Environmental Pollution 158 (2010) 1603–1607

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Chemical contamination and the ecological quality of surface water

Jan Baas*, Bas Kooijman

Vrije Universiteit of Amsterdam, Department of Theoretical Biology, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands

Daphnid populations can go extinct rapidly in surface waters if exposed to mixtures even if environmental quality standards are not exceeded.

ARTICLE INFO

Article history:
Received 18 August 2009
Received in revised form
10 November 2009
Accepted 6 December 2009

Keywords:
Maximum permissible concentration
No effect concentration
Survival
Mixtures
Water quality

ABSTRACT

In the assessment of the quality of surface waters, the typical procedure is that the concentration of contaminants in the surface water is monitored and subsequently compared with their respective Maximum Permissible Concentrations (MPCs). If the MPCs are not exceeded the water quality is considered to be safe. But can we be certain that this is true?

We compared MPCs to observed and calculated effects of measured contaminants in Dutch surface waters and showed that effects of mixtures can cause a daphnid population to go extinct within 30 h of exposure even when MPCs are not exceeded. We conclude that there are shortcomings underlying the concepts of the MPCs. And that the MPCs aim to protect 95% of all species is not met.

1. Introduction

This paper is about the level of protection that environmental quality standards in water management provide. The paper is written from the perspective of the situation in the Netherlands. However, the approach that we chose, the results and the conclusions from this research are generally applicable.

A question that is frequently raised by organizations in water management is "what is the effect of the chemical contamination in the surface waters on the ecosystem?". In current water management, typically a survey is conducted in which the most important chemical pollutants are characterized. Based on this the concentration of a number of contaminants in the surface water is monitored. If the concentration of the measured contaminants is below their respective Maximum Permissible Concentrations (MPCs) the quality of the water bodies is considered to be "good". If MPCs are exceeded appropriate measures have to be taken to lower the concentrations in the surface waters.

A recent Dutch study about effects of chemical contaminants on the survival of in situ exposed daphnids in a specific area of the Netherlands showed that there is hardly any correlation between an exceedence of an MPC and extinction of the in situ exposed daphnid populations (Postma and Keijzers, 2008). One of the explanations could lie in effects of mixtures, MPCs are derived for individual compounds and effects of mixtures are not considered in an MPC (eg. Crommentuijn et al., 2000). But we know that mixtures can exert effects in concentration ranges where the individual components do not show effects. This leads to a number of questions, most importantly (assuming that the right contaminants are measured): Can we be sure that the water quality is "good" if no MPC are exceeded? Should we consider effects of mixtures and how? And on the other hand: How bad is it if MPCs are exceeded?

In order to, at least partially, answer these questions, the Delfland Waterboard started biological monitoring already in 1990 and this monitoring continues till today. In general a waterboard is responsible for the quality and quantity of the surface waters, the dikes and if appropriate the dunes in their region. There are currently 27 waterboards in the Netherlands. The Delfland region contains "het Westland", one of the largest greenhouses areas in the world. And as the greenhouses up until 2006 typically did not have their own sewage system any excess of water containing a variety of contaminants was directly ditched on the surface waters. The surface waters could be canals, small lakes, ditches etc.

The biological monitoring consisted of in situ exposing laboratory bred *Daphnia magna* in special jars to the different the surface waters in this region and after one week of exposure the number of survivors were counted. This gives some link between the chemical water quality and the ecological status of the water body of interest. In total 81 different chemical compounds are measured in the surface waters, including pesticides, metals, nutrients, poly aromatic hydrocarbons (PAHs) and poly chloro biphenyls (PCBs).

Recently we showed that it is possible to make reliable predictions on the occurrence of survival or extinction of the exposed

* Corresponding author. Tel.: +31 20 598 71 28; fax: +31 20 598 71 30.
E-mail address: jan.baas@falw.vu.nl (J. Baas).

0269-7491/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envpol.2009.12.015

daphnid populations given the chemical contamination of the surface waters (Baas et al., 2009). In cases where extinction was observed it was possible to link the chemical contamination in the surface waters directly to the survival of the daphnids. See for an elaborate description of the approach Baas et al. (2007, 2009). Of course having a direct link between observed effects and the chemical contamination of surface waters is of great value for water management. We showed that a focus on a limited number of contaminants instead of the whole group of contaminants is feasible.

One of the key features in the approach to predict effects of mixtures is the existence of a No Effect Concentration (NEC) for survival. If this concentration is not exceeded there will be no effect on survival and if it is exceeded, it is possible to calculate a complete dose-response curve for single compounds and/or for the observed mixtures for any point in time given the measured concentrations. In Section 2 we give a more elaborate conceptual description of the approach.

The aim of this study was to compare the MPCs to the NECs that were derived for the daphnids for different compounds in order to at least partially answer the questions about the water quality in relation to the MPCs and the effects of mixtures of compounds.

In Section 2, a conceptual description of the modeling framework and its application to the in situ exposed daphnids is given. In Section 3 some background on MPCs is given. In Section 4 the NECs and MPCs are compared and in Section 5 the consequences for water quality management are discussed.

2. Conceptual description of the modeling framework

2.1. General description

The model that was used to predict the effect of chemical contamination on the survival of the daphnids consists of two parts, a one compartment model to link environmental concentrations to internal concentrations and a hazard model to link internal concentrations to survival. For each compound three parameters are needed to describe its toxic effects: the No Effect Concentration (NEC, unit μM), the killing rate ($b_{\dagger}$, unit $\mu M^{-1}\ h^{-1}$) and the elimination rate (k_e, unit h^{-1}). The killing rate is a measure for the toxicity of the compound of interest, the higher the more toxic the compound (once the NEC is exceeded). The elimination rate determines how fast the equilibrium between internal and external concentrations is achieved. With these three parameters and a blank hazard rate to correct for control mortality a complete description of the effect of a single compound on survival at any moment in time can be calculated (Bedaux and Kooijman, 1994).

A key feature of the model is the NEC; by definition the NEC is the concentration below which no effects occur even after prolonged exposure. Once the NEC is exceeded there will be an effect on survival. We showed that compounds with the same mode of action in a mixture contribute to a single NEC (similar to the classical idea of CA where different compounds can be seen as dilutions from one another) (Baas et al., 2009b). Dissimilar acting compounds all have their own independent NEC.

2.2. Application of the modeling framework to the in situ exposed daphnids

The modeling framework was used to predict the survival or extinction of the in situ exposed daphnids in the Delfland region. In Baas et al. (2009) an elaborate description of the procedures and the results is presented.

In short the effect of the mixture is built up from its individual components. So for each component in the mixture the toxicity parameters (amongst which) the NEC were derived. Then different groups of compounds in the mixture were distinguished, based on their mode of action. It was assumed that each group of compounds shares the NEC and that different groups have independent NECs (compare the approach by De Zwart and Posthuma (2005)). The following groups of compounds sharing a NEC were distinguished:

- PAHs and biphenyls with a narcotic mode of action
- Organophosphorous insecticides, inhibiting acetyl-choline esterases
- Metals

All other compounds (eg. chloride) were assumed to have their own individual NEC. Then using the chemical composition of the surface water at each sampling site the mixture model was used to calculate whether or not any of the individual or shared NECs were exceeded and subsequently the effect on survival was calculated for the exposure period of 1 week.

2.3. No effect concentrations

The NEC was either derived from raw data from exposure experiments at intermediate points in time, or (in most cases) the NEC was derived from data in the open literature (Kegley et al., 2008) from the course of LC_{50} values in time (typically determined at 24, 48 and 96 h of exposure). In the Appendix, the NECs, 48 h LC_{50}s are presented for the metals, PAHs and the pesticides respectively.

3. Maximum permissible concentrations

3.1. General procedure in deriving maximum permissible concentrations

MPCs are concentrations above which the risk of adverse effects is considered unacceptable (Kalf et al., 1997). The negligible concentration (NC) is defined as the MPC/100 and takes possible effects of combination toxicity due to the presence of other substances into account. So here it is implicitly stated that the MPC does not include effects of mixtures. Still the MPC is typically chosen as the environmental quality standard for the evaluation of water quality.

In the context of environmental risk management, risk is defined as that fraction of species that is exposed to concentrations higher than the No Observed Effect Concentration (NOEC) for any compound present. This is the potentially affected fraction of species.

To derive an MPC only data on growth, reproduction and survival (immobility in crustaceans) are included, as these endpoints have the potential to directly affect a species at the population level. EC/LC_{50}s or NOECs are derived for a number of species (typically algae, crustaceans and fish for water quality) and then the lowest value for a single species is selected as a starting point. This value has to be extrapolated to all species, using species sensitivity distributions. A cut of value of 5% is used, so it is accepted that 5% of the species present is, exposed to concentrations higher than the NOEC and therefore might experience damage. The cut off value of 5% is considered to be equivalent to a No Effect Concentration for ecosystems. Still the MPC is meant to protect all species in an ecosystem (Crommentuijn et al., 2000).

3.2. Maximum permissible concentrations for PAHs, metals and pesticides

For PAHs the MPCs are derived by Kalf et al. (1997) and are based on 4 day NOECs and short term (4 days or less) LC/EC_{50}s for single species. For some PAHs, the NOECs are derived from Quantitative Structure Acitivity Relations (QSARs). For the derivation of MPCs for PAHs it is assumed that at the level of the NOEC 10% effect occurs.

For 7 PAHs, the MPCs were derived on the basis of toxicity data on fish and crustaceans (Kalf et al., 1997), the MPCs are given in the Appendix. For PAHs secondary poisoning (bio-accumulation over species) is considered negligible because of metabolization of PAHs in most organisms. For some PAHs (chrysene, benzo[ghi]perylene and indeno[1,2,3-cd]-pyrene) direct data were not available and therefore MPCs were derived on the basis of QSARs. In Struijs et al. (1997) the MPCs for metals are derived and in Crommentuijn et al. (2000) the MPCs for pesticides are derived. The MPCs derived in these papers obtained a legal status and can now be found as the standards for Dutch surface waters (CIW, 2000).

4. Results

For a number of pesticides we did not have reliable data for the derivation of the NECs. The best available data was for nine PAHs, seven metals and seven pesticides. All these contaminants were present in measurable concentrations in the surface waters in the Delfland region, so our analysis focused on these components.

4.1. NECs and MPCs

In the Appendix the MPCs, NECs and for comparison, the 48 h LC_{50}s are presented for the metals, PAHs and the pesticides.

4.2. Measured concentrations in Dutch surface waters in the Delfland region

In this section we give a summary of actually measured concentrations in the surface waters in the Delfland region in the year 2000 in comparison with the MPCs and NECs.

4.2.1. PAHs

The concentrations of the PAHs are typically in the range of 0.1–2 nM. For the PAHs the individual NECs or MPCs are never exceeded. The solubility of the individual PAHs is also rather low and especially for the PAHs with higher K_{ow} values the solubility is not high enough to exceed the NEC.

4.2.2. Pesticides

The pesticides show a much wider variety in measured concentrations. Most pesticides are never measured in concentrations above the detection limits. But pesticides like parathion-ethyl and pirimiphos-methyl are measured in relatively high concentrations. Table 1 shows the measured concentration ranges (Baas et al., 2009) and it is indicated whether or not MPCs are exceeded and if mortality is observed in the measurements if the MPCs are exceeded.

The MPC (and the NEC) of pirimiphos-methyl and parathion-ethyl are exceeded several times, and high concentrations of these compounds also led to extinction of the in situ exposed daphnid populations (Baas et al., 2009). In one occasion there were no NECs exceeded (though MPCs were exceeded), but still the daphnid population went extinct because of the effect of the mixture. This is a good example of a mixture effect, all individual components do not show an effect, but the mixture causes mortality amongst the daphnids.

Table 1
Measured concentrations of pesticides in Dutch surface waters in the Delfland region in the year 2000 (nd denotes no data).

Pesticide	Concentration range (μM)	MPC exceeded	Observed mortality daphnids
diazinon	<3.3E-5–0.004	yes	yes
dichlobenil	1.1E-4–0.019	nd	no
dichlorvos	<1.4E-4–3.6E-4	yes	no
dieldrin	<1.3E-4–2.6E-4	yes	no
disulfoton	<2.7E-5–8.6E-4	nd	no
endosulfansulphate	<1.2E-4–5.0E-4	yes	no
ethylparathion	<6.8E-5–0.011	yes	yes
mevinphos	<4.5E-5–6.70E-4	yes	no
pirimiphos-methyl	<3.0E-5–9.0E-3	yes	yes
tolclophos-methyl	<1.0E-5–0.018	nd	yes

4.2.3. Metals

The metals also show a wide variety in measured concentrations. For chromium, copper, lead, nickel and zinc the MPCs are occasionally exceeded. But this did not lead to extinction of the daphnid populations. The NECs for the individual metals are not exceeded. Copper, cadmium and zinc have concentrations that are typically between 10 and 20% of their respective NECs and the NEC for Zn is exceeded once. For the other metals the highest measured concentrations are much lower compared to their NECs. For arsenic, chromium and mercury the highest measured concentrations are 0.12 μM (0.3%), 0.15 μM (0.05%) and 2E-4 μM (8E-4%) respectively. Table 2 shows the measured concentration ranges for metals (Baas et al., 2009) and whether MPCs are exceeded.

5. Discussion

In this section we will compare NECs for survival of daphnids with MPCs and measured concentrations. If a NEC for survival is compared to an MPC one has to keep in mind that this only gives some indication of the effects of surface waters. Effects on growth or reproduction can occur in concentration ranges far below the NEC for survival. On the other hand if the MPC is close to the NEC for survival of daphnids it is likely that the ecosystem is not adequately protected. Especially, as it was shown that daphnids are not an inherent sensitive species for toxic effects of chemicals (Jager et al., 2007).

5.1. Measured concentrations related to the MPCs

For some of the metals and some of the pesticides the MPCs are regularly exceeded. In most cases this does not lead to mortality amongst the daphnids. Only for the pesticides the exceedence of the MPCs was such that this led to extinction of the daphnid population. In most cases the MPCs are conservative for the survival of daphnids. A recent analysis of the Delfland data showed that there is a less than 25% correlation between an exceedence of an MPC and extinction of the in situ exposed daphnid populations (Postma and Keijzers, 2008).

Table 2
Measured concentrations of metals in Dutch surface waters in the Delfland region in the year 2000.

Metal	Measured concentration (μM)	MPCs exceeded	Observed mortality daphnids
Arsenic	0.015–0.12	no	no
Cadmium	<0.0018	no	no
Chromium	<0.038–1.71	yes	no
Copper	<0.0003–0.14	yes	no
Mercury	<0.00015	no	no
Lead	<0.01–0.077	yes	no
Nickel	<0.058–0.35	yes	no
Zinc	<0.077–3.67	yes	no

The Tables 1, 2 and 3 in the appendix show that for most of the compounds there is a safe margin between the NEC and the MPC, implying that the MPCs give adequate protection and some exceedence of the MPCs does not lead to an effect on the survival of the daphnids. The difference for different compounds however is striking. For most of the PAHs the typical factor is about 1000, which appears to be adequate. But for the metals and the pesticides there are large differences for the different compounds. Especially for cadmium, zinc, pirimiphos-methyl and diazinone the margin between the NEC for survival of the daphnids and the MPC is very small (<25). For these compounds a small exceedence of the MPC can result in extinction of the daphnid population, as we have shown in Baas et al. (2009). Especially for cadmium the MPC (0.0036 μM) is very close to the LC_{50} 96 h value (LC_{50} 48 h equals 0.59 μM, LC_{50} 96 h equals 0.044 μM). If the cadmium concentration would be close to the MPCs and the other metals are present in the typical concentration ranges as found in these surface waters we calculated that a daphnid population would go extinct within 30 h after exposure, because of the combined effect of the metals without exceeding any of the MPCs.

Another important observation is the ad hoc MPC of 2 ng/L, that is used for a number of different pesticides (CIW, 2000) is also very close to the NEC for survival of daphnids. For diazinone and pirimiphos-methyl this ad hoc MPC offers very little protection for daphnids, and also here we can calculate that daphnid populations go extinct rapidly if other pesticides are present in their typical concentrations. This poses questions about the level of protection that the MPCs actually offer.

5.2. Maximum permissible concentrations

In the line of reasoning where risk is defined as that fraction of species that is exposed to concentrations higher than the NOEC, the NOEC becomes something like a safe concentration, for which it is often mistaken. Van der Hoeven et al. (1997), Crane and Newman (2000) and others have shown that the NOEC may incidentally have an effect close to 100%, depending on the dataset and the test applied to a dataset. Typically the effect at the NOEC-level is between 10 and 34% (Crane and Newman, 2000). Then assuming a sensitivity distribution, based on 10–34% effect (certainly not "no effect") and subsequently accepting that 5% of species is affected compromises the whole idea of using a species sensitivity distribution to protect the most sensitive species, as it was originally posed by Kooijman (1987). Instead a cut of was accepted, where 5% of species is not protected.

One could still argue that the MPC is a political choice where it is accepted that 5% of all species present are endangered, so a daphnid population could belong to the 5% of species at risk. But if a daphnid population goes extinct within 30 h after exposure and no MPCs are exceeded, there is reason to doubt the background of the MPCs. The premise that it is acceptable that 5% of species is endangered and that it is therefore fully acceptable that daphnid populations go extinct very rapidly cannot be accepted from an environmental point of view. It is rather safe to assume that if a daphnid population goes extinct at this rate more than 5% of species will be endangered.

In addition it is important to note that it is accepted that 5% of species is allowed to undergo damage for each compound present. In the situation in "het Westland" where there are about 80 different compounds present it is very likely that well over 5% of species is affected. Accepting that 5% of species is endangered *per* compound can not be seen as the equivalent of a No Effect Concentration for ecosystems as Crommentuijn et al. (2000) argue. Especially if in the same paper it is argued that the MPC is meant to protect all species in ecosystems. In addition, there is the underlying assumption that in ecosystems the organism is as sensitive as in a laboratory experiment (Emans et al., 1993). Even if this is true, a fish for instance that preys on daphnids is affected if the daphnids are affected. The fish may not be affected by the chemical directly, but if its food source influenced also the fish population will be affected.

The final point in the derivation of MPCs is that this approach neglects that toxic effects are processes in time and effects have to build up, especially for PAHs (eg Schuler et al., 2006; Unger et al., 2007). Standardizing toxicological tests to a specific point in time (48 h for an acute with daphnids or 96 h for an acute fish test) may therefore lead to biased results. This was nicely shown for effects of cadmium on pea aphids by Laskowski (2001). Steen Redeker and Blust (2004) also show that the incipient LC_{50} for *Tubifex tubifex* exposed to cadmium is only reached after 15 days of exposure. This leads to the conclusion that in the derivation of MPCs some fundamental flaws have emerged, which questions whether or not this approach leads to protection of the ecosystem.

6. Conclusions

The main conclusion of the research is that it is possible to have a daphnid population go extinct within 30 h of exposure when it is exposed to a mixture of pollutants at the concentration level of the MPC. Therefore we conclude that the current practice in which a water body is considered of good ecological quality if no MPCs are exceeded needs revision.

In the derivation of MPCs some fundamental flaws have emerged, which questions whether or not this approach leads to protection of the ecosystem. Most importantly, the acceptance that we allow that 5% of species is affected *per compound* in the environment.

The argument that the maximum permissible concentration allows 5% of species to undergo damage (this might mean death, depending on the most sensitive endpoint in the derivation of the MPCs), and daphnids are just unlucky in the sense, that they belong to the 5% species affected at the level of the MPC does not hold. It was shown that daphnids are not an inherent sensitive species. So if daphnids go extinct other species will also go extinct, even without considering indirect secondary effects as food sources going extinct.

The lack of relation between exceeding MPCs and mortality amongst in situ exposed daphnids shows the existing problems with the MPCs. This is underlined by the narrow margin the NEC for survival of daphnids and the maximum permissible concentration for some compounds. The ad hoc MPC for some pesticides of 2 ng/L is not strict enough for the more potent insecticides, like diazinone.

Acknowledgement

The study was supported by the EU Integrated project NoMiracle (Novel Methods for Integrated Risk assessment of Cumulative Stressors in Europe; http://nomiracle.jrc.it) contract No. 003956 under the EU-theme "Global Change and Ecosystems" topic "Development of risk assessment methodologies", coordinated by Dr. Hans Løkke at NERI, DK-8600 Silkeborg, Denmark.

Appendix

In this appendix the Table 1, 2 and 3 contain the No Effect Concentrations (NECs), LC_{50} values and Maximum Permissible Concentrations (MPCs) for resp. the metals, Poly Aromatic Hydrocarbons (PAHs) and pesticides are given (see Sections 2 and 3 of the main text).

Table 1. 48 h LC_{50} values *Daphnia magna*, NECs for survival of *D. magna* and MPCs for the different metals (LC_{50} and NEC Baas et al., 2009, 2009a,b; MPC CIW, 2000, based on Struijs et al., 1997).

Metal	LC_{50} 48 h (μM)	NEC (μM)	MPC (μM)	NEC/MPC
Arsenic	51	38.1	0.3338	114
Cadmium	0.59	0.04	0.0036	2.5
Chromium	413	308	0.1673	1839
Copper	0.76	0.68	0.0236	29
Lead	46	7.8	0.0531	209
Nickel	58	4.3	0.0869	49
Zinc	29.7	3.1	0.1437	21

Table 2. 48 h LC_{50} values *Daphnia magna*, NECs for survival of *D. magna* and MPCs for the different PAHs (MPCs and LC_{50} Kalf et al., 1997, NECs Baas et al., 2009, 2009a,b).

PAH	LC_{50} 96 h (nM)	NEC (nM)	MPC (nM)	NEC/MPC
Phenanthrene	170	4400	1.68	2601
Anthracene	39	4700	0.39	11869
Fluoranthene	1480	1100	1.48	756
Benz[a]anthracene	44	260	0.04	6031
Chrysene	–	290	1.31	223
Benz[k]Fluoranthene	–	220	0.16	1380
Benz[a]Pyrene	20	200	0.20	1015
Benzo[ghi]Perylene	–	77	0.10	707
Naphthalene	94	5400	9.36	5781

Table 3. 48 h LC_{50} values *Daphnia magna*, NECs for survival of *D. magna* and MPCs for the different pesticides (LC_{50} and NEC Baas et al., 2009, 2009a,b; MPC CIW, 2000).

Pesticide	LC_{50} 48 h (μM)	NEC (μM)	MPC (μM)	NEC/MPC
diazinon	1.6 E-3	1.1 E-3	1.22E-4	9
dichlorphos	0.47	0.28	3.17E-7	89335
dieldrin	0.46	0.27	9.58E-5	2817
endosulphansulphate	1.23	1.0 E-1	4.91E-5	650
mevinphos	5.8 E-3	4.5 E-3	9.93E-6	500
parathion-ethyl	4.6 E-3	9.3 E-4	6.87E-6	165
pirimiphos-methyl	6.7 E-4	1.5 E-4	6.09E-6	25

References

Baas, J., van Houte, B.P.P., van Gestel, C.A.M., Kooijman, S.A.L.M., 2007. Modelling the effects of binary mixtures on survival in time. Environmental Toxicology and Chemistry 26 (6), 1320–1327.

Baas, J., Willems, J., Tager, T., Kraak, M., Vandenbrouck, T., Kooijman, S.A.L.M., 2009. Predicting survival of in situ exposed daphnids to Dutch surface waters. Environmental Science and Technology 43 (15), 6064–6069.

Baas, J., Tager, T., Kooijman, S.A.L.M., 2009a. A model to analyse the effect of complex mixtures on survival. Environmental Ecotoxicology and Safety 72 (3), 669–676.

Baas, J., Stefanowicz, A.M., Klimek, B., Laskowski, R., Kooijman, S.A.L.M., 2009b. Model-based experimental design for assessing effects of mixtures of chemicals. Environmental Pollution. doi:10.1016/j.envpol.2009.07.030.

Bedaux, J.J.M., Kooijman, S.A.L.M., 1994. Statistical analysis of bioassays, based on hazard modeling. Environmental and Ecological Statistics 1, 303–314.

Commissie Integraal Waterbeheer, (2000). Normen voor het waterbeheer Achtergronddocument (Standards in water control, background document NW 4). (in Dutch).

Crane, M., Newman, M.C., 2000. What level of effect is a no observed effect? Environmental Toxicology and Chemistry 19 (2), 516–519.

Crommentuijn, T., Sijm, D., de Bruijn, J., van Leeuwen, K., Van de Plassche, E.J., 2000. Maximum permissible and negligible concentrations for some organic substances and pesticides. Journal of Environmental Management 58 (4), 297–312.

De Zwart, D., Posthuma, L., 2005. Complex mixture toxicity for single and multiple species: proposed methodologies. Environmental Toxicology and Chemistry 24 (10), 2665–2676.

Emans, H.J.B., van de Plassche, E.J., Canton, J.H., Okkerman, P.C., Sparenburg, P.M., 1993. Validation of some extrapolation methods used for effect assessment. Environmental Toxicology and Chemistry 12 (9), 1541–1583.

Jager, T., Posthuma, L., de Zwart, D., van de Meent, D., 2007. Novel view on predicting acute toxicity: decomposing toxicity data in species vulnerability and chemical potency. Ecotoxicology and Environmental Safety 67 (1), 311–322.

Kalf, D.K., Crommentuijn, T., Van de Plassche, E.J., 1997. Environmental quality objectives for 10 polycyclic aromatic hydrocarbons (PAHs). Ecotoxicology and Environmental Safety 36 (1), 89–97.

Kegley, S.E., Hill, B.R., Orme, S., Choi, A.H., 2008. PAN Pesticide Database, Pesticide Action Network. North America, San Francisco, CA. http://www.pesticideinfo.org.

Laskowski, R., 2001. Why short-term bioassays are not meaningful-Effects of a pesticide (imidacloprid) and a metal (cadmium) on pea aphids (*Acyrthosium pisum* harris). Ecotoxicology 10 (3), 177–183.

Postma, J.F., Keijzers, C.M. 2008. Twee decennia monitoring van bestrijdingsmiddelen en Daphnia's (Two decades monitoring of pesticides and daphnids, Ecofide, Weesp) (in Dutch).

Schuler, L.J., Landrum, P.F., Lydy, M.J., 2006. Comparative toxicity of fluoranthene and pentachlorobenzene to three freshwater invertebrates. Environmental Toxicology and Chemistry 25 (4), 985–994.

Steen Redeker, E., Blust, R., 2004. Accumulation and toxicity of cadmium in the aquatic oligochaete *Tubifex tubifex*: a kinetic modeling approach. Environmental Science and Technology 38 (2), 537–543.

Struijs, J., van de Meent, D., Peijnenburg, W.J.G.M., van den Hoop, M.A.G.T., Crommentuijn, T., 1997. Added risk approach to derive maximum permissible concentrations for heavy metals: how to take natural background levels into account. Ecotoxicology and Environmental Safety 37 (2), 112–118.

Unger, M.A., Newman, M.C., Vadas, G.G., 2007. Predicting survival of grass shrimp (*Palaemonetes pugio*) during ethylnaphthalene, dimethylnaphthalene, and phenanthrene exposures differing in concentration and duration. Environmental Toxicology and Chemistry 26 (3), 528–534.

van der Hoeven, N., Noppert, F., Leopold, A., 1997. How to measure no effect. Part I: towards a new measure of chronic toxicity in ecotoxicology. Introduction and workshop results. Environmetrics 8 (3), 241–248.