine heavy metals. Additionally, at selected locations, a restricted number of eels was analysed for brominated flame retardants (BFRs), volatile organic pollutants (VOCs), endocrine disruptors, dioxins, perfluorooctane sulphonic acids (PFOSs), metallothioneins, and polycyclic aromatic compounds. The data have been reported in various papers (Belpaire *et al*., 2001, 2003; Goemans *et al*., 2003; Roose *et al.*, 2003; Goemans and Belpaire, 2004, 2005; Morris *et al*., 2004; Versonnen *et al.*, 2004; Hoff *et al*., 2005; Maes *et al*., 2005).

The objectives of this paper are to document the potential for pollutant monitoring using eels on both a local and international scale, using a selected set of substances. Emphasis is given to how the species meets the requirements of a good biomonitor. We also discuss the international monitoring strategy proposed in the context of the Water Framework Directive.

1 In the terms of references of the ICES/EIFAC Working Group on Eels 2006, the term ‘quality of spawners’ is suggested to be included in the stock management advice, describing *the capacity of silver eels to reach spawning areas and to produce viable offspring* (WG Eel, 2006). The term of reference specifically focused on quantifying the impact of pollution and parasitism.

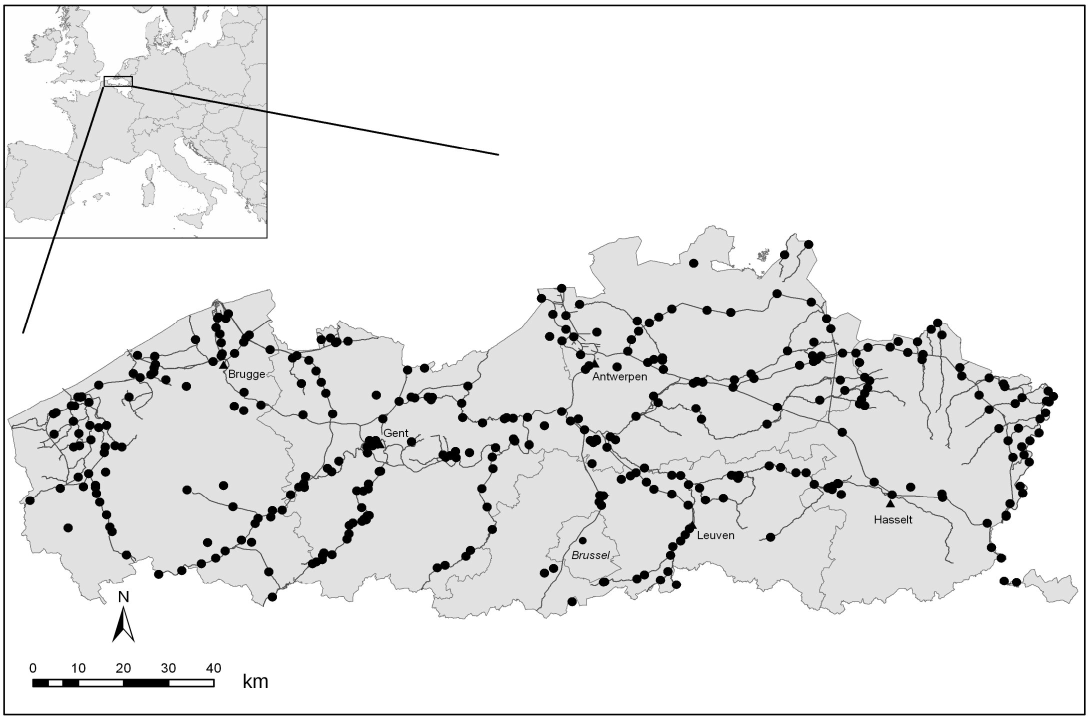


Figure 12.1. The Flemish Eel Pollutant Monitoring Network. Geographical distribution of sampling stations (n = 357).

Levels of selected chemicals in eels

Volatile organic compounds

Volatile organic compounds are atmospheric contaminants that are frequently determined in air, drinking water, fresh water, effluents, and soils. Many are substances of concern, and some are on the list of priority substances[2] proposed within the WFD (CEC, 2007). A series of 52 VOCs was analysed in eels from 20 sites, and results were reported by Roose *et al*. (2003). Only one eel was analysed from each site. The most prominent VOCs were BTEX and a number of chlorinated compounds, such as chloroform and tetrachloroethene. Here, we present data on the presence in eels of 1,2-dichlorobenzene, 1,2-dibromo-3-chloropropane, and BTEX compounds.

As reported by Roose *et al*. (2003), determination of VOCs in the water column is considered to be inadequate. Concentrations of the same VOCs as studied in Flemish eels show that these are generally below the detection limits of the analytical techniques used in the water column of Flemish rivers. VOCs detected in

2 Substances that present a significant risk to or via the aquatic environment prioritized for action on the basis of risk to or via the aquatic environment (CEC, 2000)

the water column are the same as the most prominent ones found in eels, and the highest concentrations are also found at the same sites. Further evidence supports a conclusion that concentrations in eels indeed reflect the concentrations in the water column (when detected).

1,2-dichlorobenzene (or o-dichlorobenzene)

This VOC has low water solubility (118 mg l^{-1} at 25°C) and is an intermediate for making agricultural chemicals, primarily herbicides. Other present and past uses include: use as a solvent for waxes, gums, resins, wood preservatives, and paints; as an insecticide for termites and borers; in making dyes; and as a coolant, deodorizer, or degreaser. On the basis of its volatility and the dispersive nature of its uses, it is expected that 1,2-dichlorobenzene will be released to the environment primarily in liquid effluents and atmospheric emissions from production and other facilities. It may also occur as a result of dehalogenation of more highly chlorinated chlorobenzenes (Bosma *et al.*, 1988) and can be found in emissions from incineration of organic matter containing chlorine (Young and Voorhees, 1989). 1,2-dichlorobenzene has been reported following a survey of effluents from ten Canadian textile mills conducted in 1985/86; concentrations were reported to range up to 95.5 mg l^{-1} (Environment Canada, 1989).

Analyses of this chemical in eels from 20 locations in Flanders, collected between 1996 and 1998 (Figure 12.2, drawn with data presented by Roose *et al*., 2003) show that at ten sites (50%), concentrations were below the detection limit (DL, 0.05 ng g^{-1} wet weight). However, the chemical was detectable at ten sites, and eels from two of these showed high concentrations of dichlorobenzene (Oude Leie at Wevelgem, 85 ng g^{-1} wet weight; Leie at Menen, 49 ng g^{-1} wet weight). Few studies have detailed the presence of 1,2-dichlorobenzene in other fish. In the Great Lakes in the early 1980s, the concentration of 1,2-dichlorobenzene in lake trout (*Salvelinus namaycush*) and rainbow trout (*Oncorhynchus mykiss*) averaged 0.3 ng g^{-1} and 1 ng g^{-1} wet weight, respectively (Oliver and Nicol, 1982; Oliver and Niimi, 1983).

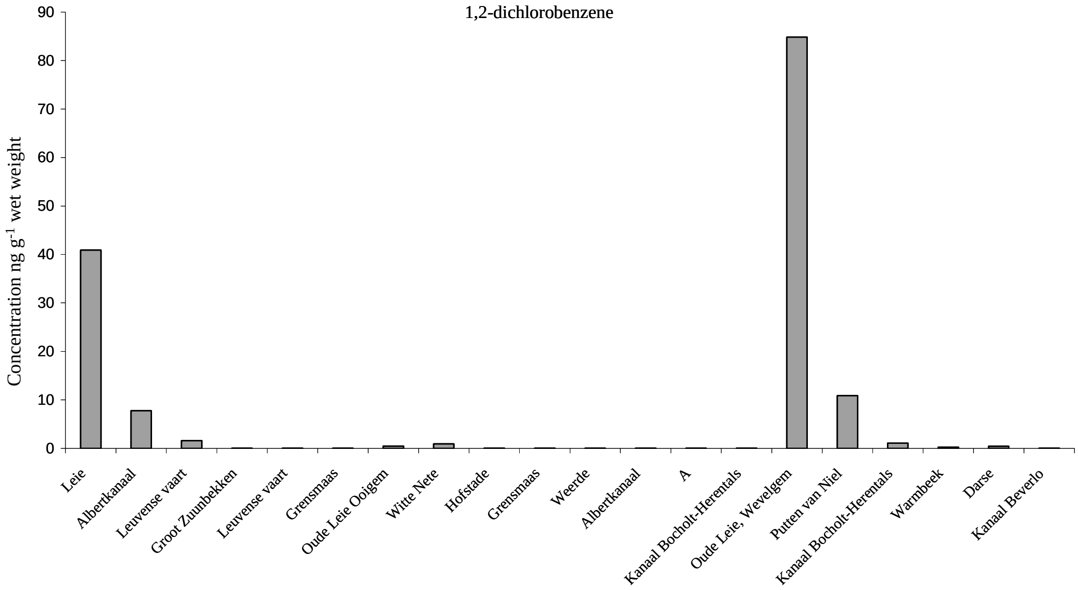


Figure 12.2. Concentrations of 1,2-dichlorobenzene in eels collected at 20 sites in Flanders (1996–1998). Values presented are the result of the analysis of one eel per location. Data from Roose *et al*. (2003).

Both sites with reported high concentrations of dichlorobenzene were situated on or in the vicinity of the River Leie, and each station was in the neighbourhood of major industrial sites. One company, located at Wevelgem, is active in the textile finishing industry, and activities conducted there include pre-treatment, dyeing, and finishing treatments, using a diverse mix of chemicals. The company is one of the largest dischargers, discharging ca. 3000 m^3 water per day directly into the river. Another large manufacturing plant producing pigments used especially by the paint, ink, and plastics industries is situated at Menen, discharging ca. 3500 m^3 water per day (Anon., 2003).

A network is in place for monitoring some VOCs in water at a selection of ca. 40 sites occupied monthly. From Figure 12.3 and Table 12.1, it is obvious that this compound is difficult to detect in water. In water, 95% of the measurements are below the detection limit, compared with 50% from analysis of eel tissue.

Little is known about the ecotoxicological effect of 1,2-dichlorobenzene on eels, but impairment of reproduction has been identified as the most sensitive toxicity endpoint reported for other aquatic organisms (Environment Canada, 1993). Two studies have measured LC_{50} values for rainbow trout (*Oncorhynchus mykiss*). Ahmad *et al.* (1984) reported the 96-h LC_{50} to be 1.61 mg l^{-1}. Black *et al.* (1982) studied its effects on embryos and larvae, exposing them from 20-30 min after fertilization of the egg to 4 d after hatching of the larva. The resultant LC_{50} was 3.01 mg l^{-1}, following total exposure times of 27 d.

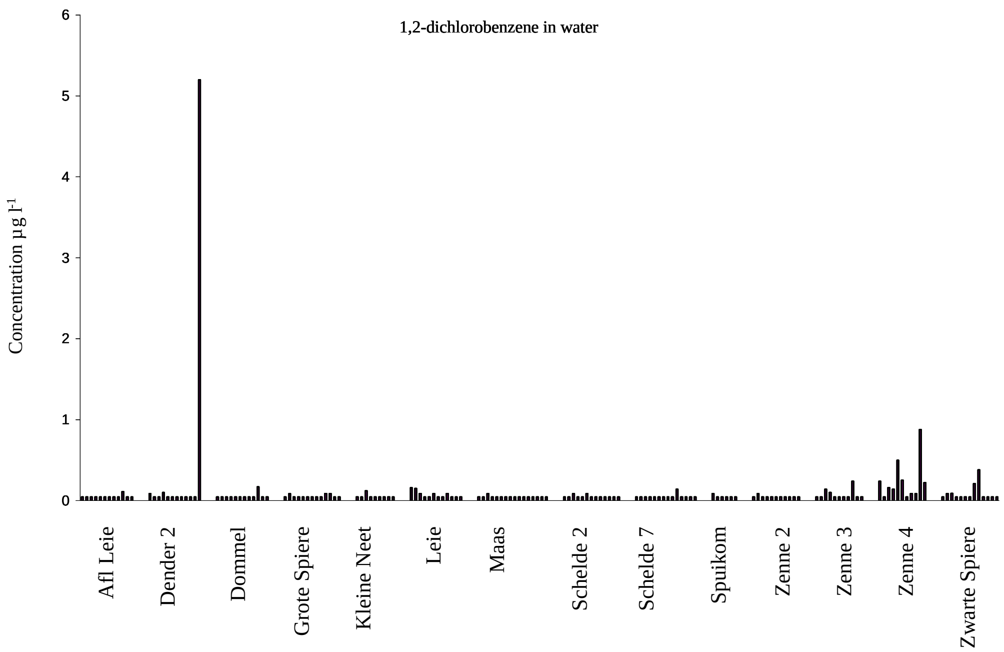


Figure 12.3. Concentrations of 1,2-dichlorobenzene in water collected monthly at 40 sites in Flanders (2005). Concentrations under the detection limit (0.044 µg $l^{-1)}$ were set at the detection limit. All measurements in the following water bodies were below the detection limit and are not shown in the graph: Demer, Dender 1, Dijle 1, Dijle 2, Dijle 3, Gaverbeek 1, Gaverbeek 2, Gent-Oostende, Gent-Terneuzen, Gete, Handzamevaart, IJzer 1, IJzer 2, Leopoldskanaal 1, Leopoldskanaal 2, Mandel, Mark, Nete, Schelde 1, Schelde 3, Schelde 4, Schelde 5, Schelde 6, Schelde-Rijnkanaal 1, Schelde-Rijnkanaal 2, and Zenne 1. Data from the Flemish Environment Agency.

Table 12.1. Concentrations of 5 VOCs in water and eel from Flanders (Belgium). Data from the Flemish Environment Agency and Roose *et al*. (2003) respectively. Values in water are expressed in µg l^{-1}, in eels in ng g^{-1} wet weight.

Substance	Water (470 measurements, 2005)			Eel (20 sites, 1996–1998)		
	Min - Max	Mean	% < DL	Min - Max	Mean	% < DL
1, 2-dichlorobenzene	0.044- 5.2	0.06	95.5	0.02-84.8	7.5	50
Benzene	0.007-2.68	0.06	83,4	1.2-18.9	5.7	0
Toluene	0.03-15	0.28	86.4	1.0-72.6	19.0	0
o-xylene	0.05-1.6	0.07	94.9	0.6-39.7	7.1	0
Ethylbenzene	0.043-2.2	0.06	94.9	1.2-35.6	14.9	0

1,2-dibromo-3-chloropropane

1,2-dibromo-3-chloropropane was previously used as a pesticide (registered by the US Environmental Protection Agency, EPA, as a soil fumigant to control nematodes during growth of crops). The US EPA banned all uses of 1,2-dibromo-3-chloropropane in 1985, and it is now used only as an intermediate in organic synthesis and for research purposes (ATSDR, 1992). Most of the 1,2-dibromo-3-

chloropropane released to the air disappears within several months. Most that enters surface water evaporates into the air within several days or a week.

In Flanders, eels from 20 sites were analysed (Figure 12.4). In 80% of the samples, 1,2-dibromo-3-chloropropane was below the detection limit (0.05 ng g^{-1} wet weight), but very high concentrations were found in eels from two canals, the Leuvense vaart and the Albertkanaal (265 and 706 ng g^{-1}, respectively). Both are important canals situated in the centre of Belgium. These data clearly indicate point sources, but the origin of these sources is unclear.

From the information presented by ATSDR (1992), 1,2-dibromo-3-chloropropane does not accumulate in sediments at the bottom of rivers, lakes, or ponds, and fish were not expected to accumulate large amounts of this chemical in their bodies. Our results nevertheless suggest that in some cases, fish may bioaccumulate this chemical.

There have been no ecotoxicological studies of the effect of this chemical on eel. Studies of workers in chemical factories that produced 1,2-dibromo-3-chloropropane showed that its main harmful effect was to the male reproductive system, resulting in a lower production of sperm and a reduced ability to reproduce.

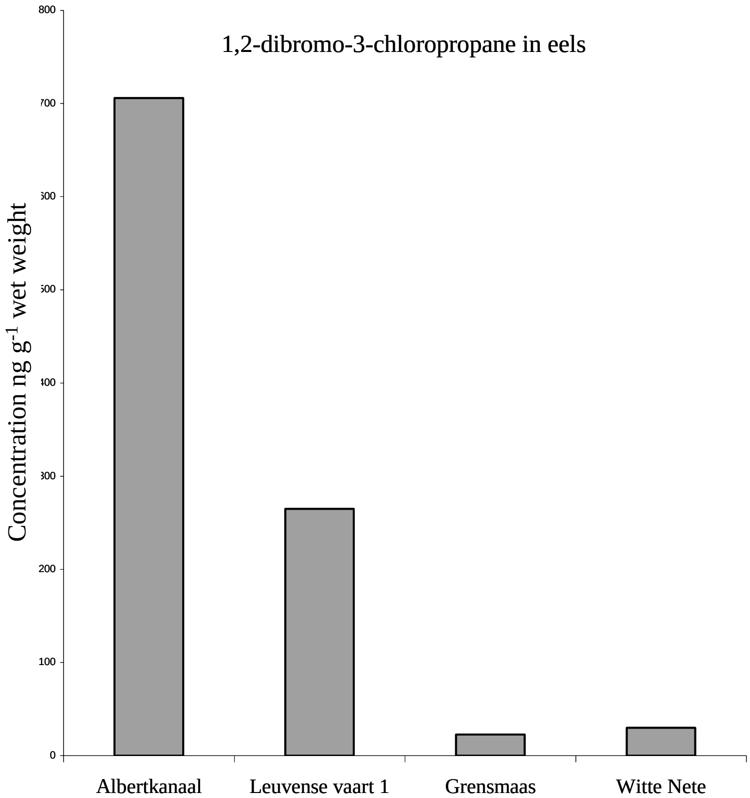


Figure 12.4. Concentrations of 1,2-dibromo-3-chloropropane in eels collected at 20 sites in Flanders (1996–1998). The values presented are the result of the analysis of one eel per location. Measurements on Leie, Groot Zuunbekken, Leuvense vaart 2, Oude Leie Ooigem, Hofstade, Maas, Weerde, Albertkanaal, A, Kanaal Bocholt-Herentals 1, Kanaal Bocholt-Herentals 2, Oude Leie Wevelgem, Putten van Niel, Warmbeek, Darse, and Kanaal Beverlo were below the detection limit and are not shown. Data from Roose *et al*. (2003).

BTEX compounds

Benzene, toluene, ethylbenzene, and the xylenes (BTEX) are important industrial compounds among the VOCs. Moreover, BTEX compounds are important constituents of unleaded gasoline and are present in crude oil. Benzene is on the list of priority substances defined by the WFD (CEC, 2007). Industrial processes are the main sources of benzene in the environment. Benzene concentrations in the air can be elevated by emissions from burning coal and oil, benzene waste and storage operations, motor vehicle exhaust, and evaporation from gasoline service stations. Industrial discharge, disposal of products containing benzene, and gasoline leaks from underground storage tanks release benzene into water and soil (ATSDR, 2005).

The concentrations of benzene, toluene, ethylbenzene, and *m*-xylene are presented in Figure 12.5. It is striking that all compounds were detectable at all sites (n = 20). The distribution of BTEX in Flanders is more widespread than most of the other chemicals studied. The variability of the data is also somewhat less than seen for other chemicals. Moreover, the BTEX compounds correlated very well with each other, with correlation coefficients between 0.77 and 0.98 (Roose *et al*., 2003). This indicates that contamination by BTEX is of a rather diffuse nature, supporting the conclusion that the use of fossil fuels in, e.g., motor vehicles is the major source of BTEX.

The high concentrations observed at the Groot-Zuunbekken station can possibly be explained by the fact that this is a pond in a densely populated and industrialized area just southwest of Brussels. Another source might be a large chemical industry located at Drogenbos (9 km from the sampling site), producing plastics in primary forms and reporting an emission of 0.46 t BTEX year^{-1} to water in 2001 (EPER, 2006). In distinct contrast, eels from rural locations, such as river A (at Poppel) or the Warmbeek (at Achel), have significantly lower concentrations.

Once again, comparison of BTEX data in eels with the concentrations water (see Table 12.1) evidence that any monitoring strategy for these compounds should be based on analysis of biota rather than water.

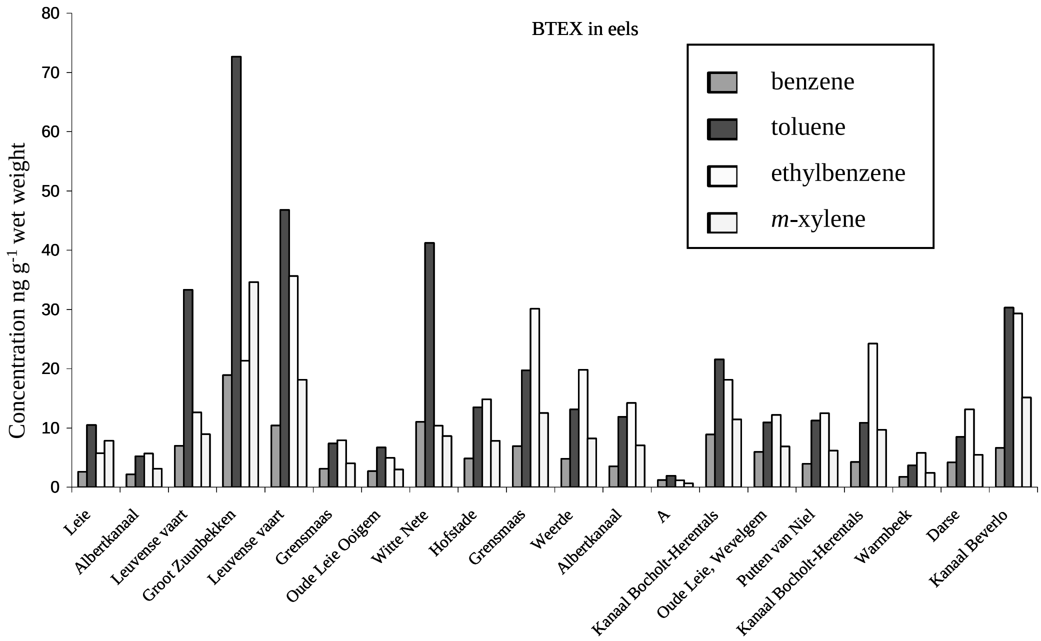


Figure 12.5. Concentrations of BTEX compounds in eels collected at 20 sites in Flanders (1996–1998). The values presented are the result of the analysis of one eel per location. Data from Roose *et al*. (2003).

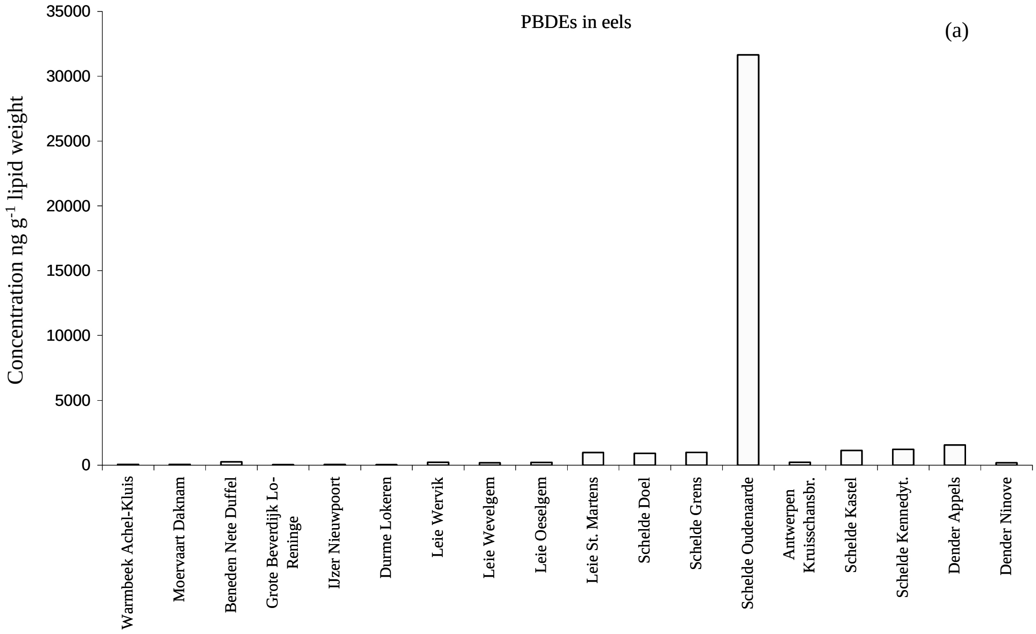
Brominated flame retardants

Brominated flame retardants are chemicals used to inhibit or impede flammability in combustible products. Several groups of BFRs exist, e.g. hexabromocyclododecane (HBCD) and polybrominated diphenylethers (PBDEs), which have different applications. HBCD is used mainly to flame-retard extruded and expanded polystyrene used for thermal insulation, but also in upholstery textiles. PBDEs are produced as three commercial formulations: penta-BDE, octa-BDE, and deca-BDE. Penta-BDE is used primarily in foam products such as seat cushions and other household upholstered furniture, as well as in rigid insulation. Octa-BDE is used in high-impact plastic products, e.g. computers. Deca-BDE is used in plastics, such as wire and cable insulation, adhesives, textile, and other coatings. Typical end-products include housing for television sets, computers, stereos, and other electronics. Deca-BDE is also used as a fabric treatment and coating on carpets and draperies. Deca-BDE is not used on clothing.

BFRs are of major concern because their occurrence in all compartments of our environment have been increasing. Penta-BDE and octa-BDE products have been removed from production and use within the EU following risk assessments, and decreasing trends in BDE have been described in some studies (e.g. in human milk samples from Sweden). These compounds have a carcinogenic, neurotoxic, and endocrine-disrupting action. PBDEs are on the list of priority substances defined by the WFD (CEC, 2007).

Figure 12.6 illustrates the presence of PBDEs and HBCD in yellow eels from 18 sites in Flanders. At each site, the muscle tissue of ten eels was pooled for analysis. Both groups of chemicals were detected in all samples, indicating the widespread distribution of these chemicals (even in remote areas). The analysis of eel tissue has also highlighted significant local pollution by HBCD and PBDEs at some locations along the rivers Leie and Scheldt. Eels from the site at Oudenaarde, along the River Scheldt, showed extremely high concentrations of PBDEs and HBCD, respectively 31 639 and 33 000 ng g^{-1} lipid weight. These are among the highest concentrations reported worldwide in fish. Although measurements in water are not a good indicator of the concentration of these chemicals because of their lipophilic character, data are available and have been published for the sediment (Belpaire *et al*., 2003), and are more or less in line with the eel data.

The primary industry in Oudenaarde is textile production, with several companies involved in coatings, dyes, auxiliaries, and services for the textile industry.



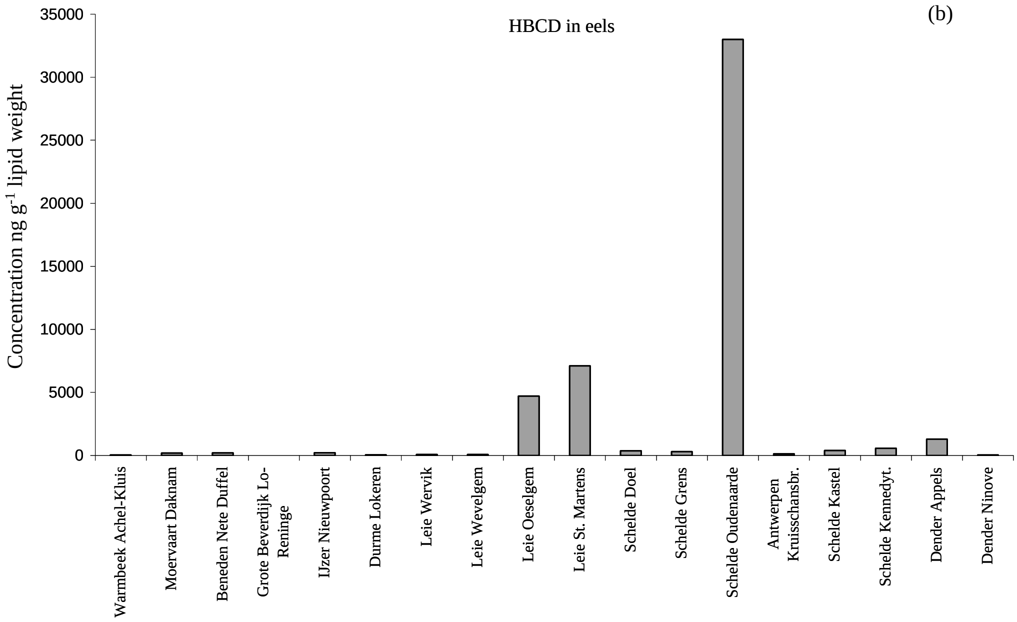


Figure 12.6. Concentrations of (a) PBDEs and (b) HBCD in eels collected at 18 sites in Flanders (2001). The values presented are the results of the analysis of pooled samples of ca. 10 eels per location (one survey in 2000). Data from de Boer *et al*. (2002) and Belpaire *et al*. (2003).

PCBs, organochlorine pesticides, and heavy metals

Ten PCBs, nine organochlorine pesticides, and nine heavy metals were analysed in each of the eels sampled. At each station, 5–10 eels were sampled and analysed individually. Results for each contaminant were averaged per station, so the data presented here represent means of 5–10 eels per station. We selected lindane and cadmium to illustrate the distribution pattern of the contaminants, because both are on the list of priority substances proposed by the WFD (CEC, 2007). Figure 12.7 shows that concentrations of lindane in eels can be very high, up to 9255 ng g^{-1} lipid weight, to our knowledge the highest recorded concentration in Europe. Lindane is an organochlorine insecticide, used on many crops, including sugar beet and oil seed rape. As it is a persistent organic pollutant known to be both carcinogenic and an endocrine disruptor, it has been banned in a number of countries for many years. However, in Belgium, it was banned only in June 2002. The pattern of distribution of this chemical in eels is related to agricultural activities. The highest values shown in Figure 12.7 are confined to areas situated in the subcatchments of the rivers IJzer, Demer, and Dijle, where there is intensive culture of sugar beet. Lindane is measured also in water and sediment. However, because of its lipophilic nature, concentrations in biota are some orders of magnitude higher than the concentrations in water or sediment. At all of our 357 sites, lindane was detectable in eels. In most cases, lindane is not detectable in sediment (15.5% above DL at 2445 sites), and in water lindane can only be detected during the season of application.

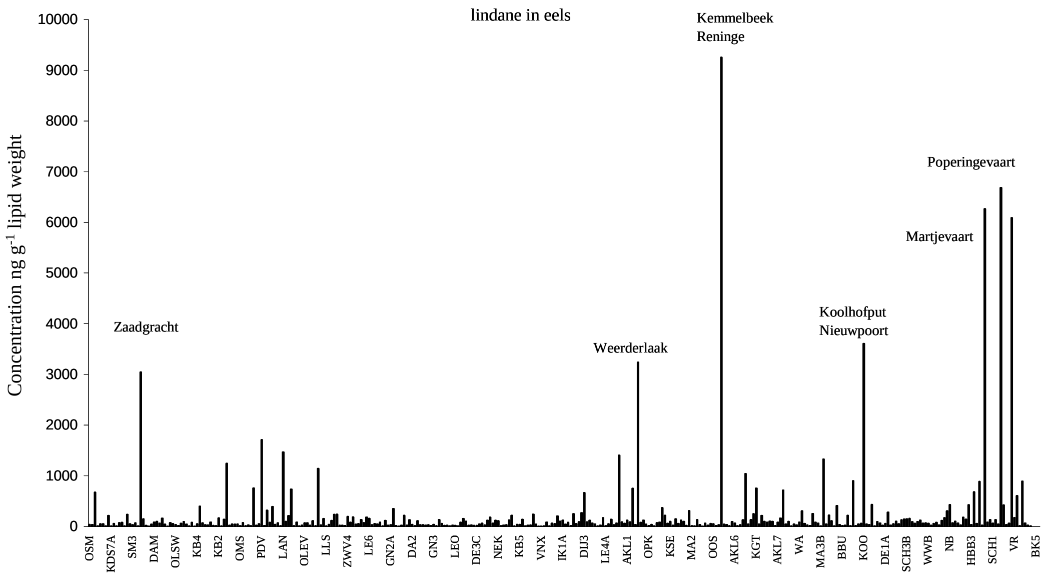


Figure 12.7. Concentrations of lindane in eels collected at 357 sites in Flanders (1994–2005). Data from the INBO Eel Pollutant Monitoring Network Database. Values represent the means of the individual analysis of 5–10 eels per location, for the most recent survey. Codes on the x-axis are location codes defined by Goemans *et al*. (2003).

Figure 12.8 shows cadmium concentrations in eels from 333 sites. The data clearly indicate local cadmium pollution. The sources may be variable, from historically polluted sediments to active industrial discharges. Some of these concentrations are above international health consumption limits. Heavy metals are well-known chemicals that are frequently determined in water and sediments. Generally spoken "black point" sites indicated by eel analyses confirmed what was known from measurements in water or sediment.

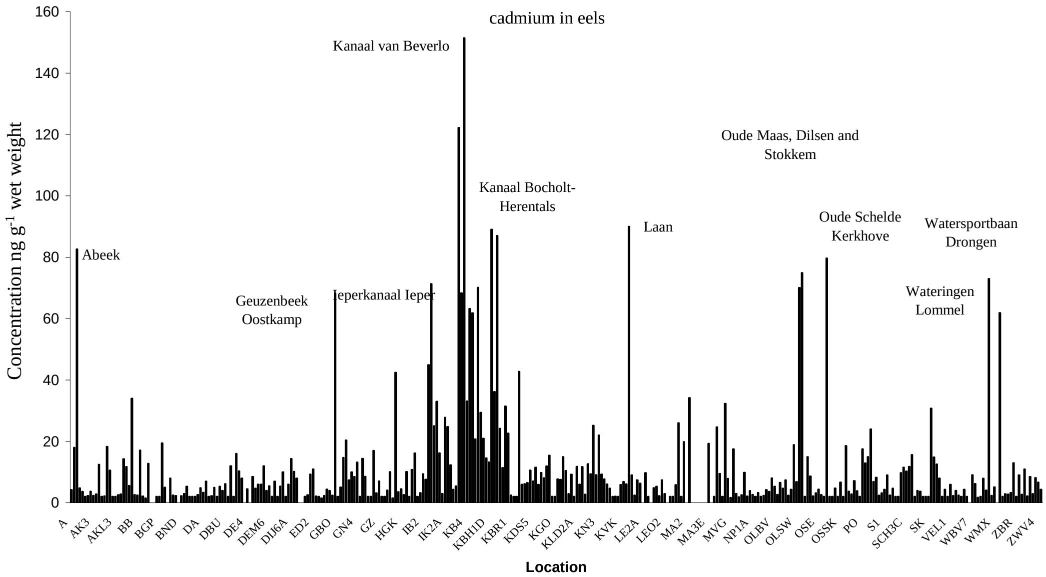


Figure 12.8. Concentrations of cadmium in eels collected at 333 sites in Flanders (1994–2005). Data from the INBO Eel Pollutant Monitoring Network Database. Values represent the means of the individual analysis of 5–10 eels per location, for the most recent survey. Codes on the x-axis are location codes defined by Goemans *et al*. (2003).

Pollutant monitoring of eels and the Water Framework Directive

The time schedule for the implementation of the EU WFD requires environmental and ecological monitoring to be in place by 2006, the development of a programme of measures by 2009, and the achievement of good ecological status by 2015. Within the Directive, emphasis is given to monitoring the ecological quality and chemical status of surface water. It is implicit in the spirit of the directive that implementation of the WFD should have a positive impact on the quantity and quality (e.g. with respect to the presence of contaminants) of silver eels migrating to the sea. It can be therefore argued that specific extensions should be implemented for eels as an indicator for river connectivity and ecological and chemical status. It was recommended by both the EIFAC/ICES Working Group on Eels (2006), and the CEC Scientific, Technical and Economic Committee for Fisheries (in its plenary meeting of April 2006) that the WFD should use the eel as a sentinel species for monitoring the chemical status of surface waters with respect to hazardous substances, because of several ecological and physiological traits. Using the eel as a biomonitor will not only give us a powerful tool for measuring harmful substances, but using the species as a “target” organism for reaching good chemical status will also guarantee in a direct way achievement of a better status for the target species itself.

However, there is no specific reference made within the WFD to the use of eels for monitoring the chemical status of our waters. The monitoring guidance document states only that, besides monitoring in water, some fish species (as well as mussels) can be used in monitoring harmful organic substances and heavy metals, because they have a high bioaccumulation capacity (WFD–CIS, 2003). In the latest proposal (CEC, 2007) for a Directive on environmental quality standards in the field of water policy, amending the WFD (2000/60/EC), emphasis is still placed on measuring concentrations of hazardous substances in the water column. According to that proposal, there seems to be enough extensive and reliable information on concentrations of priority substances available from measuring in water to provide a sufficient basis to ensure comprehensive protection and effective pollution control of the aquatic environment. Member States have to ensure, on the basis of monitoring the chemical status of water, that concentrations of listed substances do not increase significantly in sediment and relevant biota (CEC, 2007).

Moreover, the Commission of European Communities (CEC, 2007) establishes ‘Environmental quality standards’ (EQSs) for priority substances and selected other pollutants. The EQSs are differentiated for inland surface waters (rivers and lakes) and other surface waters (transitional, coastal, and territorial waters). Two types of EQS are set: (i) annual average concentrations for protection against long-term and chronic effects, and (ii) maximum allowable concentrations for short-term, direct, and acute ecotoxic effects. However, for specific substances (hexachlorobenzene, hexachlorobutadiene, and methyl-mercury), it is not possible to ensure protection against indirect effects and secondary poisoning simply by setting EQSs for surface water at a Community level. Therefore, in those cases, EQSs for biota should also be set. The directive proposes limit concentrations for hexachlorobenzene, hexachlorobutadiene, and methyl-mercury, which may not be exceeded in prey tissue of fish, molluscs, crustaceans, and other biota (see below).

The directive allows Member States flexibility regarding their monitoring strategy. Member States should be able either to monitor and check compliance against EQSs in biota, or convert the Biota EQSs to equivalents for surface water. Where necessary and appropriate, more EQSs for sediment or biota can be set (CEC, 2007). In any case, the Member States should ensure that existing levels of contamination in relevant biota and sediments do not increase significantly.

Although CEC (2007) continues to focus on the analysis of those substances in the water column, there is growing awareness that sediment and biota should also be monitored (for instance, because many substances are lipophilic and are difficult to measure in water, but can be detected in high concentrations in biota). The need for a harmonized approach to monitoring the presence of hazardous substances through aquatic biota is becoming more and more acute. A good biomonitor needs to show a high capacity for bioaccumulation (see above). However, it is clear that to be adequate, potential biomonitoring organisms need more conditions to be fulfilled. These requirements are listed and discussed with respect to the eel in Table 12.2.

The WFD proposes (CEC, 2007) 33 substances or groups of substances in the list of priority substances, including selected existing chemicals, plant protection products, biocides, and metals. Other groups include polyaromatic hydrocarbons (PAHs), and polybrominated diphenylethers (PBDEs) used as flame retardants. Another eight pollutants are not on the priority list, but fall under the scope of older directives. From various published and unpublished data of concentrations in eels from Flanders collected between 1994 and 2005, we compiled the available knowledge with respect to these WFD chemicals. Table 12.3 lists, where available, minimum and maximum concentrations, as well as the means for each. All data are expressed in ng g^{-1} wet weight. The percentage of the sites where values were below the detection limits is indicated. Data are available for more than half the substances. Table 12.3 indicates the proportion of sites under the detection limit for each substance. Of 21 (groups of) substances, just three show measurements under the DL for more than half the sampled sites. Considering the range of the measurements of these substances in eels (Table 12.3), it may be concluded that at some sites at least, some substances show extremely high levels in eels (see, e.g., maximum values for lindane, total DDT, lead, cadmium, mercury, and brominated diphenylethers). This dataset for eels in Flanders illustrates the potential of using the eel as a biomonitor over a broader geographical range, meeting the requirements of the WFD, at least for some priority substances.

CEC (2007) states that Member States have to ensure that the following concentrations of hexachlorobenzene, hexachlorobutadiene, and methyl-mercury are not to be exceeded in tissue (wet weight) of fish, molluscs, crustaceans, and other biota: 10 µg kg^{-1} for hexachlorobenzene, 55 µg kg^{-1} for hexachlorobutadiene, and 20 µg kg^{-1} for methyl-mercury. As can be seen from Table 12.3, hexachlorobutadiene is present in eels from half the sites but concentrations are always less than the limit value of 10 ng g^{-1} wet weight. However, for hexachlorobenzene the standard was exceeded at 14% of sites (total 357 sites). The situation is even more serious for mercury: the 20 ng g^{-1} wet weight was exceeded at 99% of sites (total 355 sites).

Finally, we are aware that the use of a now-endangered species, such as the eel, as biomonitor might raise some concerns. As several aspects such as fat levels, contaminants, condition, parasites, and disease are believed to play a major role in the decline of the species, we will have to monitor these to understand better the reasons for the decline. It has been calculated that our Flemish eel monitoring network, which is a very dense network, necessitates a quantity of ca. 25 kg eels annually, a negligible quantity compared with the total Belgian eel consumption (<0.005%). Still, in order to minimize culling eels for monitoring purposes, we recommend synergy in monitoring actions, e.g. by combining environmental monitoring through eel analyses with human health sanitary control of fisheries products. Also, maximum use of the eels sampled is urged (combining pollution monitoring with measuring other aspects such as condition, fat stores, and the prevalence of disease factors).

Table 12.2. Potential characteristics of a biomonitor appropriate for the monitoring of hazardous substances in the aquatic environment.

Prerequisites	Requirements	Eels : Advantage (+)/disadvantage (-)
Bioaccumulation capacity	In some species, particular ecological traits, habitat, or trophic status will enhance the bioaccumulation capacity.	+ Eels are benthic fish, carnivorous in their feeding behaviour and preying on insect larvae, worms, crustaceans, snails, mussels, and fish, in particular small bottom-dwelling species, resulting in high bioaccumulation of toxic residues. – Individual variations might occur through trophic specialization of some fish (Belpaire *et al*., 1992; Dörner *et al*., 2006). Dependent on local biotic conditions (e.g. chironomid biomass), eels might have different mean trophic positions (Dörner *et al*., 2006).
Bioavailability	The biomonitor should be at the top of the food chain, to obtain information on the degree of bioavailability of chemicals.	+ Eels are carnivorous predators (see above).
Range of chemicals measurable	The range of chemicals possible to quantify should be as broad as possible.	+ Eels have been demonstrated to be good indicators for a variety of chemical compounds, including PCBs, organochlorine pesticides, heavy metals (Goemans *et al*., 2003), brominated flame retardants (Belpaire *et al*., 2003), volatile organic pollutants (Roose *et al*., 2003), dioxins, perfluorinated chemicals (Hoff *et al*, 2005; Santillo *et al*., 2006), metallothionines (Langston *et al*., 2002), and polycyclic aromatic compounds (Ruddock *et al*., 2003). – Yellow eels are apparently not suited to indicating the extent of endocrine disruption by vitellogenin measurements (Versonnen *et al*., 2004).
Internationally accepted monitor species	Member States use diverse organisms as biomonitors: microbial assemblages, molluscs, algae, other fish species (trout, gudgeon, etc.), fish parasites, invertebrates, aquatic macrophytes, water birds, etc. There is definitely a need for harmonization and for a common approach and strategy for tracking chemicals in aquatic biota.	+ Eels have been used all over the world as (chemical) biomonitors, and studies on a local or a national scale are known for the European eel in Europe. In The Netherlands (Hendriks and Pieters, 1993; de Boer and Hagel, 1994; Pieters *et al*., 2004), France (Batty *et al*., 1996; Roche *et al*., 2002; Goursolle, 2002), Finland (Tulonen and Vuorinen, 1996), Sweden (van Leeuwen *et al*., 2002; Ankarberg *et al*., 2004), the UK (Mason and Barak, 1990; Mason, 1993; Weatherley *et al*., 1997), Spain (Usero *et al*, 2003), Italy (Bressa *et al*, 1995, 1997; Agradi *et al*., 2000; Corsi *et al*., 2005), Germany (Fromme *et al*., 1999; Wiesmüller and Schlatterer, 1999), and Belgium (Walloon region (Thomé *et al*., 2004)) and Flanders (Goemans *et al*., 2003; Goemans and Belpaire, 2004; Roose *et al*., 2003; Morris *et al*., 2004; Hoff *et al*., 2005; Maes *et al*., 2005). A regular monitoring network has been in place in The Netherlands (since 1977) and in Belgium (since 1994). More widespread studies over Europe have been presented by Greenpeace, using the eel as a bioindicator for the presence of brominated flame retardants and PCBs from rivers and lakes in 10 European countries (Santillo *et al*., 2005) and for perfluorinated chemicals (11 countries: Santillo *et al*., 2006).

Table 12.2. (continued)

Prerequisites	Requirements	Eels : Advantage (+)/disadvantage (-)
Seasonality	No or minimal seasonal changes through metabolic activities within annual cycles, linked with reproduction or seasonal environmental variation.	+ Because of the absence of annual reproductive cycles, there are no reproduction-linked seasonal metabolic variations (but see also Gorby *et al*., 2005 for seasonal variation in metallothioneins, cytochrome P450, bile metabolites and oxyradical metabolism) – Lipid content might fluctuate to some extent throughout the year (van Leeuwen *et al*., 2002).
Migratory behaviour	Sentinel species should be fairly resident to allow fingerprinting the local pollution load.	+ Yellow eels show explicit homing behaviour, and foraging movements are mostly restricted to a few hundred metres. Apparently, many eel species share this ecological trait (*A. anguilla* – Baras *et al*., 1998; Lafaille *et al*., 2005; *A. rostrata* – Oliveira, 1997; Goodwin, 1999; *A. australis* – Jellyman *et al*., 1996; *A. dieffenbachi* – Beentjes and Jellyman, 2003; *A. japonica* – Aoyama *et al*., 2002). The fingerprint value of eels has been demonstrated (Castonguay *et al*., 1989; Belpaire *et al*., 1999). – Although within tidal estuaries, home-site fidelity is obvious, home range may be larger than in fresh-water habitats (Parker, 1995), and seasonal movements might occur (Hammond, 2003). Also, seasonal migration activities have been reported, as well as the occurrence of erratic eels (nomads) (Feunteun *et al*., 2003). Because of migrations at the silver eel stage, the bioindicator value of the eel is restricted to the yellow eel phase.
Occurrence	The species should be widespread and should occur in a wide range of aquatic habitats. In the context of the WFD, an overall European distribution is recommended.	+ Eels are widespread and can be found in almost all aquatic habitats. They occur in fresh, brackish, and coastal waters in almost all Europe (even northern Scandinavia and from the Azores to the eastern Mediterranean), as well as in northern Africa. In Flanders, the species is the third most widespread fish species. – The presence of eels in upstream reaches might be limited by the presence of migration barriers. Mitigating management procedures such as restocking programmes can counter this.
Size	The size of the organism must be large enough to permit adequate analysis.	+ The targeted length of 40 cm means a weight of ca. 100 g, large enough to distribute eel tissue for the various analytical procedures and to laboratories linked to the various contaminants.
Standardization	Standardization on length and/or age is recommended.	+ Standardizing through the choice of an eel length class for monitoring is ~40 cm. – Bias attributable to growth heterogeneity.
Physiological properties	Besides size, physiological traits such as high lipid content will facilitate analysis of (mostly lipophylic) substances.	+ Eels show extremely high lipid values (mean for Flemish eels: 14.7%, n = 1164; Goemans *et al*., 2003). – There can be heterogeneity in lipid content between eels and sites.

Table 12.2. (continued)

Prerequisites	**Requirements**	**Eels : Advantage (+)/disadvantage (-)**
Reference values	Evaluation procedures, risk analysis, management decision trees, are dependent on the availability of normative values such as reference values, target values, action threshold values, and consumption standards.	+ On the basis of data distribution analysis, reference values for eels have been presented for Flanders for PCBs, OCPs, and heavy metals (Goemans *et al*., 2003, Belpaire and Goemans, 2004) and exist in The Netherlands (Hendriks and Pieters, 1993). Action threshold values are in place in The Netherlands. Many countries have national consumption standards, and EU consumption standards are in place or under development. – For many substances, threshold values are still missing
Life history	There should be a sufficiently long life cycle to be capable to accumulate hazardous substances.	+ The eel spends between 3 and 20 years in inland and coastal waters (Vøllestad, 1992)
Robustness of the biomonitor	It is essential that also in (highly) polluted waters, contaminants can be monitored through the sentinel species; therefore, the species should be (fairly) resistant to environmental degradation.	+ Eels are highly resistant to degradation of water quality and endure low levels of oxygen and high eutrophication levels. – Eels are sensitive to failure in river connectivity, but their presence is enhanced by restocking.
Multiple use biomonitor	Simultaneous use of one sentinel species for multiple goals is economical beneficial (cost-effficient).	+ Choosing eel as a chemical biomonitor allows triple usage: (i) Environmental health and chemical status (national level and WFD level); (ii) Human food safety and sanitary control of fisheries products; (iii). Monitoring of eel (spawner) quality within the requirements of the international eel restoration plan and the national Eel Management Plans (STECF, 2006).

Table 12.3. WFD substances mentioned under CEC (2006), and available data from measurements of Flemish eels. All data are expressed in ng g^{-1} wet weight. DL, detection limit.

Substance	Note	Range Min – Max (Mean)	% <DL	Number of sites	Years	Reference
Benzene	a	1.2-18.9 (5.7)	0	20	1996-1998	j
Brominated diphenylethers	a	6.9-5 284.4 (369.1)[c]	0	18	2001	l
Cadmium and its compounds	a	DL-151.4 (11.7)[d]	19	357	1994-2005	k
1,2-Dichloroethane	a	DL-4.9 (1,2)	55	20	1996-1998	j
Hexachlorobenzene	a	DL-61.6 (5.7)	<1	357	1994-2005	k
Hexachlorobutadiene	a	DL-12.2 (1.8)	50	20	1996-1998	j
Alfa-Hexachlorocyclohexane	a	DL-13.7 (0.8)[e]	13	357	1994-2005	k
(gamma-isomer, Lindane)	a	0.1-2 076.4 (46.9)	0	357	1994-2005	k
Lead and its compounds	a	DL-1 744.2 (56.6)[f]	3	357	1994-2005	k
Mercury and its compounds	a	10-535.4 (113.5)[g]	0	355	1994-2005	k
Naphthalene	a	1.5-63 (5.8)	20	20	1996-1998	j
Nickel and its compounds	a	DL-2 944.7 (186.2)[h]	16	297	1994-2005	k
(1,2,4-Trichlorobenzene)	a	DL-30.9 (6.0)	15	20	1996-1998	j
Trichloromethane (chloroform)	a	DL-96.0 (13.4)	25	20	1996-1998	j
DDT total	b	6.6-1 102.7 (90.2)[i]	0	357	1994-2005	k
p,p'-DDT	b	DL-62.6 (2.9)	38	357	1994-2005	k
Aldrin	b	DL-11.4 (1.3)	33	96	1994-2005	k
Dieldrin	b	DL-237.6 (19.1)	15	357	1994-2005	k
Endrin	b	DL-29.1 (1.1)	80	346	1994-2005	k
Tetrachloroethylene	b	DL-88.9 (13.4)	50	20	1996-1998	j
Trichloroethylene	b	DL-30.3 (2.0)	95	20	1996-1998	j

[a] Priority substances.
[b] Other pollutants, which fall under the scope of Directive 86/280/EEC and which are included in List I of the Annex to Directive 76/464/EEC, are not in the priority substances list. Environmental quality standards for these substances are included in the Commission's proposal to maintain the regulation of the substances at Community level.
[c] The data present the Sum of 10 BDEs.
[d] Cd.
[e] alpha-hexachlorocyclohexane.
[f] Pb.
[g] Hg.
[h] Ni.
[i] Sum of *p,p'*-DDD, p,p'-DDT, and *p,p'*-DDE.
[j] Data from Roose *et al*. (2003).
[k] INBO Eel Pollutant Monitoring Database.
[l] Data from de Boer *et al*. (2002) and Belpaire *et al*. (2003).

Conclusions

From the examples given, it is clear that the use of eels as sentinel species can pinpoint sources of pollutants. Owing to the ecological and physiological traits of the species, the European eel in its yellow eel phase is a suitable sentinel species for a variety of chemical substances. Its value as a biomonitoring tool for chemical environmental contamination, for both local and international purposes, is clear. The eel may be the best of all available aquatic species when monitoring lipophilic chemicals in aquatic biota for the purposes of the Water Framework Directive, whereas results show that, at least for some substances, monitoring in water is insufficient and does not guarantee sufficient protection of the aquatic environment. More effort is required to elaborate and optimize techniques for the analysis of additional chemicals in eel tissue. There is inadequate knowledge on the effects of these chemicals on eels but, considering the concentrations of some chemicals measured at some sites, these toxic substances are very likely to have detrimental effects on the reproductive success of the species. Considering the variation in contaminant profile and concentrations, the degree and reproductive potential of eels leaving our system will vary considerably, depending on the level of pollution in the habitat where the eels grow and mature.

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