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THE EUROPEAN EEL *ANGUILLA ANGUILLA*, A RAPPORTEUR OF THE CHEMICAL STATUS FOR THE WATER FRAMEWORK DIRECTIVE?

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EUROPEAN EEL
ANGUILLA ANGUILLA
WATER FRAMEWORK DIRECTIVE
CHEMICAL STATUS
MONITORING
BIOACCUMULATION
PCBS
PESTICIDES
HEAVY METALS

ABSTRACT. – The Water Framework Directive recently (2006) proposed to monitor a selection of priority substances and to report on the chemical status of European water bodies. The final objective is the protection of aquatic life and human health. The majority of these substances are lipophilic, nevertheless it is proposed to monitor them in the water-phase. As there is serious concern about whether measurements of these lipophilic compounds in water will give results that will guarantee the protection of aquatic life, monitoring in biota seems to be more appropriate. The advantages of using the European eel (*Anguilla anguilla*) as a model for evaluating the chemical status within the WFD are discussed. A wide range of studies over Europe exists and has pinpointed various types of environmental contamination. Eel contaminant profiles seem to be a fingerprint of the contamination pressure of a specific site. This is illustrated with results from 12 years of contaminant monitoring in eel in Flanders, where the database comprises at present analyses of 2946 eels from 365 sites. From this database, reference values and quality classes for PCBs, OCPs and heavy metals in eel were deduced and are presented. The establishment of a harmonised, Europe-wide chemical monitoring programme of eels could enable three separate objectives to be addressed: (1) the evaluation of environmental health and chemical status, (2) the sanitary control of fisheries products within human food safety regulations, and (3) the monitoring of eel quality within the requirements of the international eel restoration plan. Because of high concentration of some contaminants in certain eel subpopulations and the ecotoxicological effects of these substances, achieving good chemical status of EU waters will directly be beneficial for restoration of eels stocks.

INTRODUCTION

During the last decade, many countries have reported the development of local monitoring programmes for specific contaminants within biotic matrices. Bioindicators belonging to very different classes are used for evaluating pollution in fresh water ecosystems, e.g. microbial assemblages, algae, Bryozoa, aquatic macrophytes, molluscs, fish parasites, invertebrates, fish, turtle eggs, aquatic birds and mammals.

As described by Belpaire & Goemans (2007), a good chemical status indicator should fulfil a number of requirements. It is essential that the species shows a high bioaccumulation capacity for a wide range of chemicals. Specific ecological traits of the indicator species should allow representative information of the chemical status of the sample site to be gained. Furthermore the species should present analytical advantages. Standard procedures for sampling and analysis should be available and a normative framework should be developed. It is an economic advantage when the data obtained through an indicator species can be used for multiple purposes (e.g. other (inter)national monitoring programmes), thus allowing better cost efficiency and effectiveness of the monitoring efforts. It is an additional benefit if monitoring networks are already in place in certain countries and expertise is already available. Evidently the indicator species should be widely distributed, to allow its use on a large geographical scale.

In recent years, an increasing number of studies have focused on the use of eel to monitor harmful substances. It is known for many years that, due to specific physiological and ecological features, eels bioaccumulate many substances in their muscle tissue (e.g. Bruslé 1991, de Boer & Hagel 1994, Maes *et al*. 2007). Specific characteristics of the species (size, long life span, fat content, feeding and habitat ecology, distribution, euryhyalinity, one reproductive cycle) are considered as favourable for the choice of the eel as a chemical sentinel species. The European eel is distributed over a wide geographical area, extending from North Africa in the south to Northern Scandinavia in the north, and from the Azores in the west to the Eastern Mediterranean region in the south-east. The natural distribution of the eel covers most EC countries (Fig. 1). Its distribution in remote places far from the sea where accessibility is hampered by migration barriers is quite often enforced by restocking with glass eel. Eels are thus widespread and can be found in a wide range of aquatic habitats of various typology. They occur in the fresh, brackish and coastal waters of a large part of the EC territory.

In this paper we will assess the indicator value of this species and, specifically, the possibility to use the eel as an indicator for the chemical status within the Water

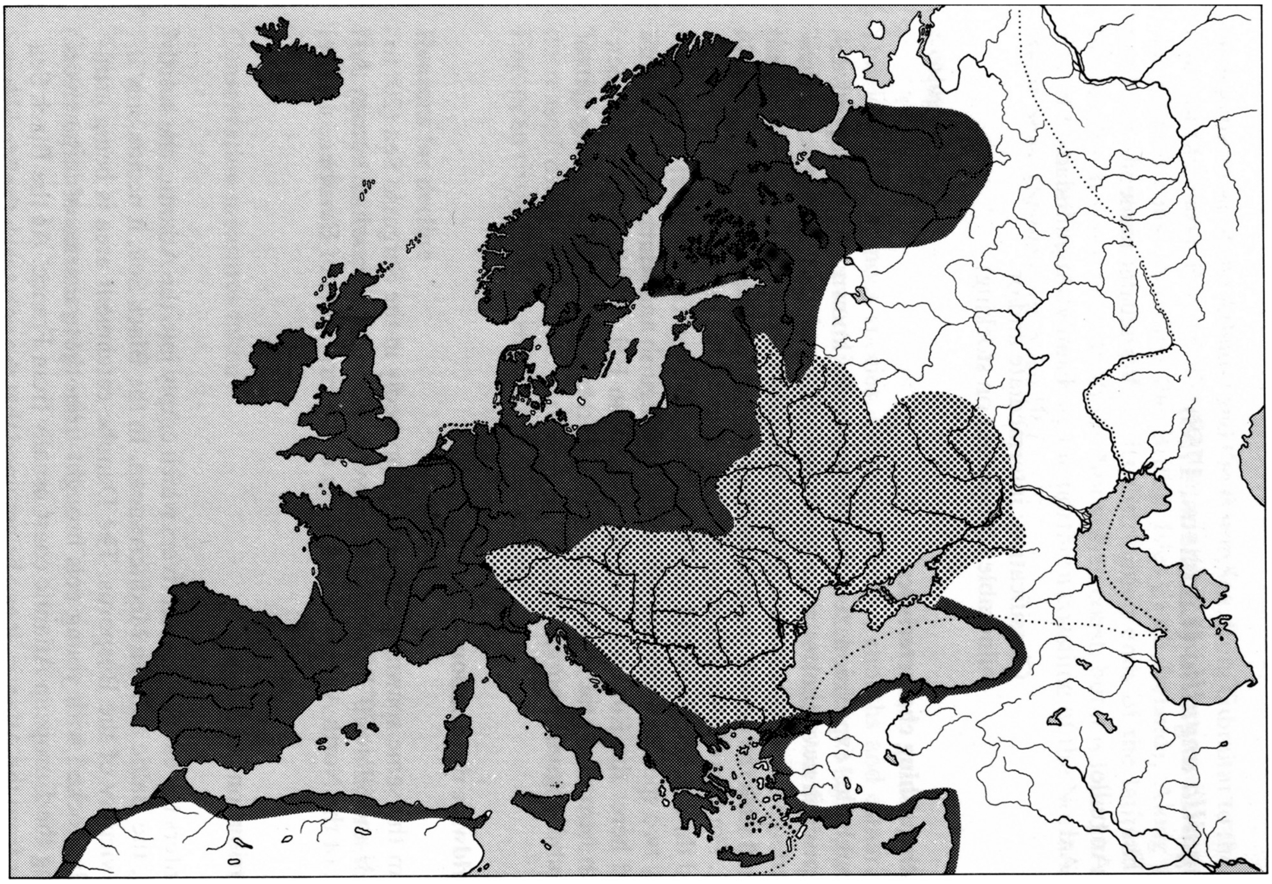

Fig. 1. – Distribution map of the European eel. Dark area: natural distribution area. Dotted area: enlarged distribution by stocking (Lelek 1987).

Framework Directive (WFD), using the results and experiences of 12 years of eel monitoring in Flanders. Since 1994 the Research Institute for Nature and Forest (INBO) has developed a pollutant monitoring network for public water bodies in Flanders (Belgium) using eel (*Anguilla anguilla*) as a sentinel species. During this monitoring within the river basins of Yser, Scheldt and Meuse (ca. 13 500 km^2), 2 946 eels have been sampled on 365 sites between 1994 and 2005. Muscle tissue of individual eels was routinely analysed for a series of c.30 polychlorine biphenyls (PCBs), organochlorine pesticides (OCPs) and heavy metals (see Goemans *et al.* (2003) and Maes *et al.* (2007) for sampling analytical procedures and quality assurance). In addition to this routine analysis, other contaminants were analysed on a restricted selection of sites. These contaminants included brominated flame retardants, volatile organic pollutants (VOCs), endocrine disruptors, dioxins, perfluorooctane sulfonic acids (PFOSs), metallothioneins and polycyclic aromatic compounds. These results are reported in various papers (Belpaire *et al.* 2001, 2003, Goemans *et al.* 2003, Roose *et al.* 2003, Goemans & Belpaire 2003, 2004; 2005, Morris *et al.* 2004, Versonnen *et al.* 2004, Hoff *et al.* 2005, Maes *et al.* 2005, Belpaire & Goemans 2007, Maes *et al.* 2007).

The WFD (CEC 2000) and, more specifically amendment CEC (2006a), enforces the monitoring of a selection of harmful substances in the aquatic environment. The monitoring strategy described sets out to measure most of these contaminants in the water-phase. However, the final aim of the Directive is to protect aquatic organisms and the aquatic ecosystem health. Belpaire & Goemans (2007) have discussed, and to some extent criticised, the monitoring strategy mainly on the basis of analytical features of those compounds. Basically, most of the substances selected under CEC (2006a) are highly lipophilic, and consequently are hardly (if ever) traceable in water. On the other hand, they may attain very high concentrations in organisms, as a result of bioconcentration and biomagnification. Belpaire & Goemans (2007) argued that within the WFD, at least for some substances, monitoring in water is inadequate and does not guarantee sufficient protection of the aquatic environment, and concluded that, as an alternative, the eel may be a suitable species for monitoring lipophilic chemicals in aquatic biota. From the INBO Eel Pollutant Monitoring Network (EPMN), specific examples of how eels can pinpoint environmental pollution by chemicals have been demonstrated. Belpaire & Goemans (2007) further illustrate the potential of using the eel as a biomonitor over a broader geographical range, meeting the requirements of the WFD

PCB 153	Water	Sediment	Suspended solids	Eel
ZWV	<DL	<DL	16	436
KBL	<DL	13	No data	142
WEE	<DL	12	54	429
OAV	<DL	<DL	<DL	13.5
LEI	<DL	5.2	16	128

Lindane	Water	Sediment	Suspended solids	Eel
ZWV	0.006	<DL	<DL	9.3
KBL	<DL	<DL	<DL	7.5
WEE	<DL	<DL	<DL	1.1
OAV	0.300	<DL	210	216
LEI	0.057	0.7	7.9	40.4

Cadmium	Water	Sediment	Suspended solids	Eel
ZWV	<DL	8	10	1.5
KBL	0.012	570	350	30
WEE	<DL	<DL	6	8.7
OAV	<DL	<DL	<DL	7.8
LEI	<DL	0.9	16	2.2

Table I. – Concentrations of PCB 153, lindane and cadmium measured simultaneously in water, sediment, suspended solids and eel at 5 stations in Flanders (2001). Concentrations are expressed as $\mu g.L^{-1}$ (water), in $\mu g.kg^{-1}$ dry matter (sediment and suspended solids) and in $\mu g.kg^{-1}$ wet weight of muscle tissue (eel). Stations are the canals Zuidwillemsvaart (ZWV) and Kanaal van Beverlo (KBL), a lake at Weerde (WEE), a polder water course Oude Avaart (OAV) and a river Leie (LEI) (after Belpaire & Goemans 2004). DL: detection limit.

for reporting on the chemical status of water bodies at least for some priority substances.

In this paper, we present evidence from results collected through the EPMN to further document and assess the potential advantage of using eel within the WFD chemical status monitoring. An overview of current eel monitoring work in Europe is given and possibilities for a standardised framework are described. Finally, other environmental constraints related to eel chemical monitoring will be discussed briefly.

Analytical issues

A number of specific traits of the eel, such as habitat preferences, trophic position, lipid content and size, give specific advantages when considering selecting eel as a chemical bioindicator species. Being benthic and carnivorous animals, eels are particularly vulnerable to high contamination levels through bioaccumulation and biomagnification. The lipid content of the eel is high compared to other species and especially the lipophilic contaminants can attain high levels. As a consequence these contaminants are easily traceable. Eel size is sufficient to provide the required quantity of tissue for the analyses of a series of different contaminants.

From an analytical perspective, biota have the advantage of containing much higher concentrations of contaminants compared with abiotic samples, as a result of processes like bioaccumulation and biomagnification. Organisms at higher trophic levels are known to have higher contaminant levels than their preys. During an assessment of the occurrence and partitioning of an extended series of chemicals in the aquatic environment at 5 polluted sites in waters of different typology in Flanders, suspended solids, sediments and organisms of different trophic levels were analysed (Weltens *et al.* 2002, 2003, Table I). It is clear that even on sites with high levels of various pollutants, a lot of measurements in the abiotic compartments fall below the detection limit (D.L.). In contrast, concentrations in eel are always measurable and attain higher values (and thus are better detectable) than in the sediment or suspended solids. For heavy metals, e.g. cadmium, differences in concentration levels between biotic and abiotic compartments are generally less pronounced. For monitoring heavy metals it could be recommended to measure eel liver concentrations instead of muscle tissue, as concentrations of most metals are higher in liver tissue (Durrieu *et al.* 2005). However metal measurements in muscle tissue are easily detectable (see below and Fig. 2) and present an added value towards human health risk assessment (see below).

Trophic position is not the only factor determining the degree of contamination of a species. Top-predators like northern pike (*Esox lucius*) and pikeperch (*Sander lucioperca*) feeding exclusively on fish show 3 to 15 times lower levels of contamination by lipophilic substances than eel (on a muscle wet weight basis) dependent on the specific contaminant, due mainly to their significant lower muscle lipid contents (ca 0.5 %) (Goemans, pers comm). Interspecific differences in contamination load within several field studies have been attributed to differences in lipid content (for an overview see Nowell *et al.* 1999). Amongst the various biota, eel has particular analytical advantages due to its very high fat content: Maes *et*

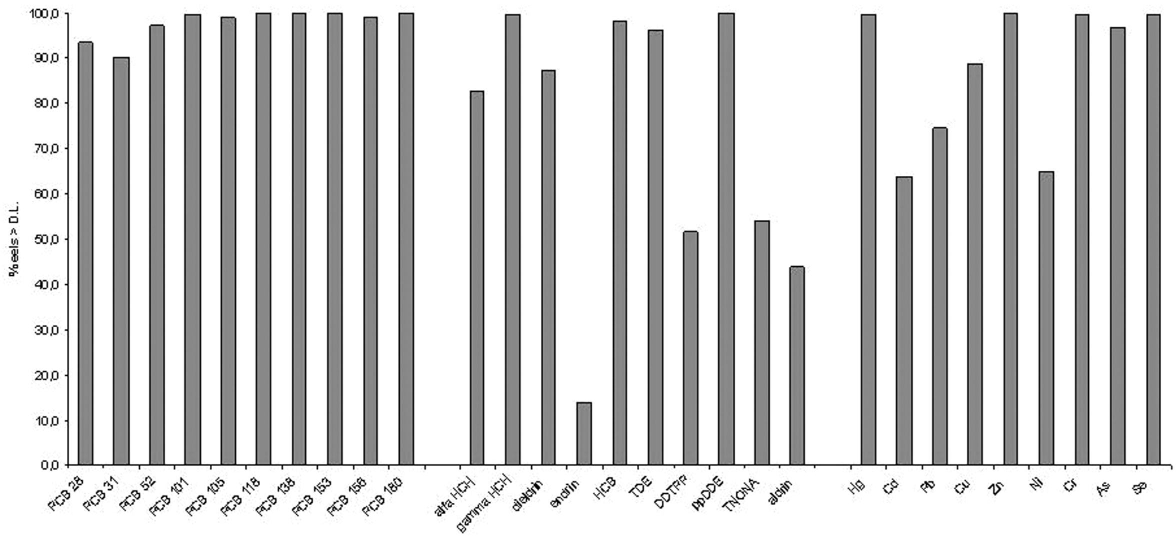

Fig. 2. – Percentage of individual yellow eel measurements above the detection limit for 10 PCB congeners and 10 organochlorine pesticides and 9 heavy metals in eels from Flanders collected in the period 1994-2005. N = 2528 for the PCBs, hexachlorocyclohexanes (HCHs), dieldrin, hexachlorobenzene (HCB), DDTs, trans-Nonachlor (TNONA) and endrin, N = 546 for aldrin, N = 2769 for Hg, Cd and Pb, N = 2117 for Cu, Zn, Ni and Cr and N = 1410 for As and Se (data from INBO Eel Pollution Monitoring Network). For an overview of the mean eel life history statistics (length, weight and lipid content) see Maes *et al.* (2007).

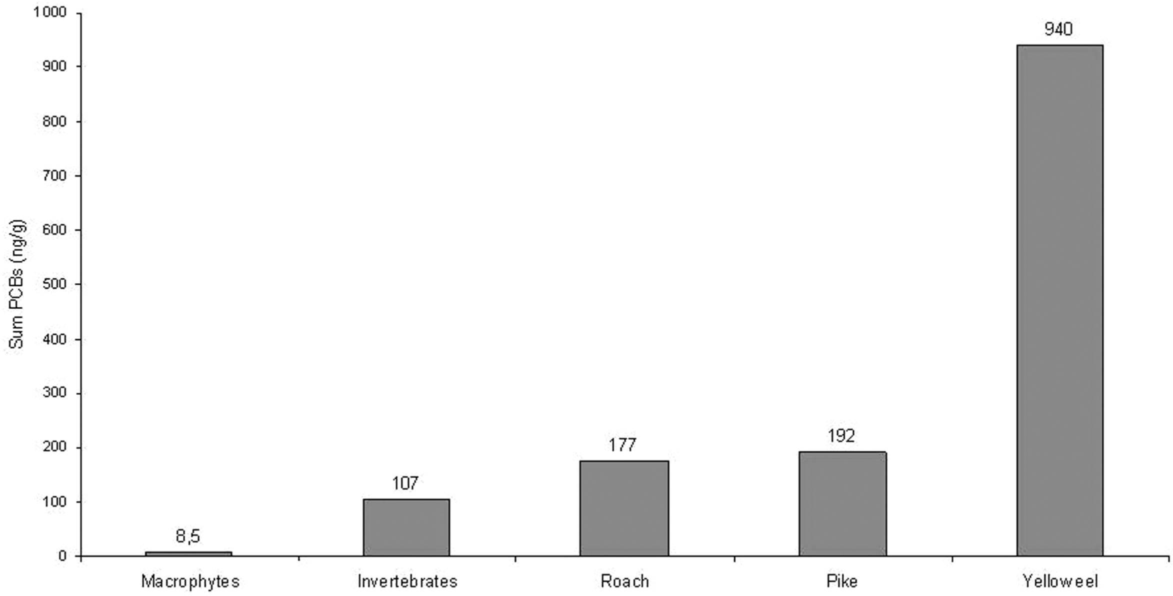

Fig. 3. – Concentration of Sum PCBs over various trophic levels in Lake Weerde (Flanders) in 2001 (spring). Data expressed as ng/g total wet weight for macrophytes and invertebrates and as ng/g wet weight of muscle tissue for fish (from Weltens *et al.* 2002). Fish analysis was performed on muscle tissue samples (N = 5 for roach and pike, N = 10 for yellow eel).

al. (2007) reported a mean muscle lipid content of 14.92% ± 10.18 (s.d.) in 2528 yellow eels collected over Flanders. High lipid content in eels is partly responsible for the high bioaccumulation of lipophilic contaminants in their tissues.

Figure 3 illustrates the concentrations of PCBs measured in various biota. Lipophilic contaminants like PCBs seem to be five times higher in eel than in other fish species (on a muscle wet weight basis) and ten times higher than in invertebrates (on a total wet weight basis), as can be deduced from measurements in Lake Weerde, a shallow contaminated lake in Flanders (Weltens *et al.* 2002).

Consequently tracing of these chemicals in eel, as an environmental indicator, is particularly meaningful, since only few fall below D.L. From the results of the EPMN including quantitative data of 2946 eels collected from 365 sites between 1994-2005, it is clear that most of the PCBs, OCPs and heavy metals analysed are easily detectable. Figure 2 represents the proportion of eels above D.L. for the PCBs and OCPs. Of the higher chlorinated PCBs 99.0-100 % are above D.L., while for the lower chlorinated PCBs 28, 31 and 52, the proportion is slightly lower

(90.2-97.3). For the OCPs the situation is more variable. Very high proportions (> 98%) are noticed for the γ isomer of hexachlorocyclohexane (gamma-HCH), hexachlorobenzene (HCB) and p,p'-DDE (1,1'-(2,2-dichlor-ethenylidene)- bis[4-chlorobenzene]). Also alfa-HCH, dieldrin and p,p'-DDD (1,1'-(2,2 dichloroethylidene)bis [4-chlorobenzene]) can be detected in at least 8 out of 10 samples. P,p'-DDT (dichlorodiphenyltrichloroethane) and trans-Nonachlor (TNONA) can be measured in more than 50 % of the eels. The cyclodienes endrin and aldrin are obviously less common in Flanders and can be measured in 13 and 43 % of the cases respectively.

Heavy metals were also measurable for the majority of sites. Mercury, zinc, chromium, arsenic and selenium were detectable in more than 96 % of the samples. Cadmium, lead, cupper and nickel were measured in 60 to 90 % of the samples.

Similarly, brominated flame retardants and even a number of volatile organic compounds were described as omnipresent in eels (Belpaire & Goemans 2007). Chemicals like HBCD (hexabromocyclododecane), PBDEs (polybrominated diphenylethers) and the volatile organic compounds BTEX (benzene, toluene, ethylbenzene and the xylenes) were found in all samples. This is in contrast with measurements in the water phase (as proposed by the WFD): as most of these compounds are lipophilic, measurements in water are frequently below the D.L. e.g. PCBs and VOCs are hardly traceable in water. For the VOCs this was documented by Belpaire & Goemans (2007). Even in sediments, the presence of PCBs and VOCs is quite often below the D.L.

Another advantage of using eels as a chemical bioindicator is their size. Eels are long-lived and their size enables to obtain enough material for analysis of various contaminants in individual fish. An individual eel of 40 cm has a back-calculated weight of 110 g, allowing removal of enough muscle tissue for at least six samples (10 g wet weight each) to be labelled and frozen at -20 °C. In the EPMN two samples (from the mid part of the body) were analysed for heavy metals, OCPs and PCBs. Other samples can be sent to specialised laboratories and analysed for BFRs, VOCs, dioxins,... The remaining samples are routinely stored as back up in a tissue bank at -20 °C.

From bioaccumulation studies in other fish species, it is known that the concentrations of lipophilic contaminants are related to length, weight or age, biological factors which are mostly covariant. Furthermore, length and age tend to correlate positively with lipid content. The relation between level of contamination and length or age is not always clearly positive: e.g. Reinert & Bergman (1974) described increasing DDT concentration with length in lake trout and in coho salmon from Lake Michigan, whereas in some other studies (e.g. Hubert & Ricci 1981) effects related to size or age were smaller or nonexistent when contaminant concentrations were expressed on a lipid weight basis (Nowell *et al.* 1999). Size and age effects may vary depending on the contaminant. During a recent study assessing the contaminants in muscle of white perch (*Morone americana*) from Hackensack River (New Jersey, USA), Weis & Ashley (2007) found no significant correlations between PCB concentrations and length or weight. However, for mercury a significant correlation for both length and weight was observed. For environmental monitoring purposes it should be recommended that the size of the eels sampled be standardised as much as possible. Sample selection within the EPMN focuses on eels between 35 and 45 cm, thereby precluding possible sex-related bias. We are well aware that for other monitoring purposes, like monitoring eel quality within the eel restoration plans or monitoring for human consumption quality (see below), it may be more appropriate to analyse eels from larger sizes, as these may attain higher contaminant concentrations.

Eels as chemical bioindicators of the contaminant pressure of their habitat

As was described earlier (Belpaire & Goemans 2007) a sentinel species should be fairly sedentary to allow fingerprinting of the local pollution load. Yellow eels show explicit homing behaviour and foraging movements are mostly restricted to a few hundred meters. Apparently most eel species share this ecological trait (*A. anguilla*: Baras *et al.* 1998, Laffaille *et al.* 2005, *A. rostrata*: Oliveira 1997, Goodwin 1999, *A. australis*: Jellyman *et al.* 1996, *A. dieffenbachi*: Beentjes & Jellyman 2003, *A. japonica*: Aoyama *et al.* 2002). Although home site fidelity is obvious also within tidal estuaries, the home range may be larger than in freshwater habitats (Parker 1995) and seasonal movements might occur (Hammond 2003). The occurrence of erratic eels ('nomads') has also been reported (Feunteun *et al.* 2003). Due to the migration activities in the silver eel stage, the bioindicator value of the eel is restricted to the yellow eel phase.

The potential of the eel to fingerprint the pollutant pressure at a specific site can be illustrated by several examples from within the EPMN. Belpaire & Goemans (2007) have illustrated with a number of examples (1,2-dichlorobenzene, 1,2-dibromo-3-chloropropane, BTEX, HBCD (hexabromocyclododecane), PBDEs (polybrominated diphenylethers), cadmium and lindane) the possibility of discovering environmental contamination through eel biomonitoring. They related high levels of specific contaminants in eel with local industrial or agricultural activities.

The EPMN covers a dense network of 365 sampling sites; each site is characterized by a series of c.30 chemicals for each individually analysed eel. This dataset allowed us to show how local land use at each site characterizes the pollution profile within eel muscle tissue. Belpaire *et al.* (1999) illustrated the usefulness of using eels

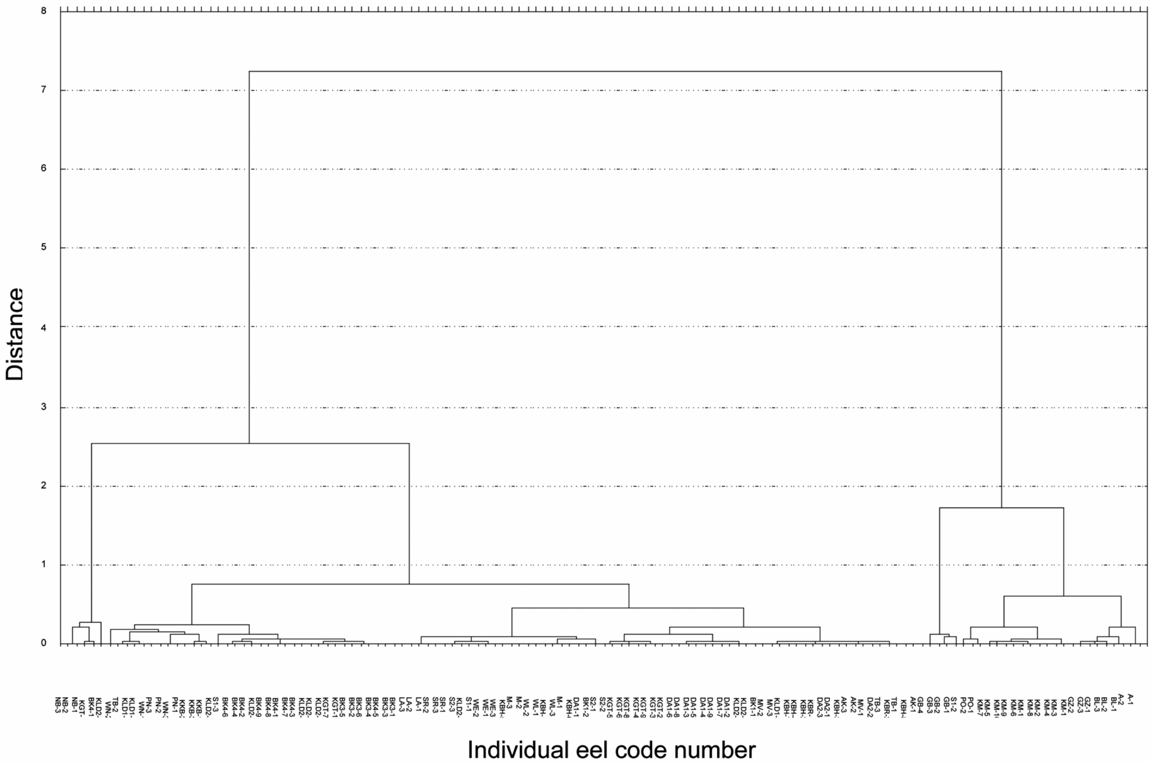

Fig. 4. – Cluster analysis based on the PCB and OCP (lipid weight basis) profiles of 129 yellow eels from 30 sites in Flanders sampled between 1994 and 1998 (Belpaire *et al*., 1999). Eels from the same site cluster mostly together.

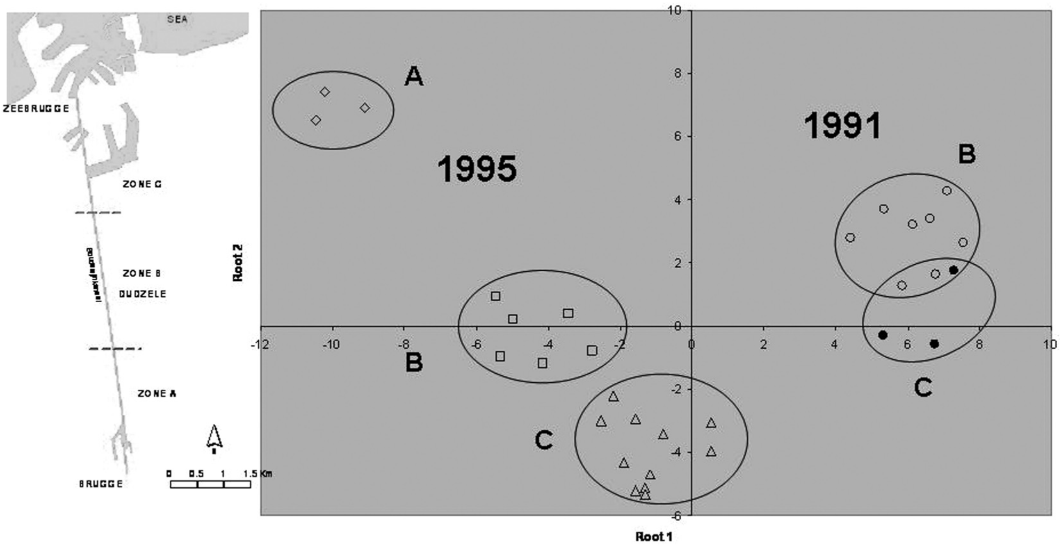

Fig. 5. – Discriminant analysis on the concentrations of 16 PCBs and OCPs (on lipid weight basis) in 31 eels from three zones in the Boudewijnkanaal from 1991 (11 eels) and 1995 (20 eels) (after Belpaire *et al*. 1999). Left: location of the three zones A, B and C on the Boudewijnkanaal.

as a sentinel species for measuring pollution by persistent pollutants. They presented (Fig. 4) a cluster analysis of the PCB and OCP concentration in 129 yellow eels from 30 sites in Flanders and showed that intra-site variability between eels is generally lower than the inter-site variability. On the basis of their contaminant load, eels from the same location were mostly clustered (Fig. 4). The pollution profile of individual yellow eels from one site seems to be a fingerprint of the local contaminant pressure. Even within water bodies and on a small local scale eels may show variations depending on where they lived. A study on the canal Boudewijnkanaal demonstrated differences in pollution load in eels within the canal (Belpaire *et al*. 1999). The Boudewijnkanaal is relatively short (14 km) and situated in the northwest of Flanders, mouthing in the North Sea at Zeebrugge harbour. The canal was

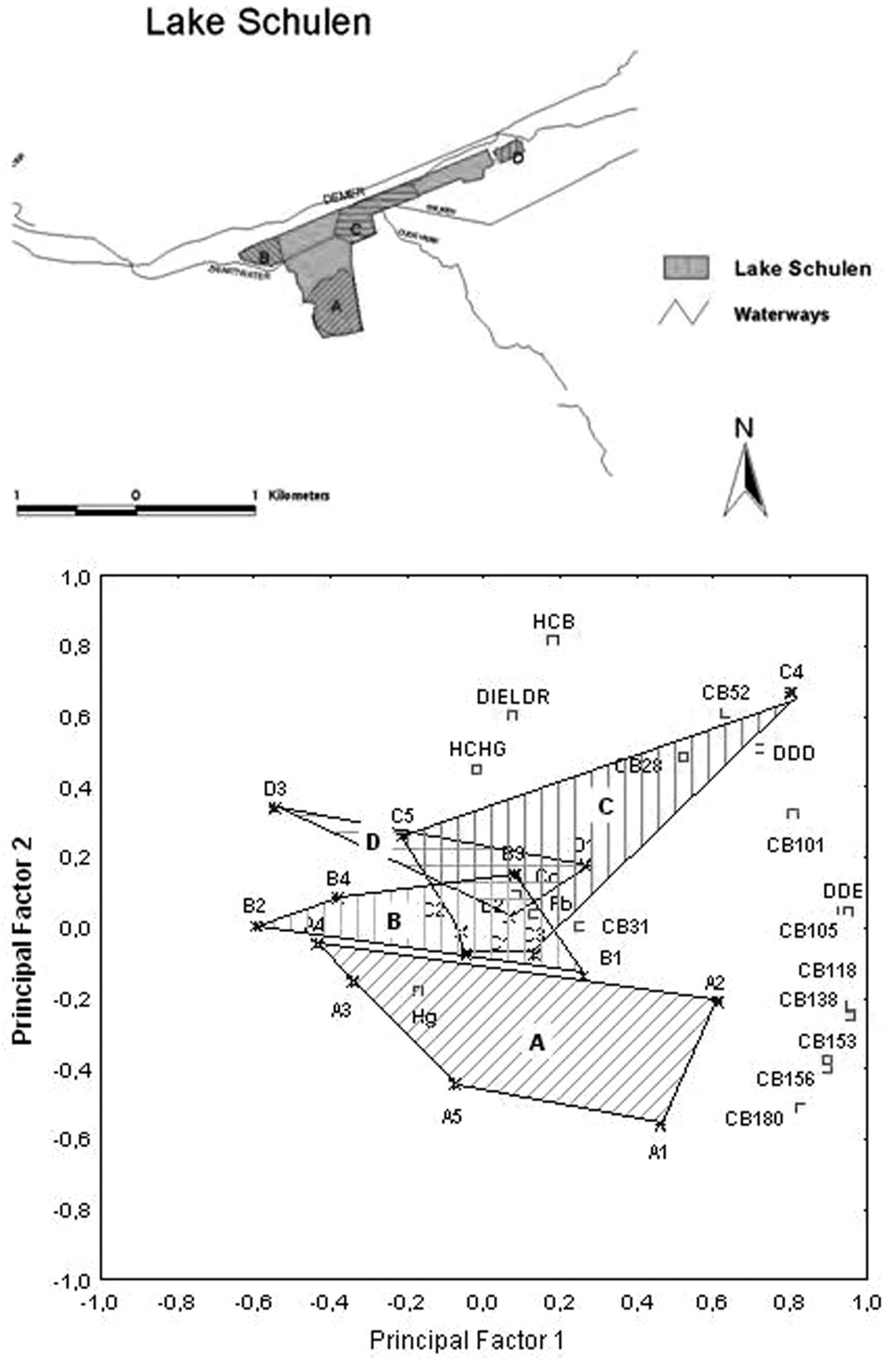

Fig. 6. – Factor analysis of contaminant concentrations (PCBs and OCPs) in 17 yellow eels from the zones A, B, C and D in Lake Schulen. Eels are numbered per zone (A1, A2,…). HCB: hexachlorobenzene, DIELDR: dieldrin, HCHG: γ-hexachlorocyclohexane (lindane), DDD: p,p'-DDD (1,1'-(2,2 dichloroethylidene)bis [4-chlorobenzene]), DDE: p,p'-DDE (1,1'-(2,2-dichlor-ethenylidene)- bis[4-chlorobenzene]) (Belpaire *et al*. 2001).

divided into three zones each c.4 km long: zone A which included the southernmost part nearby Brugge, zone B being the intermediate zone nearby Dudzele and zone C the northern part of the canal in front of the sea sluices (Zeebrugge) (Fig. 5). Eels were analysed for PCBs and OCPs in 1991 (8 eels from zone B and 3 eels from zone C) and in 1995 (3 eels from zone A, 6 eels from zone B and 11 eels from zone C). Discriminant analysis (Fig. 5)

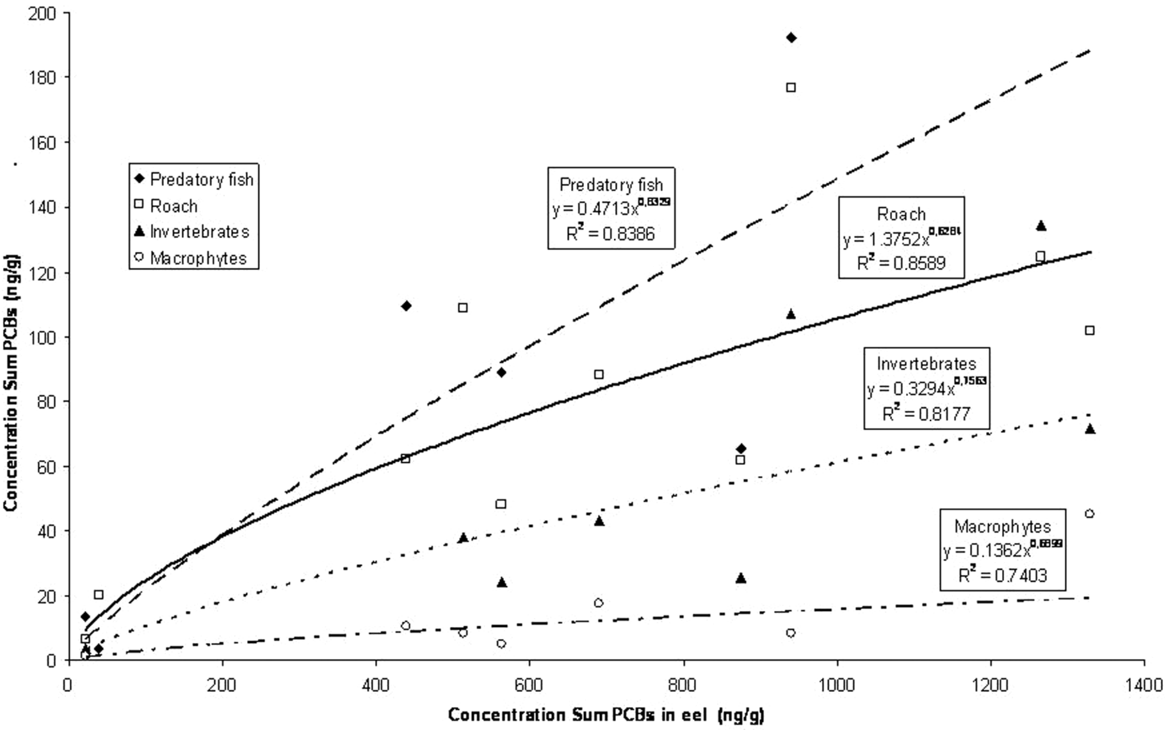

Fig. 7. – Correlation between the concentration of Sum PCBs measured simultaneously in predator fish species, roach, invertebrates and macrophytes, compared to the concentration of Sum PCBs in eel. Data acquired from sampling on five polluted water bodies in Flanders during spring and autumn 2001 (Weltens *et al.* 2002). Concentrations are expressed in ng/g wet weight of muscle tissue for fish and in ng/g total wet weight for invertebrates and macrophytes.

of the concentrations of 16 PCBs and OCPs (on a lipid weight basis) between these five groups showed differences between the 1991 and 1995 eels. With the exception of lindane, concentrations of most of the contaminants were higher in 1995 compared to the 1991 levels. Moreover, within a year, very distinct regional variations occurred, with eels from zone A being very distinct from the other zones. Also eels from B and C clearly belonged to separate groups, both in 1995 and in 1991. Differences between zones were explained by differences in local pollution pressure on the canal (with zone A being the most polluted zone). This gives strong evidence that eels do reflect differences in the pollution load of their habitat, even between locations which are relatively close to each other, as was the case here with the 4 km zones. It also supports the hypothesis that eels are very sedentary.

Other evidence exists for stations within the Meuse river basin, as reported by Goemans & Belpaire (2003), combining data from Flanders and The Netherlands. Goemans & Belpaire (2005) also showed that within the group of the PCBs, congener profiles (e.g. ratio of PCB 118 to Sum PCBs) in eels from a specific location are almost constant, but can vary considerably between eels originating from different locations.

An example within a lacustrine environment has been presented by Belpaire *et al.* (2001). Lake Schulen is a 90 ha eutrophic, oblong lake (length not exceeding 3 km) in central Flanders. 17 eels captured from 4 areas of the lake were analysed individually for polychlorinated biphenyls, organochlorine pesticides and heavy metals. Although no significant differences were found between eels from the different areas for most of the individual pollutants, there seemed to be a variation in overall pollution pattern, as illustrated in the factor analysis in Fig. 6. The study revealed significant differences in lindane (gamma HCH) concentrations in muscle tissue of eels from different areas. No evidence was found for potential causes of this pollution. This study illustrates the potential of using eel as a monitoring organism for pollution by some persistent substances within lacustrine environments, even within rather small lakes.

Weltens *et al.* (2002) described the results of a study investigating contamination through the various compartments of the aquatic ecosystem. PCBs, heavy metals and pesticides were analysed in water, suspended solids, sediment and biota of different trophic levels on 5 polluted sites in Flanders. Fig. 7 presents the relationships between Sum PCBs in wet weight of muscle tissue of eel with Sum PCBs in wet weight of muscle tissues of predator fish species and roach and with Sum PCBs on total wet weight basis in invertebrates and macrophytes. Fairly good correlations were found.

The contaminant fingerprint value of eels has already been illustrated, to some extent, in the 1980's for *A. rostrata* in the St. Lawrence river. Moreau and Barbeau (1982) distinguished eels of different origins on the basis

Table II. – Overview of recent reports describing bioaccumulation data of various chemicals in *Anguilla anguilla* within EC countries (PCBs: polychlorinated biphenyls, OCPs: organochlorine pesticides, HM: heavy metals, DIO: dioxines, BFRs: brominated flame retardants, PAHs: polyaromatic hydrocarbons, VOCs: volatile organic compounds, PFCs: perfluorinated compounds, MT: metallothioneins).

Reference	Country	PCBs	OCPs	HM	DIO	BFRs	PAHs	VOCs	PFCs	MT	Specification
Van Leeuwen *et al*. 2002	EU	x			x						Wild, farmed, imported eels (8 countries)
Karl and Lehmann 1993	EU	x	x								54 eels from 11 countries
Santillo *et al*. 2005	EU	x				x					10 countries, PBDEs, HBCD, TBBP-A
Santillo *et al*. 2006	EU								x		11 countries
Goemans *et al*. 2003	BE	x	x	x							Country wide (Flanders)
Maes *et al*. 2005	BE			x							Country wide (Flanders)
Hoff *et al*. 2005	BE								x		Country wide (Flanders)
Roose *et al*. 2003	BE							x			Country wide (Flanders)
Belpaire *et al* 2003	BE					x					Country wide (Flanders)
Thomé *et al*. 2004	BE	x			x						Country wide (Walloonia)
Batty *et al*. 1996	FR			x							Camargue
Roche *et al*. 2002	FR		x				x				Camargue
Roche *et al*. 2003	FR	x	x				x				Camargue
Bragigand *et al*. 2006	FR					x					PBDEs in Seine and Loire
Oliveira Ribeiro *et al*. 2005	FR		x	x			x				Camargue Reserve
Jørgensen *et al*. 2001	DK	x	x	x							Market eels
Food Standards Agency 2004	UK					x					Skerne – Tees River System
Edwards *et al*.1999	UK			x							River Yare & Ormesby Broad
Mason & Barak 1990	UK			x							11 rivers
Mason 1993	UK	x	x								11 reedbeds
Weatherley *et al*. 1997	UK	x	x								41 sites (Wales)
Ruddock *et al*. 2003	UK						x				Estuaries
Langston *et al*. 2002	UK									x	Thames estuary
Pieters *et al*. 2004	NL	x	x	x							Country wide
Hendriks & Pieters 1993	NL	x	x	x							Rhine
de Boer & Hagel 1994	NL	x									Country wide
van der Oost *et al*. 1996a&b	NL	x	x		x		x				PCBs, DDTs, HCB, PAHs, PCDFs and PCDDs in six Amsterdam freshwater sites
van den Heuvel-Greve *et al*. 2006	NL	x			x	x	x		x		Western Scheldt
Tulonen & Vuorinen 1996	FI	x	x								Vanajavesi watercourse
Fromme *et al*. 1999	DE	x									synthetic musks; bromocyclene, Berlin
Wiesmüller & Schlatterer 1999	DE	x			x						Rivers Havel and Oder in Brandenburg
Gaumert *et al*. 2000	DE	x	x	x							River Elbe
Lehmann *et al*. 2005	DE				x						Nordrhein-Westfalen, 7 sites
Lehmann *et al*. 2006	DE	x	x	x	x						River Rhine, regular sampling
Linde *et al.* 2004a	ES			x							Rivers
Linde *et al.* 2004b	ES			x						x	
Usero *et al.* 2004	ES			x							Salt marshes
Ankarberg *et al*. 2004	SE	x			x						PCDD/Fs and PCBs Baltic Sea
Poole & McCarthy 2006	IR	x			x	x					Work under way
Corsi *et al*. 2005	IT	x	x								Orbetello lagoon
Bressa *et al,* 1997	IT	x	x								Po delta
Mariottini *et al*. 2005	IT					x					PBDEs, Orbetello lagoon
Mariottini *et al*. 2006	IT	x									Orbetello and Santa Giusta lagoons
Storelli *et al*. 2007	IT	x	x	x							Lesina lagoon, Adriatic Sea

of their heavy metal (Hg) content. Dutil *et al*. (1985) got similar results on the basis of the presence of mirex. They concluded that organic chemicals could be a better instrument for discriminating stocks than heavy metals. In the same region, Castonguay *et al*. (1989) found a relatively high discrimination among eels from various sampling sites based on their contamination level with organochlorines. More recently, many EC countries have reported the use of the European eel to monitor the presence of a variety of substances. Extensive reviews have been made by Bruslé (1990; 1991) for respectively, heavy metals, and OCPs and PCBs. He assembled reports on the bioaccumulation of contaminants within several eel species. Since then, for a whole variety of contaminants, reports on eels as bioindicators have been published all over the world. Knights (1997) made a review of available literature on persistent xenobiotic organochlorines in eel species and Robinet & Feunteun (2002) gave examples of concentrations of some pollutants in yellow European and American eel. In Table II we summarize reports published recently for the EC countries. In some countries like The Netherlands and Belgium, a nationwide monitoring network is operational (respectively since 1977 & 1994). In other countries like Sweden, Finland, Denmark, Germany, United Kingdom and Northern Ireland, France, Spain and Italy, eel biomonitoring studies have been undertaken on a local scale. In Ireland investigations are in progress.

Table II shows that a whole variety of contaminants were analysed. The PCBs, OCPs and heavy metals are the most commonly analysed contaminants. Lately, groups of brominated flame retardants and dioxins are being analysed more frequently, illustrating the increasing concern for these compounds, and following the new EU dioxin regulation in foodstuffs (CEC 2006e). Locally, other contaminants have been analysed within specific research programs (polycyclic aromatic hydrocarbons, volatile organic compounds, synthetic musks, perfluorinated compounds, metallothioneins,…).

It is remarkable that until now no pan-European comprehensive reports are available on the chemical status of the eel, considering the increasing number of recent papers that point towards chemicals as being responsible for the decline of the eel. Two studies have compared bioaccumulation data in eels from several countries with allowable values for human consumption: Karl & Lehmann (1993) reported on OCPs and PCBs in 54 eel samples, both wild and farmed, from 11 different countries, and Van Leeuwen *et al*. (2002) compared PCBs, dioxins and furans in wild and farmed eels from The Netherlands, and in imported eels from 7 countries. More recently, two Europe-wide studies have been presented by Greenpeace using the eel as a bioindicator of brominated flame retardants and PCBs from rivers and lakes in 10 European countries (Santillo *et al.* 2005) and of perfluorinated chemicals in 11 countries (Santillo *et al*. 2006). These studies were

Table III. – Reference values and boundary values of the quality classes for a series of heavy metals, PCB congeners and organochlorine pesticides as defined in the EPMN. Values are expressed in $ng.g^{-1}$ wet weight of muscle tissue, unless indicated as * in $ng.g^{-1}$ lipid weight or ** in $\mu g.g^{-1}$ wet weight of muscle tissue.

Contaminant	Reference value (RV)	Not deviating log RV < 0.4	Slightly deviating 0.4 ≤ log RV < 0.8	Deviating 0.8 ≤ log RV < 1.2	Strongly deviating log RV ≥ 1.2
Mercury	40	< 100	100 - < 252	252 - < 634	≥ 634
Cadmium	2	< 5	5 - < 12.6	12.6 - < 31.7	≥ 31.7
Lead	10	< 25	25 - < 63	63 - < 158	≥ 158
Cupper**	0.25	< 0.6	0.6 - < 1.6	1.6 - < 4	≥ 4
Zinc**	14	< 35	35 - < 88	88 - < 222	≥ 222
Nickel	14	< 35	35 - < 88	88 - < 222	≥ 222
Chrome	96	< 241	241 - < 606	606 - < 1521	≥ 1521
Arsenic	41	< 103	103 - < 259	259 - < 650	≥ 650
Selenium	205	< 515	515 - < 1293	1293 - < 3249	≥ 3249
PCB 28	0.12	< 0.3	0.3 - < 0.8	0.8 - < 1.9	≥ 1.9
PCB 31	0.1	< 0.3	0.3 - < 0.6	0.6 - < 1.6	≥ 1.6
PCB 28+31	0.25	< 0.6	0.6 - < 1.6	1.6 - < 4	≥ 4
PCB 52	1	< 2.5	2.5 - < 6.3	6.3 - < 15.8	≥ 15.8
PCB 101	2.5	< 6	6 - < 16	16 - < 40	≥ 40
PCB 105	1.2	< 3	3 - < 7.6	7.6 - < 19	≥ 19
PCB 118	3.5	< 9	9 - < 22	22 - < 55	≥ 55
PCB 138	7.7	< 19	19 - < 49	49 - < 122	≥ 122
PCB 153	10	< 25	25 - < 63	63 - < 158	≥ 158
PCB 156	0.6	< 1.5	1.5 - < 3.8	3.8 - < 9.5	≥ 9.5
PCB 180	4.5	< 11	11 - < 28	28 - < 71	≥ 71
Sum PCBs	29	< 73	73 - < 183	183 - < 460	≥ 460
Sum PCBs*	240	< 603	603 - < 1514	1514 - < 3804	≥ 3804
α–HCH	0.05	< 0.1	0.1 - < 0.3	0.3 - < 0.8	≥ 0.8
γ–HCH	1.3	< 3.3	3.3 - < 8.2	8.2 - < 20.6	≥ 20.6
Dieldrin	1.1	< 2.8	2.8 - < 6.9	6.9 - < 17.4	≥ 17.4
HCB	0.5	< 1.3	1.3 - < 3.2	3.2 - < 7.9	≥ 7.9
p.p’-DDD	2.5	< 6	6 - < 16	16 - < 40	≥ 40
p.p’-DDT	0.005	< 0.01	0.01 - < 0.03	0.03 - < 0.08	≥ 0.08
p.p’-DDE	13	< 33	33 - < 82	82 - < 206	≥ 206
Sum DDTs	16	< 40	40 - < 101	101 - < 254	≥ 254

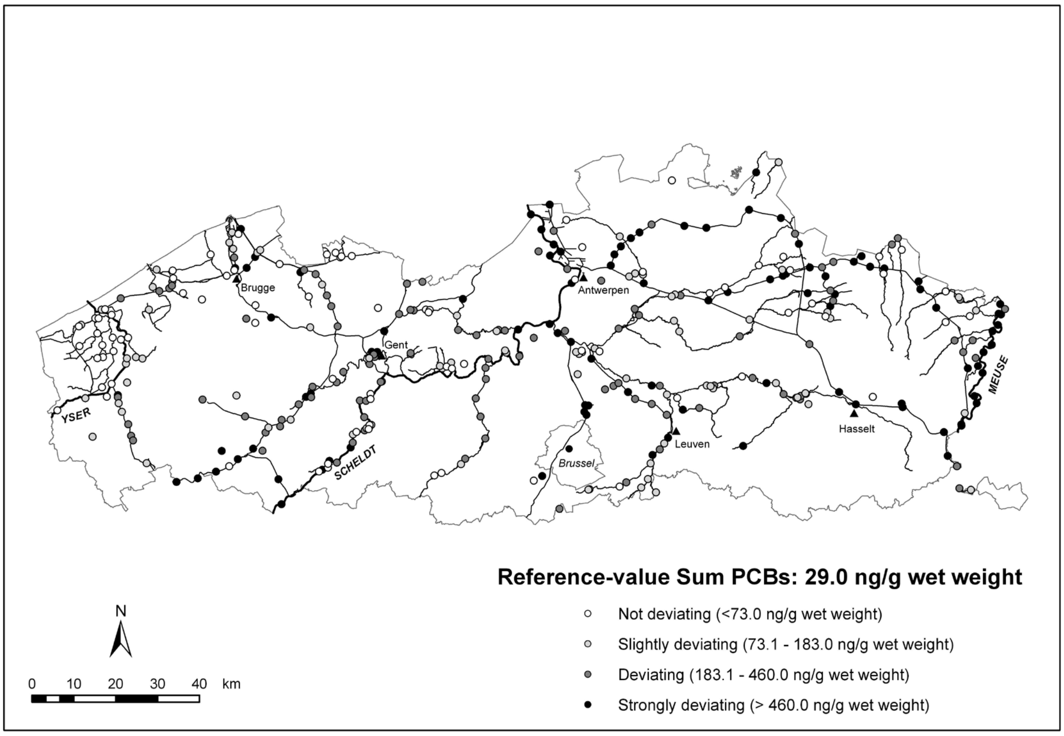

Fig. 8. – Sampling sites of the Eel Pollutants Monitoring Network in Flanders and geographical distribution of quality classes in Flemish eels for Sum PCBs (N = 351 sites, 1994-2005). Reference value and quality class boundaries are given. Sum PCBs equals the sum of the 7 indicator congeners (CB 28, 52, 101, 118, 138, 153 and 180).

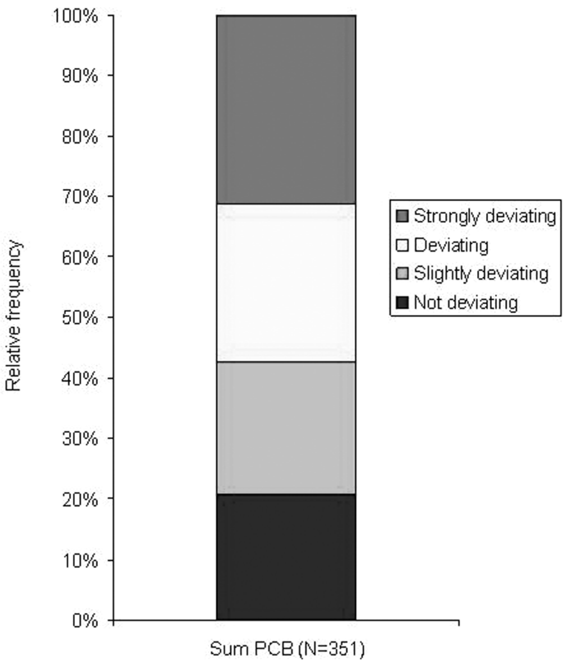

Fig. 9. – Distribution of Sum PCB quality classes in Flemish eels (N = 351 sites, 1994-2005). See Table III or Fig. 8 for reference values and boundary values of the quality classes. At 57.2 % of the sites, PCB levels in eels are deviating or strongly deviating from the reference value.

however rather restricted with respect to the number of eels or sites analysed.

Eel contaminant quality classes and standards

Analyses of a series of chemicals generates a database of quantitative data which have to be interpreted. There is a strong need for a normative framework with clear benchmarks to which the data should be compared. This framework can consist of various types of benchmarks. The WFD (CEC 2006a) proposes 'Environmental quality standards' (EQS), limit concentrations (e.g. in hexachlorobenzene, hexachlorobutadiene and methyl-mercury) which can not be exceeded in 'prey' tissue of biota. No Observed Effect Concentrations (NOEC) have been described for specific chemicals for certain organisms, including eel (see PAN Pesticides Database, 2007). For some compounds (e.g. Hg, Pb, Cd, dioxins, furans and dioxin-like PCBs (WHO-PCDD/F-PCB-TEQ),....) human health safety standards for fish have been set by the European Commission (CEC 2001; 2006e) or by additional national legislation (e.g. consumption limit for indicator-PCBs for fisheries products in Belgium, Belgisch Staatsblad 2002), some with special values for eel. In some countries (e.g. The Netherlands), concentrations of some substances in eel are used as environmental tolerance values and action thresholds (ecotoxicological values).

In Flanders, quality classes were developed based on quantitative distribution of the data (means per location) for PCBs, OCPs and heavy metals (Goemans *et al.* 2003). Reference values were fixed for each chemical. These reference values were defined as the 5 percentile value of the means of all sites. A common procedure was used to distinguish four quality classes as a measure of deviation from the reference value, and class boundary values were set. Class limits and reference values for each contaminant are listed in Table III. Class boundary calculations were based on the distribution of the relationship between the recorded values and the reference value. Class 1 represents the 'not deviating' class (blue colour) with 'unpolluted or low polluted' sites. Sites with a slight to moderate pollution level are classified as class 2 'slightly deviating' (green). The more polluted sites are assigned to class 3 'deviating' (yellow) or 4 'strongly deviating' (red).

On Figs. 8, 9, an example is given of a cartographic and graphic representation of the distribution of Sum PCBs in eel. Fig. 9 indicates that, of a total of 351 sites, only 21 % of the sites are relatively clean, while 57 % of the sites are polluted and assigned to classes 3 or 4 (deviating or strongly deviating from the reference value). The map shows that most of the unpolluted or low polluted sites are located in the Yser basin, which is mainly characterized by agricultural land use.

In order to allow general status reports, more condensed reporting can be achieved by representing a combination of various chemicals e.g. within a region or as a function of time. This has been done in the annual state of the environment and the nature reports of Flanders. An example is given in Fig. 10 (Peeters *et al.* 2006). These representations are useful for showing temporal changes or spatial variation in environmental and biotic quality.

For Sum PCBs, possible management objectives and benchmarks have been proposed by Belpaire & Goemans (2004) and are illustrated in Fig. 11. Action and target threshold values are proposed at 460 and 183 ng/g wet weight respectively. The action threshold can be seen as a limit which never may be exceeded; sites above this limit should be sanitized. The target threshold is the objective to attain within a planned timeframe.

Eel biomonitoring for evaluating chemical status within the Water Framework Directive

The eel has a wide geographical, pan-European distribution range. It is exceptional that one bioindicator species occurs over such a vast diversity of habitats: the whole river trajectory from source to estuary and even in seawater, but also in canals, lakes, ponds and salt water lagoons. Consequently, eels can be used in reporting the chemical status of all categories of water bodies within the river basin approach of the WFD (rivers, lakes, transitional water bodies, coastal water bodies, artificial or heavily modified water bodies).

We are aware that some methodological problems still exist. Problems related to sampling procedures, laboratory procedures and quality assurance can hamper comparison and harmonisation. Some analytic procedures for the analysis of certain new chemicals will need further development. Nevertheless, from our own work presented in this paper and elsewhere, we are confident that the European eel is a suitable bioindicator species to use throughout its distribution area for monitoring a variety of priority substances in order to evaluate the chemical status of our waters.

In CEC (2006a), the latest amendment to the WFD (CEC 2000), 33 substances or groups of substances were selected as priority substances, some of them of very high

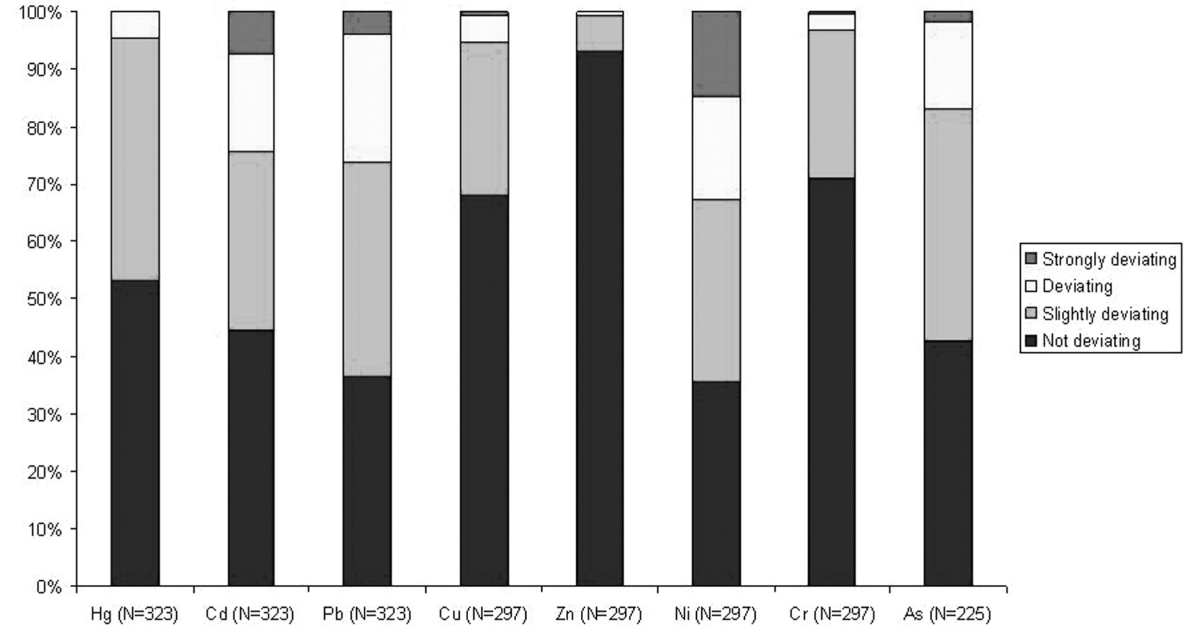

Fig. 10. – Status of heavy metals in eel in Flanders (after Peeters *et al.* 2006 in Flanders environmental report 2006). Data distribution is based on the means per site sampled between 1994 and 2005; the number of sites is indicated. See Table III for reference values and boundary values of the quality classes of the heavy metals.

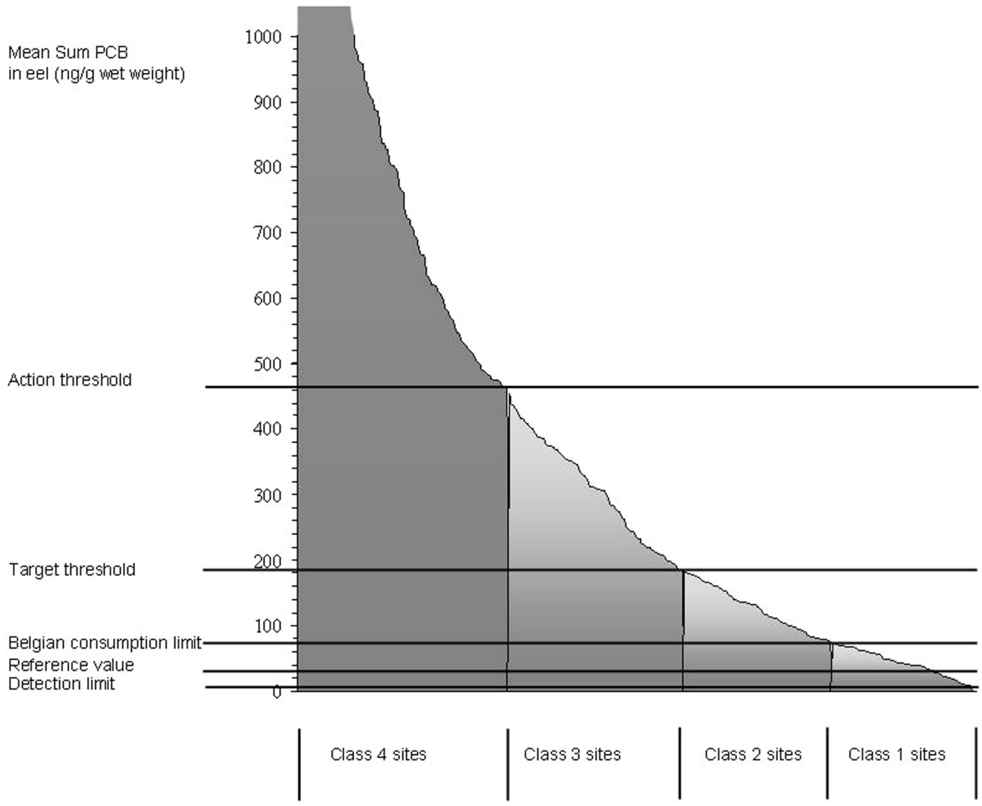

Fig. 11. – Mean Sum PCB values in eel from 351 sites in Flanders (1994-2005): distribution between quality classes and comparison with threshold values for action or target values as proposed by Belpaire & Goemans (2004). Detection limit (2 $ng.g^{-1}$ wet weight), reference value (29 $ng.g^{-1}$ wet weight) and the Belgian consumption limit (75 $ng.g^{-1}$ wet weight) are included in the figure.

concern and identified as 'priority hazardous substances'. These include some existing chemicals, plant protection products, biocides, metals and other groups like polyaromatic hydrocarbons (PAH) and some polybrominated biphenylethers (PBDE). Another 8 pollutants are not on the priority list but fall under the scope of older directives. The environmental objectives of the WFD are to ensure the ecological integrity of aquatic ecosystems and the protection of humans (CEC 2006b). In this approach, there is definitely a need to have a harmonised basis for assessment, in particular for international river basins (CEC 2006b). Emphasis is placed on the measurement of these hazardous substances in the water column. It is important to define clear and harmonised standards for priority substances within the most cost-effective and appropriate approach. According to CEC (2006a), there seems to be enough extensive and reliable information on concentrations of priority substances from measurements made in water to provide a sufficient basis to ensure comprehensive protection and effective pollution control. Based on information concerning the toxicity, persistency and bioaccumulation potential of a substance, together with information on what happens to this chemical in the environment, it is possible to determine threshold concentrations to protect people, flora and fauna. This assessment will be based on 'environmental quality standards' (EQS) which are defined as "the concentration of a particular pollutant or group of pollutants in water, sediment or biota which should not be exceeded in order to protect human health and the environment" (CEC 2006a). It is recognised that sediment and biota remain important matrices for the monitoring of certain substances by member states in order to assess long term impacts of anthropogenic activity and trends. Furthermore, the member states have to ensure, on the basis of monitoring of the water status carried out in accordance with the WFD, that concentrations of substances listed do not increase in sediment and biota. It has been decided, however, that no EQS would be proposed for sediments and only three for biota (see above).

We found evidence that current legal chemical quality standards for the water column are wholly insufficient to guarantee the health of our aquatic ecosystems. After comparing the levels of contamination in all compartments of several polluted environments, Weltens *et al.* (2003) concluded that legal chemical criteria for the water column are not suitable to protect the health of the aquatic organisms. Simple partition models did not adequately predict the field concentrations in the different compartments nor in biota. We demonstrated that in particular lipohilic substances are hard to trace in water and the majority of measurements fall under the D.L., even on sites where these contaminants attain (very) high levels in fish. Therefore we strongly support the idea that monitor-

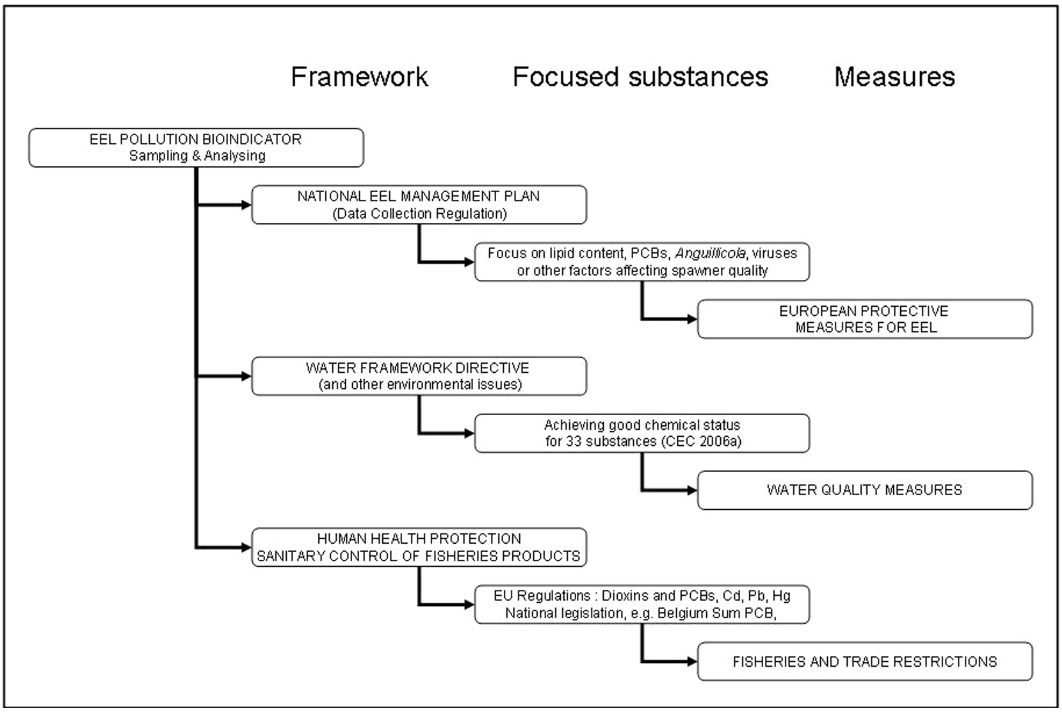

Fig. 12. – Possibilities of combined use of monitoring contaminants in the eel.

ing programmes for lipophilic substances should be focused on biota.

It was admitted by CEC (2006d) that some of the substances are difficult to determine due to the low concentrations and that EQSs based on waterborne exposures are not protective of aquatic invertebrates and fish in all cases. It is stated by CEC (2006d) that monitoring programmes for lipophilic substances should be focused on biota (and possibly sediment). Following CEC (2006c), the biggest obstacle to develop EQS for sediment and biota was the considerable lack of data. Apparently, on the basis of the given information, it was not possible to derive systematically such EQS for all those priority substances. It was however strongly recommended to produce the required ecotoxicological information for supporting sound EQS at least for these substances. In general CEC (2006d) believes that specific quality standards can and should be developed for sediment and biota. These should be based on direct assessment and monitoring of sediments and biota. Given the biological relevance of sediment and biota standards and the fact that many persistent substances accumulate in these media, CEC (2006c) underlined the priority need to develop the methodologies and gather further data in order to ensure that such EQS can be set in the near future.

We documented the availability of bioaccumulation data for various hazardous substances in one common aquatic organism within EC countries. Countrywide monitoring networks for eel are already in place in some member states and there is additionally a large amount of data available from short term local studies. The data within member states however are widely scattered over research institutes and universities, and not always available to national agencies committed in the WFD reporting.

We may conclude that, at the time being, the WFD urges the monitoring of toxic substances in the aquatic environment to protect aquatic organisms, but fails to present an appropriate model efficient enough to guarantee this protection.

However, monitoring of contaminants in biota and the development of biota based EQS is essential to preserve or restore the ecological integrity of the aquatic environment and the aquatic organisms themselves. Belpaire & Goemans (2007) recommended using eel for monitoring the chemical status of waters within the requirements of the Water Framework Directive. They give details about monitoring WFD substances in eels and the percentage of measurements above D.L. In this paper we further discussed the analytical advantages of using eel among other aquatic biota and documented the suitability of this species for tracing local and specific chemical pressures. We provided a normative framework on the basis of the EPMN bioaccumulation data for a number of PCBs, OCPs and heavy metals. We compiled an overview of current monitoring work over the EC. As the eel seems to be a suitable model when monitoring chemical status in aquatic biota, we propose to further compile existing data on a European scale, as a basis to set up eel-based EQS and for further work. We recommend that a comprehensive research and monitoring project should be started and coordinated on a European level. A first initiative has been taken recently by the Working Group on eel (WG

Eel 2007) starting to compile data on contaminants and diseases in eel within an European Eel Quality Database. Twelve countries submitted data on contaminants in eel for inclusion into this database. Monitoring of the quality of eel received increased attention. Countries like The Netherlands and Belgium continue their monitoring programmes on contaminants, whilst other countries have initiated eel quality studies. Preliminary interrogation of the database illustrates the wide variability of contaminants and the presence of 'black spots' over the distribution area of the eel. Such examples highlight the benefits of an eel quality database, and the need for a harmonised eel quality monitoring network across Europe to feed such a database (WG Eel 2007).

Using eel as an indicator for the chemical status within the WFD forms the basis for other required monitoring programmes, i.e. the required monitoring of the quality of human foodstuffs (fisheries products) (e.g. CEC 2001, 2006e) and the sampling for eel quality within the European efforts for the restoration of the species (Data Collection Regulation) as proposed by the Working Group on Eel (WG Eel 2006) and the Scientific, Technical and Economic Committee for Fisheries of the EC (STECF 2006) (see Fig. 12). Of course, by combining sampling procedures and analytic efforts, these monitoring programmes become more cost-efficient and -effective. The set up of a harmonised, Europe-wide chemical monitoring programme of eels could stand for triple usage: the evaluation of environmental health and chemical status (national level and WFD level), the sanitary control of fisheries products within human food safety regulations, and the monitoring of eel (spawner) quality within the requirements of the international eel restoration plan and the national Eel Management Plans (STECF 2006). To this end, it might be envisaged to extend the contaminant monitoring in yellow eel with analysis in silver eel populations from specific locations, to trace the quality of the spawners (e.g. in European basins with high production of spawners), and to measure against food safety standards (e.g. within exploited silver eel stocks).

Up-scaling the European monitoring strategy of chemicals in the European eel to a worldwide scale seems to be possible. Other eel species occur in other parts of the world, and at least some of them share similar ecological and physiological traits (migration and homing behaviour, trophic position, fat content,…). In the U.S. and Canada (Hodson *et al.* 1994, Castonguay *et al.* 1994) and in New Zealand (Buckland *et al.* 1998) there is already a long history in using anguillids as sentinel species for selected chemicals.

Taking into account the high concentration of some contaminants in certain eel subpopulations (Maes *et al.* 2007, WG Eel 2007), and the ecotoxicological and reprotoxic effects of these substances (e.g. Maes *et al.* 2005, Palstra *et al.* 2006), the authors believe that achieving good chemical status of EU waters will directly benefit eel restoration efforts. How better to assess the status of its environment, than using the eel itself?

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REFERENCES

Ankarberg E, Bjerselius R, Aune M, Darnerud PO, Larsson L, Andersson A, Tysklind M, Bergek S, Lundstedt-Enkel K, Karlsson L, Törnkvist A, Glynn A 2004. Study of dioxin and dioxin-like PCB levels in fatty fish from Sweden 2000-2002. *Organohal Comp* 66: 2061-65.

Aoyama J, Sasai S, Miller MJ, Shinoda A, Nakamura A, Kawazu K, Tsukamoto K 2002. A preliminary study of the movements of yellow and silver eels, *Anguilla japonica*, in the estuary of the Fukui River, Japan, as revealed by acoustic tracking. *Hydrobiologia* 470: 31-36.

Baras E, Jeandrain D, Serouge B, Philippart JC 1998. Seasonal variations in time and space utilization by radiotagged yellow eels *Anguilla anguilla* (L.) in a small stream. *Hydrobiologia* 371/372: 187-198.

Batty J, Pain D, Caurant F 1996. Metal concentrations in eels *Anguilla anguilla* from the Camargue region of France. *Biol Conserv* 76: 17-23.

Beentjes MP, Jellyman DJ 2003. Enhanced growth of longfin eels, *Anguilla dieffenbachii*, transplanted into Lake Hawea, a high country lake in South Island, New Zealand. *N Z J Mar Freshw Res* 37: 1-11.

Belgisch Staatsblad 2002. Koninklijk besluit tot wijziging van het koninklijk besluit van 19 mei 2000 tot vaststelling van maximale gehaltes aan dioxines en polygechloreerde bifenylen in sommige voedingsmiddelen. Brussel, 6 march 2002. Publication 2002-04-16.

Belpaire C, Van Thuyne G, Callaars S, Roose P, Cooreman K, Bossier P 1999. Spatial and temporal variation in organochlorine pesticide and polychlorinated biphenyl pollution in fresh water aquatic ecosystems in Flanders using the European eel (*Anguilla anguilla* L.) as an indicator. EIFAC/ICES, Working Group on Eel, Silkeborg (DK), 20-25 Septembre 1999.

Belpaire C, Derwich A, Goemans G, Van Thuyne G, Cooreman K, Guns M, Ollevier F 2001. Intra lake spatial variations in pollution patterns of eel *A. anguilla*. *In* Aida K *et al.*, eds, Proceedings of the International Symposium 'Advances in Eel Biology', Univ Tokyo, 28-30 September 2001: 170-174.

Belpaire C, Goemans G, de Boer J, Van Hooste, H. 2003.Verspreiding van gebromeerde vlamvertragers. *In* Van Steertegem M ed, Mira T 2003, Milieu- en Natuurrapport Vlaanderen, LannooCampus, Leuven : 387-395.

Belpaire C, Goemans G 2004. Monitoring en normering van milieugevaarlijke stoffen in paling: bruikbaarheid en relevantie voor het milieubeleid. *Water* 2004: 1-16.

Belpaire C, Goemans G 2007. Eels: contaminant cocktails pinpointing environmental pollution. *ICES J Mar Sci* doi:10.1093/icesjms/fsm121

Bligh EG, Dyer WJ 1959. A rapid method of total lipid extraction and purification for organic compounds. *Can J Biochem Physiol* 37: 911-917.

Bragigand V, Amiard-Triquet C, Parlier E, Boury P, Marchand P, El Hourch M 2006. Influence of biological and ecological factors on the bioaccumulation of polybrominated diphenyl ethers in aquatic food webs from French estuaries. *Sci Total Environ* 368: 615-626.

Bressa G, Sisti E, Cima F 1997. PCBs and organochlorinated pesticides in eel (*Anguilla anguilla* L.) from the Po Delta. *Mar Chem* 58: 261-266.

Bruslé J 1990. The effect of heavy metals on eels (*Anguilla* sp). *Aquat Living Res* 3: 131-141.

Bruslé J 1991. The eel (*Anguilla* sp) and organic chemical pollutants. *Sci Total Environ* 102: 1-19.

Buckland SJ, Jones PD, Ellis HK, Salter RT, 1998. Organochlorines in New Zealand: Ambient concentrations of selected organochlorines in rivers. Ministry for the Environment, Wellington (New Zealand), 72 p.

Castonguay M, Dutil JD, Desjardins C 1989. Distinction between American eels (*Anguilla rostrata*) of different geographic origins on the basis of their organochlorine contaminant levels. *Can J Fish Aquat Sci* 46: 836-843.

Castonguay M, Hodson PV, Moriarty C, Drinkwater KF, Jessop, BM 1994. Is there a role of ocean environment in American and European eel decline? *Fish Oceanogr*. 3: 197-203.

Corsi I, Mariottini M, Badesso A, Caruso T, Borghesi N, Bonacci S, Iacocca A, Focardi S 2005. Contaminants and sub-lethal toxicological effects of persistent organic pollutants in the European eel (*Anguilla anguilla*) in the Orbetello lagoon (Tuscany, Italy). *Hydrobiologia* 550: 237-249.

CEC 2000. Directive of the European parliament and of the council 2000/60/EC establishing a framework for community action in the field of water policy. *Off J Eur Comm* 22.12.2000, L 327/1.

CEC 2001. Commission Regulation (EC) 466/2001 of 8 March 2001 setting maximum levels for certain contaminants in foodstuffs. *Off J Eur Comm*, 16 March 2001, L77/1.

CEC 2006a. Proposal for a Directive of the European parliament and of the Council on environmental quality standards in the field of water policy and amending Directive 2000/60/EC (presented by the Commission) {COM(2006) 398 final} {SEC(2006) 947} Commission of the European Communities, Brussels, 17.7.2006 COM(2006) 397 final 2006/0129 (COD).

CEC 2006b. Communication from the Commission to the Council and the European Parliament. Integrated prevention and control of chemical pollution of surface waters in the European Union {SEC(2006) 947} {COM(2006) 397 final} Commission of the European Communities Brussels, 17.7.2006 COM(2006) 398 final.

CEC 2006c. Commission Staff Working Document Impact Assessment Proposal for a Directive of the European Parliament and of the Council on environmental quality standards in the field of water policy and amending Directive 2000/60/EC {COM(2006) 397 final} {COM(2006) 398 final} Commission of the European Communities, Brussels, 17.7.2006 SEC(2006) 947.

CEC 2006d. Opinion of the Scientific Committee on Toxicology, Ecotoxicology and the Environment (CSTEE) on "The Setting of Environmental Quality Standards for the Priority Substances included in Annex X of Directive 2000/60/EC in Accordance with Article 16 thereof " Adopted by the CSTEE during the 43rd plenary meeting of 28 May 2004. European Commisssion, Health & Consumer Protection Directorate-General, Directorate C – Public Health and Risk Assessment C7 – Risk Assessment Brussels, C7/GF/csteeop/WFD/280504 D(04).

CEC 2006e. Commission Regulation (EC) 199/2006 of 3 February 2006 amending Regulation (EC) No 466/2001 setting maximum levels for certain contaminants in foodstuffs as regards dioxins and dioxin-like PCBs. *Off J Eur Comm* 04.02.2006, L 32/34.

De Boer J, Hagel P 1994. Spatial differences and temporal trends of chlorobiphenyls in yellow eel (*Anguilla anguilla*) from inland waters of the Netherlands. *Sci Total Environ* 141: 155-174.

Durrieu G, Maury-Brachet R, Girardin M, Rochard E, Boudou A 2005. Contamination by heavy metals (Cd, Zn, Cu, and Hg) of eight fish species in the Gironde estuary (France). *Estuaries* 28 (4): 581-591

Dutil JD, Legare B, Desjardins C 1985. Discrimination d'un stock de poisson, l'Anguille (*Anguilla rostrata*), basée sur la présence d'un produit chimique de synthèse, le mirex (Discrimination of a fish stock, *Anguilla rostrata*, on the basis of the presence of synthetic chemical product, the mirex). *Can J Fish Aquat Sci* 42 (3): 455-458.

Edwards SC, MacLeod CL, Lester JN Mercury 1999. Contamination of the eel (*Anguilla anguilla*) and roach (*Rutilus rutilus*) in East Anglia, UK. *Environ Monitor Assess* 55: 371-387

Feunteun E, Lafaille P, Robinet T, Briand C, Baisez A, Olivier JM, Acou A 2003. A review of upstream migration and movements in inland waters by anguillid eels: towards a general theory. *In* Aida K, Tsukamoto K, Yamauchi K eds, Eel biology, Springer Verlag, Tokyo: 191-213.

Food Standards Agency 2004. Brominated flame retardants in trout and eels from the Skerne-Tees river system and total diet study samples. Food Surveillance Information Sheet No. 52/04, April 2004, FSA, London, available at http://www.food.gov.uk/science/surveillance/fsis2004branch/fsis5204.

Fromme H, Otto T, Pilz K, Neugebauer F 1999. Levels of synthetic musks: bromocyclene and PCBs in eel (*Anguilla anguilla*) and PCBs in sediment samples from some waters of Berlin/Germany. *Chemosphere* 39: 1723–1735.

Gaumert T, Löffler J, Bergemann M, Reincke H. 2000. Schadstoffe in Elbefischen. Belastung und Vermarktungsfähigkeit. Arbeitsgemeinschaft für die Reinhaltung de Elbe, 103 p.

Goemans G, Belpaire C 2003. The Flemish eel monitoring network: PCB-concentrations in eel from the Meuse catchment area. Proceedings of the First International Scientific Symposium on the River Meuse, November 27-28, 2002, Maastricht, Netherlands: 58-62.

Goemans G, Belpaire C, Raemaekers M, Guns M 2003. Het Vlaamse palingpolluentenmeetnet, 1994-2001 : gehalten aan polychloorbifenylen, organochloorpesticiden en zware metalen in paling. [The Flemish eel pollution monitoring network 1994-2001: polychlorine biphenyls, organochlorine pesticides and heavy metals in eel]. Report of the Institute for Forestry and Game Management, IBW. Wb.V.R.2003.99,169 p.

Goemans G, Belpaire C 2004. The eel pollutant monitoring network in Flanders, Belgium. Results of 10 years monitoring. *Organohal Comp* 66: 1834-1840.

Goemans G, Belpaire C 2005. Congener profiles in European eel (*Anguilla anguilla* L.) as a method of tracing the origin of PCB contamination. *Organohal Comp* 67: 1304-1307.

Goodwin KR 1999. American Eel subpopulation characteristics in the Potomac river drainage, Virginia. Thesis Faculty of Virginia Polytechnic Institute and State Univ Blacksburg, Virginia, 116 p.

Hammond SD 2003. Seasonal movements of yellow-phase American eels (*Anguilla rostrata*) in the Shenandoah River, West Virginia. Thesis. Davis College of Agriculture, Forestry, and Consumer Sciences at West Virginia Univ, Morgantown WV, 32 p.

Hendriks AJ, Pieters H 1993. Monitoring concentrations of microcontaminants in aquatic organisms in the Rhine delta: a comparison with reference values. *Chemosphere* 26: 817-836.

Hodson PV, Castonguay M, Couillard CM, Desjardins C, Pelletier E, McLeod R 1994. Spatial and temporal variations in chemical contamination of American eels, *Anguilla rostrata*, captured in the estuary of the St. Lawrence river. *Can J Fish Aquat Sci* 51 (2): 464-478.

Hoff PT, Van Campenhout K, de Vijver K, Covaci A, Bervoets L, Moens L, Huyskens G, Goemans G, Belpaire C, Blust R, De Coen W 2005. Perfluorooctane sulfonic acid and organohalogen pollutants in liver of three freshwater fish species in Flanders (Belgium): relationships with biochemical and organismal effects. *Environ Poll* 137: 324-333.

Hubert W, Ricci ED 1981. Factors influencing dieldrin and DDT residues from Des Moines Rivers, Iowa, 1977-1980. *Pest Monit* J 15 (3): 111-116.

Jellyman DJ, Glova GJ, Todd PR 1996. Movements of shortfinned eels, *Anguilla australis*, in Lake Ellesmere, New Zealand: results from mark-recapture studies and sonic tracking. *N Z J Mar Freshw Res* 30: 371-381.

Jørgensen K, Larsen EH, Petersen A, Lund KH, Hilbert G, Andersen NL, Hallas-Møller T, Larsen JC 2001. Chemical contaminants. Food monitoring, 1993-1997. Part 2. Ministry of Food, Agriculture and Fisheries, Danish Veterinary and Food Administration.

Karl H, Lehmann I 1993. Organochlorine residues in the edible part of eels of different origins. *Z Lebensm Unters Forsch* 197: 385-388.

Knights B 1997. Risk assessment and management of contamination of eels (*Anguilla* spp) by persistent xenobiotic organochlorine compounds. *Chem Ecol* 13: 171-212.

Laffaille P, Acou A, Guillouët J 2005. The yellow European eel (*Anguilla anguilla* L.) may adopt a sedentary lifestyle in inland freshwaters. *Ecol Freshw Fish* 14: 191-196.

Langston WJ, Chesman BS, Burt GR, Pope ND, McEvoy J 2002. Metallothionein in liver of eels *Anguilla anguilla* from the Thames Estuary: an indicator of environmental quality? *Mar Environ Res* 53: 263-293.

Lehmann J, Stürenberg F, Ingendahl D 2006. Analysis of health status of yellow eel and silver eel of the River Rhine. In WG EEL 2006. FAO European Inland Fisheries Advisory Commission; International Council for the Exploration of the Sea. Report of the 2006 session of the Joint EIFAC/ICES Working Group on Eels. Rome, 23-27 January 2006. EIFAC Occasional Paper. No. 38, ICES CM 2006/ACFM:16. Rome, FAO/Copenhagen, ICES. 2006, 352 p.

Lehmann J, Stürenberg FJ, Kullmann Y Kilwinski J 2005. Umwelt- und Krankheitsbelastungen der Aale in Nordrhein-Westfalen. LÖBF-Mitteilungen Nr. 2/2005:35-40.

Lelek A 1987. The freshwater fishes of Europe. Vol. 9 Threatened fishes of Europe. Aula Verlag Wiesbaden, 343 p.

Linde AR, Sanchez-Galan S, Garcia-Vazquez E 2004a. Heavy metal contamination of European eel (*Anguilla anguilla*) and brown trout (*Salmo trutta*) caught in wild ecosystems in Spain. *J Food Prot* 67 (10): 2332-2336.

Linde AR, Sanchez-Galan S, Klein D, Garcia-Vazquez E, Summer KH 2004b. Metallothionein and heavy metals in brown trout (*Salmo trutta*) and European eel (*Anguilla anguilla*): a comparative study. *Ecotoxicol Environ Saf* 44 (2): 168-173.

Maes GE, Raeymaekers JAM, Pampoulie C, Seynaeve A, Goemans G, Belpaire C, Volckaert FAM 2005. The catadromous European eel *Anguilla anguilla* (L.) as a model for freshwater evolutionary ecotoxicology: relationship between heavy metal bioaccumulation, condition and genetic variability. *Aquat Toxicol* 73: 99-114.

Maes J, Belpaire C, Goemans G 2007. Spatial variations and temporal trends between 1994 and 2005 in polychlorinated biphenyls, organochlorine pesticides and heavy metals in European eel (*Anguilla anguilla* L.) in Flanders, Belgium. Environ Pollut doi:10.1016/j.envpol.2007.07.021

Mariottini M, Bianchini A, Focardi S 2005. Distribution and profile of polybrominated diphenyl ethers in European eel (*Anguilla anguilla*) from a Mediterranean coastal lagoon (Orbetello, Italy). *Organohal Comp* 67: 467-470.

Mariottini M, Corsi I, Focardi S 2006. PCB levels in European eel (*Anguilla anguilla*) from two coastal lagoons of the Mediterranean. *Environ Monitor Assess* 117: 519-528.

Mason CF, Barak NAE 1990. A catchment survey for heavy metals using the eel (*Anguilla anguilla*). *Chemosphere* 21: 695-699.

Mason CF 1993. Organochlorine pesiticide residues and PCBs in eels *Anguilla anguilla* from some British reedbeds. *Chemosphere* 26: 2289-2292.

Moreau G, Barbeau C 1982. Les métaux lourds comme indicateurs d'origine géographique de l'anguille d'Amérique (*Anguilla rostrata*). *Can J Fish Aquat Sci* 39: 1004-1011.

Morris S, Allchin CR, Zegers BN, Haftka JJH, Boon JP, Belpaire C, Leonards PEG, Van Leeuwen SPJ, de Boer J 2004. Distribution and fate of HBCD and TBBPA brominated flame retardants in North Sea estuaries and aquatic food webs. *Environ Sci Technol* 38: 5497-5504.

Nowell LH, Capel PD, Dileanis PD 1999. Pesticides in stream sediment and aquatic biota. Distribution, trends, and governing factors. Boca Raton, Fla., CRC Press, Pesticides in the Hydrologic System series, v. 4, 1040 p.

Oliveira K 1997. Movements and growth rates of yellowphase American eels in the Annaquatucket river, Rhode Island. *Trans Am Fish Soc* 126: 638-646.

Oliveira Ribeiro CA, Vollaire Y, Sanchez-Chardi A, Roche H 2005. Bioaccumulation and the effects of organochlorine pesticides, PAH and heavy metals in the Eel (*Anguilla anguilla*) at the Camargue Nature Reserve, France. *Aquat Toxicol* 74: 53-69.

Palstra AP, van Ginneken VJT, Murk AJ, van den Thillart GEEJM 2006. Are dioxin-like contaminants responsible for the eel (*Anguilla anguilla*) drama? *Naturwissenschaften* 93: 145-148.

PAN Pesticides Database, 2007. Chemical Toxicity Studies on Aquatic Organisms. Available at htttp://www.pesticideinfo.org/List_AquireAll.jsp?Species=574&Effect=&offset=0

Parker SJ 1995. Homing ability and home range of yellowphase American eels in a tidally dominated estuary. *J Mar Biol Ass U K* 75: 127-140.

Peeters B, De Cooman W, Vos G, Gabriels W, Martens K, Timmermans G, Van Hoof K, Breine J, Van Thuyne G, Goemans G, Belpaire C, Geeraerts C 2006. Oppervlaktewater: Biologische kwaliteit nog steeds ondermaats. *In* Van Steertegem M ed, Mira-T 2006 Milieurapport Vlaanderen: Focusrapport. Leuven Lannoo Campus, 89-104.

Pieters H, van Leeuwen SPJ, de Boer J 2004.Verontreinigingen in aal en snoekbaars: monitorprogramma ten behoeve van de Nederlandse sportvisserij 2003. RIVO report C063/04, 20 p.

Poole R, McCarthy K 2006. Report on the eel stock and fishery in the Republic of Ireland 2005. *In* WG EEL 2006. FAO European Inland Fisheries Advisory Commission; International Council for the Exploration of the Sea. Report of the 2006 session of the Joint EIFAC/ICES Working Group on Eels. Rome, 23–27 January 2006. EIFAC Occasional Paper. No. 38, ICES CM 2006/ACFM:16. Rome, FAO/Copenhagen, ICES. 2006, 352 p.

Reinert RE, Bergman HL 1974. Residues of DDT in lake trout (*Salvelinus namaycush*) and Coho salmon (*Oncorhynchus kisutch*) from the Great Lakes. *Can J Fish Aquat Sci* 31 (2): 191-199.

Robinet T, Feunteun E 2002. Sublethal effects of exposure to chemical compounds: a cause for the decline in Atlantic eels? *Ecotoxicology* 11: 265-277.

Roche H, Buet A, Ramade F 2002. Accumulation of lipophilic microcontaminants and biochemical responses in Eels from the Camargue biosphere reserve. *Ecotoxicology* 11: 155-64.

Roche N, Buet A, Ramade F 2003. Characterization and validation of ecotoxicological biomarkers in an eel population exposed to persistent organic pollutants in the Vaccares lake, French national reserve of Camargue. *Revue d'Ecologie (La Terre et La Vie)* 58: 127-141.

Roose P, Van Thuyne G, Belpaire C, Raemaekers M, Brinkman U 2003. Determination of VOCs in yellow eel from various inland water bodies in Flanders (Belgium). *J Environ Monitor* 5: 876-884.

Ruddock PJ, Bird DJ, McEvoy J, Peters LD 2003. Bile metabolites of polycyclic aromatic hydrocarbons (PAHs) in European eels *Anguilla anguilla* from United Kingdom estuaries. *Sci Total Environ* 301: 105-117.

Santillo D, Johnston P, Labunska I, Brigden K 2005. Widespread presence of brominated flame retardants and PCBs in eels (*Anguilla anguilla*) from rivers and lakes in 10 European countries. Greenpeace Research Laboratories, Technical Note 12/2005, Greenpeace International, October 2005, 56 p.

Santillo D, Allsopp M, Walters A, Johnston P, Perivier H 2006. Presence of perflurionated chemicals in eels from 11 European countries. Investigating the contamination of the European eel with PFCs, substances used to produce non-stick and water-repellant coatings for a multitude of products. Report Greenpeace Research laboratories Technical Note 07/2006, publ. Greenpeace International, September 2006, 32 p.

STECF 2006. Scientific, Technical and Economic Committee for Fisheries of the Commission of the European Communities, 22nd Report of STECF, draft version of 27 April 2006.

Storelli MM, Barone G, Garofalo R, Marcotrigiano GO 2007. Metals and organochlorine compounds in eel (*Anguilla anguilla*) from the Lesina lagoon, Adriatic Sea (Italy). *Food Chem* 100: 1337-1341.

Thomé JP, Bertrand A, Brose F, Carabin O, De Pauw E, Dukmans C, Eppe G, Gaspar P, Leroy A, Louvet M, Maghuin-Rogister G, Marneffe Y, Massart AC, Philippart, JC, Rimbaut G, Scippo ML 2004. Evaluation du niveau de contamination des rivières par les PCBs et les dioxines.Report Univ Liège. Convention avec la Région Wallonne, Ministère de l'Aménagement du Territoire, de l'Urbanisme et de l'Environnement, Engagement n° 01/4143, 167 p.

Tulonen J, Vuorinen PJ 1996. Concentrations of PCBs and other organochlorine compounds in eels (*Anguilla anguilla* L.) of the Vanajavesi watercourse in southern Finland, 1990-1993. *Sci Total Environ* 187: 11-18.

Usero J, Izquierdo C, Morillo J, Gracia I 2004. Heavy metals in fish (*Solea vulgaris*, *Anguilla anguilla* and *Liza aurata*) from salt marshes on the southern Atlantic coast of Spain. *Environ Int* 29: 949-956.

Van den Heuvel-Greve MJ, Leonards PEG, Vethaak D 2006. Food web transfer of dioxins and other organic contaminants in the Western Scheldt: implications for human and environmental health. ICES Annual Science Conference, Maastricht, CM 2006/G:08.

Van der Oost R, Opperhuizen A, Satumalay K, Heida H, Vermeulen NPE 1996a. Biomonitoring aquatic pollution with feral eel (*Anguilla anguilla*) I. Bioaccumulation: biota sediment ratios of PCBs, OCPs, PCDDs and PCDFs. *Aquat Toxicol* 35: 21-46.

Van der Oost R, Goksøyr A, Celander M, Heida H, Vermeulen NPE 1996b. Biomonitoring aquatic pollution with feral eel (*Anguilla anguilla*) II. Biomarkers: pollution-induced biochemical responses. *Aquat Toxicol* 36: 189-222.

Van Leeuwen SPJ, Traag WA, Hoogenboom LAP, Booij G, Lohman, Dao QT, de Boer J 2002. Dioxines, furanen en PCBs in aal. Onderzoek naar wilde aal, gekweekte aal, geïmporteerde en gerookte aal. RIVO Nederlands Instituut voor Visserijonderzoek, IJmuiden, report CO34/02, 34 p, 7 annexes.

Versonnen BJ, Goemans G, Belpaire C, Janssen CR 2004. Vitellogenin content in European eel (*Anguilla anguilla*) in Flanders, Belgium. *Environ Pollut* 128: 363-371.

Weatherley NS, Davies GL, Ellery S 1997. Polychlorinated biphenyls and organochlorine pesticides in eels (*Anguilla anguilla* L.) from Welsh rivers. *Environ Pollut* 95: 127-134.

Weis P, Ashley JTF 2007. Contaminants in Fish of the Hackensack Meadowlands, New Jersey: Size, Sex, and Seasonal Relationships as Related to Health Risks. *Arch Environ Contam Toxicol* 52: 80-89

Weltens R, Goemans G, Huyskens G, Witters H, Belpaire C 2002. Wetenschappelijke onderbouwing voor de normering van polluenten in Vlaamse oppervlaktewateren en selectie van ecologische en exotoxicologische indicatoren voor de waterkwaliteit. Report for VMM, VITO and IBW, IBW.Wb. VR.2002.88.

Weltens R, Goemans G, Huyskens G, Belpaire C, Witters H 2003. Evaluatie van de kwaliteitsnormering voor oppervlaktewater in Vlaanderen: een praktijkstudie. *Water* 2003: 1-9.

Wiesmüller T, Schlatterer B 1999. PCDDs/PCDFs and coplanar PCBs in eel (*Anguilla anguilla*) from different areas of the rivers Havel and Oder in the state of Brandenburg (Germany). *Chemosphere* 38 (2): 325-334.

WG Eel 2006. FAO European Inland Fisheries Advisory Commission; International Council for the Exploration of the Sea. Report of the 2006 session of the Joint EIFAC/ICES Working Group on Eels. Rome, 23-27 January 2006. EIFAC Occasional Paper. No. 38, ICES CM 2006/ACFM:16. Rome, FAO/Copenhagen, ICES. 2006, 352 p.

WG Eel 2007. FAO European Inland Fisheries Advisory Commission; International Council for the Exploration of the Sea. Report of the 2007 session of the Joint EIFAC/ICES Working Group on Eels. Bordeaux, 2-7 September 2007. In press.

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