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CONSENSUS SEDIMENT QUALITY GUIDELINES FOR POLYCYCLIC AROMATIC HYDROCARBON MIXTURES

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Abstract—Sediment quality guidelines (SQGs) for polycyclic aromatic hydrocarbons (PAHs) have been derived from a variety of laboratory, field, and theoretical foundations. They include the screening level concentration, effects ranges–low and–median, equilibrium partitioning concentrations, apparent effects threshold, ΣPAH model, and threshold and probable effects levels. The resolution of controversial differences among the PAH SQGs lies in an understanding of the effects of mixtures. Polycyclic aromatic hydrocarbons virtually always occur in field-collected sediment as a complex mixture of covarying compounds. When expressed as a mixture concentration, that is, total PAH (TPAH), the guidelines form three clusters that were intended in their original derivations to represent threshold (TEC = 290 μg/g organic carbon [OC]), median (MEC = 1,800 μg/g OC), and extreme (EEC = 10,000 μg/g OC) effects concentrations. The TEC/MEC/EEC consensus guidelines provide a unifying synthesis of other SQGs, reflect causal rather than correlative effects, account for mixtures, and predict sediment toxicity and benthic community perturbations at sites of PAH contamination. The TEC offers the most useful SQG because PAH mixtures are unlikely to cause adverse effects on benthic ecosystems below the TEC.

Keywords—Polycyclic aromatic hydrocarbons   Mixtures   Sediment quality guideline   Sediment toxicity

INTRODUCTION

A plethora of marine sediment quality guidelines (SQGs) have been proposed for polycyclic aromatic hydrocarbons (PAHs) [1–10]. Existing PAH SQGs were derived from a variety of laboratory, field, and theoretical foundations. They have engendered considerable controversy over issues of correlative versus causal relations between chemistry and biological effects, bioavailability of sediment contaminants, effects of covarying chemicals and mixtures, and ecological relevance [see editorials, 11–19].

In this paper I attempt to resolve these issues and show that the different SQGs are more similar than dissimilar. The existing PAH SQGs are described and quantitatively compared. Consensus guidelines for PAHs are proposed for threshold, median, and extreme effects concentrations (TEC, MEC, EEC). The consensus guidelines are then evaluated with respect to their ability to predict sediment toxicity (10-d mortality to estuarine and marine amphipods) and in situ ecological effects (reduction in the areal species richness of macrobenthic assemblages).

EXISTING PAH SEDIMENT QUALITY GUIDELINES

Screening level concentration (SLC)

The SLC was derived from field data on PAH concentrations and the presence/absence of a number of benthic species [1]. A cumulative frequency distribution of stations at which a particular species was present was plotted against the organic carbon (OC)-normalized concentration of an individual PAH to derive the species screening level concentration (SSLC). The SSLC was defined as the concentration at the 90th percentile of this frequency distribution. The SSLCs for a large number of species were then plotted in another frequency distribution. The SLC was defined as the individual PAH concentration above which 95% of the SSLCs were found.

Effects range–low (ERL), effects range–median (ERM)

The ERL and ERM were developed from an extensive database of biological effects determined by a variety of methods (toxicity tests, field observations, other sediment guidelines including equilibrium partitioning-derived [EqP] criteria and the apparent effects threshold [AET]) [2,9]. The dry weight-normalized database for each PAH compound was sorted and the ERL and ERM identified as the lower 10th (ERL) and 50th (ERM) percentiles of effects data.

Equilibrium partitioning-derived (EqP) criteria

The EqP concentration is the OC-normalized individual PAH concentration in sediment that is in equilibrium with an interstitial water PAH concentration equal to the U.S. Environmental Protection Agency (U.S. EPA) Water Quality Criterion Final Chronic Value [3,5–7]. The U.S. EPA has proposed EqP criteria for acenaphthene, phenanthrene, and fluoranthene.

Apparent effects threshold (AET)

The AET is the dry weight-normalized individual PAH concentration above which statistically significant biological effects always occurred in the Puget Sound database used to create the values [4]. Four kinds of AET values are based on sediment toxicity tests with amphipods, oyster larvae, Microtox, and on biological effects in the field as measured by the abundance of benthic infauna. In addition, AET SQGs are expressed as the highest (HAET) and lowest (LAET) of the four kinds of AETs.

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Table 1. The ΣPAH mixture LC50 and effects range–median (ERM)[a] sediment quality guidelines for total PAHs (μg/g organic carbon [OC])

PAH	ΣPAH LC50	Mean percent of ΣTU[b]	ΣPAH mixture LC50	ERM
Naphthalene	7,146	1.0	71	210
Acenaphthylene	4,900	0.3	15	64
Acenaphthene	2,310	1.0	23	50
Fluorene	4,478	2.0	90	54
Phenanthrene	2,220	7.0	155	150
Anthracene	4,220	2.7	114	110
Low molecular weight PAH[c]			468	638
Fluoranthene	3,310	11.2	371	510
Pyrene	2,810	17.1	481	260
Benz[*a*]anthracene	2,136	5.2	111	160
Chrysene	2,136	7.9	169	280
Benzo[*b*]fluoranthene	1,096	16.4	180	188[d]
Benzo[*k*]fluoranthene	892	17.4	155	162[d]
Benzo[*a*]pyrene	1,655	10.8	179	160
High molecular weight PAH[c]			1,646	1,720
Total PAH[b]			2,114	2,358

[a] ERM at 1% OC.
[b] ΣTU = sum of toxic units.
[c] By addition.
[d] No ERM. Estimate assuming mean ratio to ΣPAH mixture LC50 for other HPAH.

ΣPAH model

The ΣPAH model estimates the probability that a PAH-contaminated sediment will be toxic to marine and estuarine amphipods [8]. Two SQGs can be derived from the ΣPAH model, the ΣPAH mixture LC50, and the ΣPAH toxicity threshold. The ΣPAH mixture LC50 is the concentration of individual compounds, low molecular weight (LPAH), high molecular weight (HPAH), or total PAHs (TPAH) that is expected when the TPAH is sufficient to cause 50% amphipod mortality (Table 1). The ΣPAH mixture LC50 is calculated as the product of the LC50 for an individual compound (e.g., in a spiked sediment toxicity test) and the mean fractional contribution of that compound to the sum of toxic units in field-collected sediments contaminated by a PAH mixture [8]. For example, the naphthalene LC50 estimated by the ΣPAH model is 7,146 μg/g OC, and naphthalene accounts for about 1% of the PAH toxic units in contaminated sediment [8]. The ΣPAH mixture LC50 for naphthalene is therefore 1% of 7,146 μg/g OC (~71 μg/g OC, Table 1). The threshold of significant amphipod toxicity occurs at 0.186 toxic units [8]. Because the ΣPAH mixture LC50 represents 1.0 toxic units, the ΣPAH toxicity threshold SQGs are 18.6% of the ΣPAH mixture LC50 SQGs (Tables 1 and 2).

Threshold effects level (TEL), probable effects level (PEL)

The TEL and PEL were derived from a biological effects data set (BEDS) that included all observations of adverse biological effects that occurred at chemical concentrations at least twofold above reference conditions, and a no effects data set that included all observations of no adverse biological effects at reference sites or at chemical concentrations within a twofold elevation above reference conditions [10]. The TEL was calculated as the geometric mean of the 15th percentile of the effects data set and the 50th percentile of the no effects data set. The PEL was calculated as the geometric mean of the 50th percentile of the effects data set and the 85th percentile of the no effects data set.

Normalization

Sediment quality guidelines have been proposed for PAH concentrations normalized on both an OC and dry weight basis.

Table 2. Sediment quality guidelines for total polycyclic aromatic hydrocarbons (TPAHs, μg/g organic carbon [OC])

	Sediment quality guidelines (SQGs)[a]									
PAH	ERL[b]	ERM[b]	TEL[b]	PEL[b]	SLC	LAET[b]	HAET[b]	EqP	ΣPAH toxicity threshold	ΣPAH mixture LC50
Naphthalene	16	210	3	39	41	210	270		13	71
Acenaphthylene	4	64	1	13	5	>56	130		3	15
Acenaphthene	2	50	1	9	6[c]	50	200	230	4	23
Fluorene	2	54	2	14	10	54	360		17	90
Phenanthrene	24	150	9	54	37	150	690	240	29	155
Anthracene	9	110	5	24	16	96	1,300		21	114
Low molecular weight PAH[d]	57	638	21	153	115	616	2,950		87	468
Fluoranthene	60	510	11	149	64	170	3,000	300	69	371
Pyrene	66	260	15	140	66	260	1,600		90	481
Benz[*a*]anthracene	26	160	7	69	26	130	510		21	111
Chrysene	38	280	11	85	38	140	920		31	169
Benzo[*b*]fluoranthene	32[c]	188[c]	7[c]	71[c]	32[c]	160	445		33	180
Benzo[*k*]fluoranthene	28[c]	162[c]	6[c]	61[c]	28[c]	160	445		29	155
Benzo[*a*]pyrene	43	160	9	76	40	160	360		33	179
High molecular weight PAH[d]	293	1,720	66	651	294	1,180	7,280		306	1,646
Total PAH[d]	350	2,358	87	804	409	1,796	10,230	211	393	2,114

ERL = effects range–low [2]; ERM = effects range–median [2]; TEL = threshold effects level [10]; PEL = probable effects level [10]; SLC = screening level concentration [1]; LAET = low apparent effects threshold [4]; HAET = high apparent effects threshold [4]; EqP = U.S. Environmental Protection Agency criteria derived from equilibrium partitioning theory [3,5–7].
SQG at 1% OC.
No SQG. Estimate assuming mean ratio to ΣPAH mixture LC50 for other high molecular weight PAHs.
By addition.

The PAH concentrations in this paper are OC-normalized to facilitate comparisons among SQGs and because of the important role of OC in determining PAH partitioning and bioavailability [3]. The mean OC concentration in the BEDS was 1.0% [10]. A sediment OC concentration of 1.0% was therefore assumed in the OC-normalization of SQGs that were originally normalized to dry weight.

Sediment guidelines for PAH mixtures

In addition to SQGs for individual PAH compounds, guidelines have been proposed for LPAH, HPAH, and TPAH. The present analysis is restricted to six LPAH compounds (naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene) and seven HPAH compounds (fluoranthene, pyrene, benz[*a*]anthracene, chrysene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, benzo[*a*]pyrene). The LPAH, HPAH, and TPAH SQGs are calculated here as the sum of the OC-normalized concentrations of the 6, 7, or 13 compounds listed above. Because different sets of compounds were included in the original derivation of LPAH, HPAH, and TPAH SQGs [2,4,8–10], the original values differ from those recalculated here. When a SQG was missing for 1 to 3 of the 13 compounds (e.g., there is no ERM for benzo[*b*]fluoranthene), it was estimated assuming the same ratio to TPAH as the guideline based on the ΣPAH mixture LC50 (Table 2). Because there are only three EqP values [5–7], an estimate of the EqP value for TPAH was made by multiplying the mean ratio of EqP to amphipod LC50 times the ΣPAH mixture LC50 for TPAH (Table 2).

Data sets

Sediment toxicity. Two data sets were used in the analysis and comparison of SQGs in relation to sediment toxicity. The first was restricted to surveys at sites where PAHs were known to be a principal contaminant and is therefore referred to as the PAH data set [8]. It includes 102 samples from San Diego Bay, California, USA [8], Eagle Harbor, Washington, USA [20,21], Curtis Creek, Virginia, USA [22], and Halifax Harbor, Nova Scotia, Canada [23] plus data from 30 sites in Elliott Bay, Washington, USA (S.P. Ferraro, unpublished data). The second set is called the EMAP data because it includes 678 samples collected in U.S. EPA's Environmental Monitoring and Assessment Program surveys in Long Island Sound, New York, USA (1989, 1991), and the Virginian (1990, 1991) and Louisianian provinces (1991, 1992), USA. The EMAP surveys were based on a probabilistic sampling design so that sites were selected without bias toward the presence or absence of PAH contamination [24–26]. Data collected for all of the PAH and EMAP samples included 10-d sediment toxicity to amphipods (*Rhepoxynius abronius, Ampelisca abdita, Eohaustorius estuarius, Leptocheirus plumulosus,* or *Corophium volutator*) following the American Society for Testing and Materials (ASTM) protocol [27], and the sediment concentration of OC and the 13 PAH compounds listed above.

Benthic community structure. Benthos samples were collected along with sediment toxicity and chemistry samples at two of the PAH-contaminated site surveys. In San Diego Bay, a single 8-cm-diameter (50-cm²) core was collected for benthos analysis from each of five replicate 0.1-m² Van Veen grabs at each station. Crustacean and mollusc species (S) retained on a 1.0-mm sieve were collected, identified, and counted to estimate areal species richness at each station, that is, S/0.025 m². In Elliott Bay, three 8-cm-diameter cores were collected from an unreplicated 0.1-m² Van Veen grab at each station Areal species richness of crustaceans and molluscs retaine on a 1.0-mm sieve was therefore estimated as S/0.015 m² i Elliott Bay.

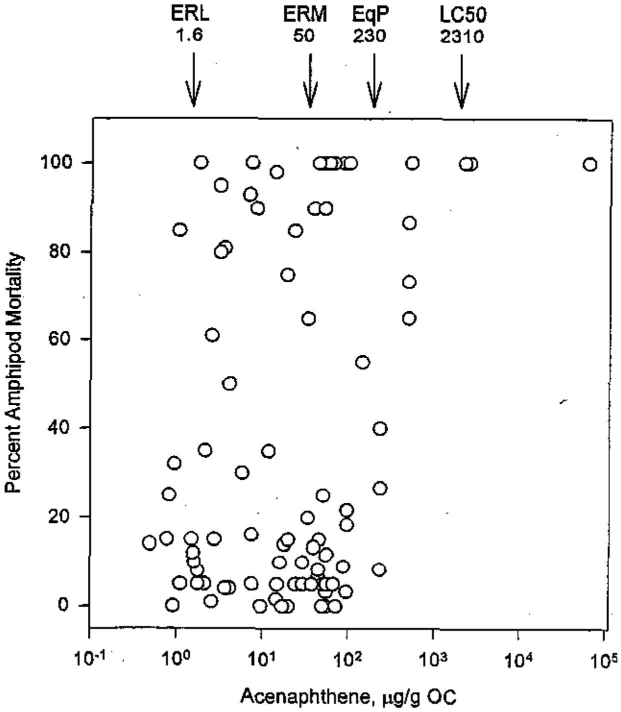

Fig. 1. Amphipod mortality in relation to acenaphthene concentratio in 10-d sediment toxicity tests of sediment samples from sites of PA contamination.

COMPARISON OF SEDIMENT QUALITY GUIDELINES

The mixture paradox

Polycyclic aromatic hydrocarbons virtually always occur i field-collected sediment as a complex mixture of covaryin compounds [28,29]. Thus, ecological perturbations result fro the cumulative effects of multiple PAHs. A principal key t resolving differences among the SQGs is offered by wha might be called the "mixture paradox." The paradox lies i the fact that an SQG derived from accurate, experimental determination of toxicologic effects caused by an individual PAH compound (e.g., through spiked-sediment experiments) wil greatly underestimate ecological effects in the field that ar associated with the SQG, but actually caused by the PAH mixture. As a corollary, an SQG derived from the correlatio of ecological effects with the concentration of an individua PAH in field-collected sediment will greatly overestimate th effects actually caused by the single compound.

The mixture paradox is evident in the relation betwee amphipod toxicity and the concentration of acenaphthene i field-collected sediments (Fig. 1). The LC50 of acenaphthen to amphipods (2,310 µg/g OC) and the EqP value (230 µg/g OC), both derived from experiments with single compounds, substantially underestimate the toxicity of field-collected sediments (Fig. 1). The ERL (1.6 µg/g OC) and ERM (50 µg/g OC), derived from correlative techniques, accurately indicate low and median toxicologic effects associated with acenaphthene in the field, but are one or two orders of magnitude

below acenaphthene concentrations that could cause the observed effects (Fig. 1).

Long et al. [9] recognized that "the cumulative effects of mixtures" may tend to reduce the "apparent effective concentration of individual toxicants" and make field-derived SQGs "more protective than SQGs based upon only single-chemical approaches." Predictions of the ΣPAH model allow an explicit test of the hypothesis that field-derived SQGs represent concentrations of individual compounds in a PAH mixture whose cumulative toxicologic action is responsible for observed effects. The ΣPAH mixture LC50 guidelines (derived from spiked-sediment tests with single compounds) estimate the concentrations of individual PAHs in a mixture that would cause 50% amphipod mortality. None of the PAHs at the ΣPAH mixture LC50 SQG concentration would be sufficient, by itself, to cause significant toxicity. Note the remarkable similarity of the ERM and ΣPAH mixture LC50 guidelines (Table 1). On average these two guidelines for median effects (50% mortality or 50th percentile of ecological/toxicologic effects) differ by a factor of only 1.5. Agreement is better for the summary guidelines (LPAH, HPAH, TPAH) than for most of the guidelines for individual compounds. Clearly, each of the ERM SQGs for individual compounds is an independent estimate of the effects of the PAH mixture associated with the guideline concentration.

The results of SQG quotient (sediment concentration/SQG) analyses also provide evidence that PAH SQGs derived from correlative techniques are, in fact, mixture guidelines. Assuming additivity of the toxic effects of narcotic chemicals [8,30,31], toxicity should occur when the sum of ERM quotients exceeds unity if the ERMs reflect the effects of individual compounds. However, in a comprehensive investigation of freshwater SQGs, the frequency of toxicity of field-collected sediment samples did not increase above background levels until the sum of ERM quotients exceeded 10 and the frequency of ERM exceedances was 3 to 7 [32]. That result is consistent with the hypothesis that PAH ERMs are mixture guidelines because most of the ERMs would be simultaneously exceeded when the concentration of the PAH mixture reached a toxic level.

CONSENSUS SEDIMENT QUALITY GUIDELINES

Guidelines for individual PAHs seem inappropriate regardless of whether they are derived from correlative, experimental, or theoretical methods. Because of the mixture paradox, they will either be ecologically irrelevant or create the false impression that the individual compound has caused the observed effects. Because the effects are actually caused by multiple, covarying PAHs, it seems reasonable to define the guideline in the mixture context. In particular, a guideline based on TPAH would resolve the mixture paradox and reduce the variability among guidelines for individual compounds.

Several TPAH guidelines have been proposed, but the actual compounds included in TPAH have varied among investigations. Therefore, TPAH guidelines have been recalculated for 13 PAH compounds identified as U.S. EPA priority pollutants [33] and commonly measured in sediment surveys (Table 2).

The TPAH SQGs form three clusters that were intended in their original derivations to represent TECs, MECs, and EECs (Table 3). The TPAH guidelines in these clusters agree within a factor of about four. Excluding the TEL and PEL, which are derived from a combined effects/no effects database, the TPAH guidelines in these clusters agree within a factor of two. This agreement is remarkable because of the different theoretical, empirical, and experimental methods used in the development of the guidelines. The clusters appear to represent independent estimates of the same TPAH concentrations. Consensus SQGs for TPAH are derived simply as the arithmetic mean of the values in each cluster: TEC, 290 μg/g OC; MEC, 1,800 μg/g OC; EEC, 10,000 μg/g OC.

Table 3. Consensus sediment quality guidelines (SQGs) for total polycyclic aromatic hydrocarbons (TPAHs)[a]

SQG	TPAH (μg/g OC)	95% confidence limits
Threshold effect concentration (TEC)		
Threshold effect level	87	
Equilibrium partitioning	211	
ΣPAH toxicity threshold	393	
Effects range–low	350	
Screening level concentration	409	
Mean (consensus) TEC	290	119–461
Median effects concentration (MEC)		
Probable effects level	804	
Low apparent effects threshold	1,796	
ΣPAH mixture LC50	2,114	
Effects range–median	2,358	
Mean (consensus) MEC	1,800	682–2,854
Extreme effects concentration (EEC)		
High apparent effects threshold	10,230	
Consensus EEC	10,000	NA

[a] OC = organic carbon; NA = not applicable.

FIELD AND EXPERIMENTAL VERIFICATION OF CONSENSUS GUIDELINES

Sediment toxicity

In the data set for surveys where PAHs were the dominant ecotoxicologic factor, significant sediment toxicity (>24% mortality [34]) occurred in 2 of 36 samples (5.6%) with TPAH concentrations below the TEC (Fig. 2, Table 4). The background frequency of significant amphipod toxicity in reference marine sites is 5.0% [8]. Toxicity was significant in all 12 samples with TPAH concentrations above the EEC (Fig. 2 and Table 4). Few false negatives occurred below the TEC and no false positives occurred above the EEC.

The frequency of significantly toxic sediments increased, but not substantially, between the TEC to MEC (43% toxic) and MEC to EEC (50% toxic) concentration ranges (Fig. 2 and Table 4). Thus, a broad range of concentrations exists between the TEC and the EEC in which there is about a 50% probability of 10-d toxicity to amphipods. An SQG cannot be set within that range that would have a low frequency of both false negatives and false positives. The mean percent mortality of amphipods exposed to sediment with TPAH concentrations between the TEC and EEC guidelines was only about 36% (Table 4).

The MEC proved to be what it was expected to be, that is, an indicator of median effects. Of the 52 significantly toxic samples, 28 were less than the MEC and 24 exceeded the MEC (Fig. 2 and Table 4). The MEC lies within the transition between nontoxic and highly toxic sediment. It is literally a guide line for a median probability of adverse effects. The MEC is not an unequivocal indicator that sediments are toxic or otherwise unacceptable.

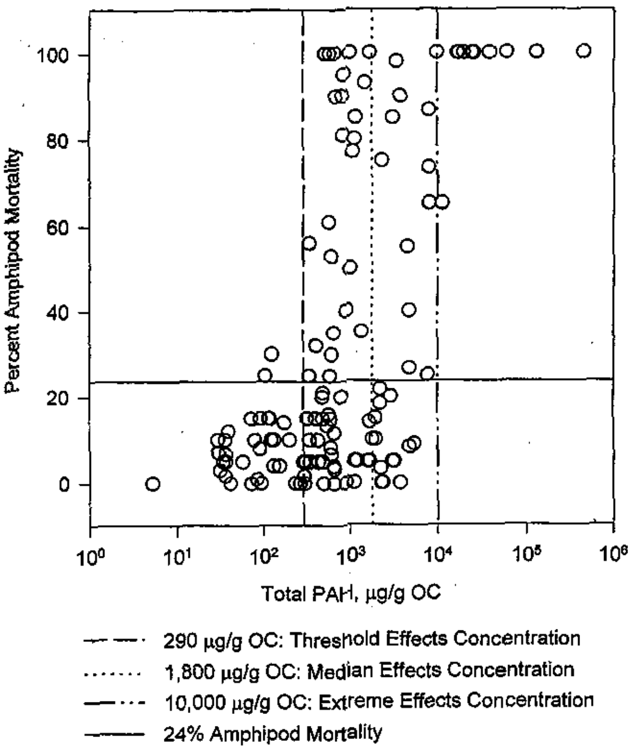

Fig. 2. Amphipod mortality in relation to total PAH concentration in 10-d sediment toxicity tests of sediment samples from sites of PAH contamination.

Sediments at relatively few sites exceed the consens TPAH guidelines. Among 678 EMAP samples that were co lected with a probabilistic sampling design from Long Islan Sound in 1989 through 1990, the Virginian Province in 199 through 1991, and the Louisianian Province in 1991, 45 (6.6% exceeded the TEC, 2 (0.3%) exceeded the MEC, and non exceeded the EEC (Fig. 3 and Table 4). The other major di ference between the EMAP data set and the PAH data set wa the much higher proportion of toxic sediments below the TE among EMAP samples (13%) than among PAH sample (5.6%) (Table 4). The increase in the frequency of toxicity low PAH concentrations among the EMAP samples is probabl attributable to other stressors. Above the TEC, the frequenc of toxicity and the mean percent amphipod mortality are quit similar for the EMAP and PAH data sets, as would be expecte if the consensus TPAH guidelines are valid indicators of PA effects (Table 4). Finally, the TEC was exceeded in 20 of th 104 toxic sediments in the entire EMAP data set suggestin that PAHs alone could cause approximately 20% of the ambient sediment toxicity in the EMAP provinces.

Benthic community structure

Areal species richness of crustaceans and molluscs decreased as the consensus SQGs were exceeded in San Dieg Bay (Fig. 4) and Elliott Bay (Fig. 5). In San Diego Bay, th mean number of species per 0.025 m² decreased from 10.5 a sites with sediment TPAH concentrations below the TEC t 6.8 at sites with sediment TPAH between the TEC and ME (Table 4). Sediment TPAH contamination and benthic community impacts were greater in Elliott Bay where the numbe of species per 0.015 m² decreased from 12.4 between the TEC and MEC, to 9.6 between the MEC and EEC, to 3.9 at sites with TPAH concentration above the EEC (Table 4). Only one or two crustacean and mollusc species occurred in the benthic

Table 4. Sediment toxicity and benthic community structure in relation to consensus sediment quality guidelines

	Total PAH concentration (µg/g organic carbon [OC])			
	<290	290–1,800	1,800–10,000	>10,000
Sediment guideline[a]	<TEC	>TEC <MEC	>MEC <EEC	>EEC
PAH-contaminated sites				
n (%) toxic[b] samples	2 (5.6%)	26 (43%)	12 (50%)	12 (100%)
n (%) nontoxic[c] samples	34 (94%)	34 (57%)	12 (50%)	0 (0%)
Mean % amphipod mortality	7.6	34.1	38.3	97.1
EMAP sites				
n (%) toxic[b] samples	84 (13%)	19 (44%)	1 (50%)	ND[d]
n (%) nontoxic[c] samples	549 (87%)	24 (56%)	1 (50%)	
Mean % amphipod mortality	11.2%	28.3%	40%	
Crustacean and mollusc species				
San Diego Bay, California, USA				
Species/0.025 m²: Mean	10.5	6.8	ND	ND
Range	9–12	4–11		
Elliott Bay, Washington, USA				
Species/0.015 m²: Mean	ND	12.4	9.6	3.9
Range		10–17	1–16	1–7

[a] TEC = threshold effects concentration, 290 µg/g OC; MEC = median effects concentration, 1,800 µg/g OC; EEC = extreme effects concentration, 10,000 µg/g OC.

[b] Amphipod mortality > 24%.

[c] Amphipod mortality < 24%.

[d] ND = no data.

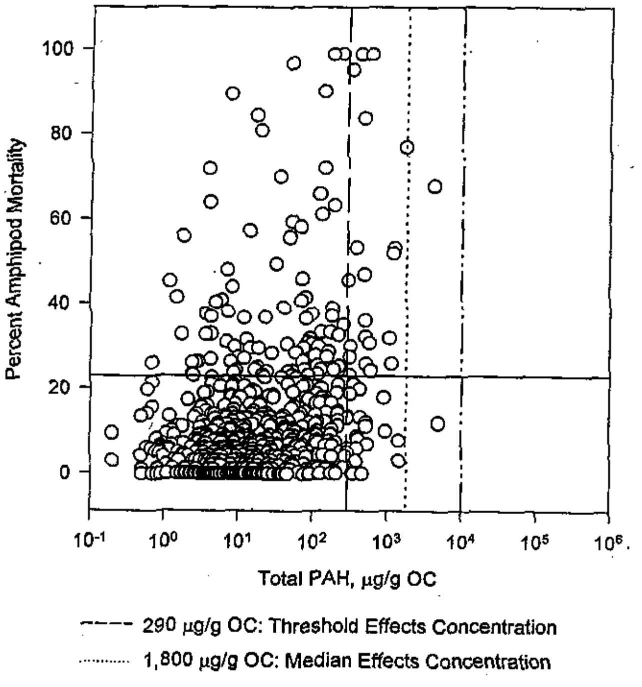

Fig. 3. Amphipod mortality in relation to total PAH concentration in 10-d sediment toxicity tests of Environmental Monitoring and Assessment Program (EMAP) sediment samples from the Virginian and Louisianian provinces, USA.

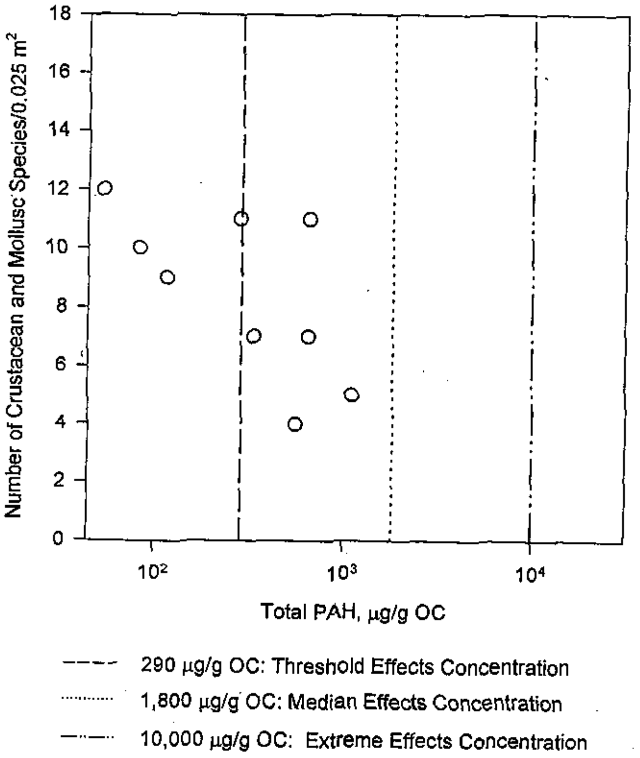

Fig. 4. Areal species richness of crustaceans and molluscs in relation to total PAH concentration in San Diego Bay, California, USA.

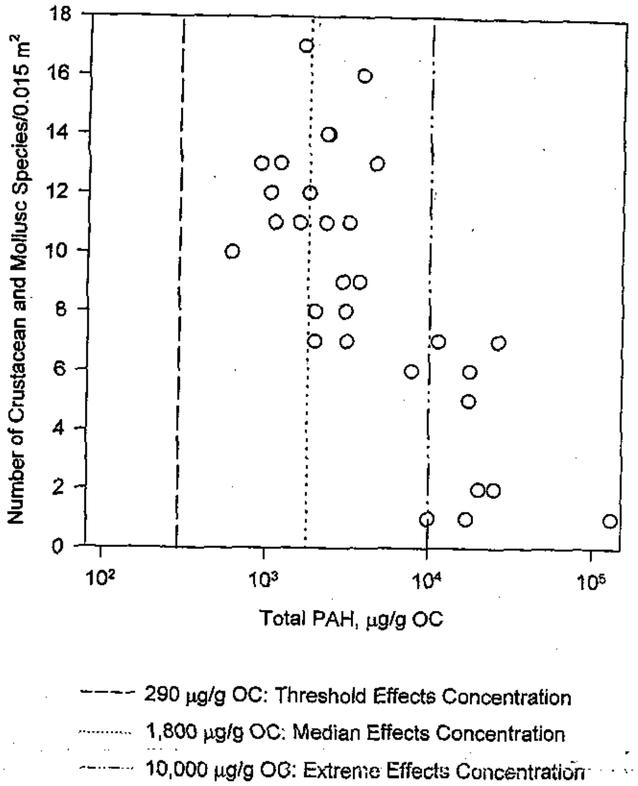

Fig. 5. Areal species richness of crustaceans and molluscs in relation to total PAH concentration in Elliott Bay, Washington, USA.

assemblage at five sites in Elliott Bay that were highly contaminated by PAHs.

DISCUSSION

Consensus guidelines

The TEC/MEC/EEC sediment quality guidelines for PAH mixtures provide a unifying synthesis of other guidelines including the SLC, ERL/ERM, EqP criteria, AET, ΣPAH, and TEL/PEL. When interpreted in the context of PAH mixtures, all of these guidelines arrive at similar concentrations for threshold, median, or extreme effects (Table 3). This similarity is unlikely to be coincidental. Rather, the agreement of guidelines derived from a diversity of theoretical and empirical approaches helps establish the validity of the consensus values. Their validity is further established by the ability of the consensus guidelines to predict sediment toxicity and benthic community perturbations at sites of PAH contamination (Table 4 and Figs. 2, 4, and 5). Expression of these guidelines for TPAH, rather than individual compounds, resolves the mixture paradox, that is, they account for mixtures and reflect causal rather than correlative effects.

Effective use of SQGs

Guidelines should guide, not dictate. The TEC offers the most useful SQG because it is reasonable to conclude that PAH mixtures are unlikely to cause adverse effects on benthic ecosystems below the TEC. The EEC indicates virtual certainty of adverse effects, but the EEC is rarely exceeded and contamination is so extreme above the EEC that the unacceptability of ecological degradation is usually obvious. The region of greatest uncertainty lies between the TEC and EEC. Here,

a broad gradient of sediment contamination occurs along which effects are increasingly more probable. The MEC is simply a point near the middle of this gradient and, therefore, should not be used to discriminate acceptable from unacceptable conditions.

Bulk sediment chemistry cannot resolve the uncertainty of toxicity and ecological effects at TPAH concentrations between the TEC and EEC. However, the issue can be resolved through independent, empirical data on sediment toxicity and benthic communities, as suggested by Long and Chapman [35] in their seminal paper on the sediment quality triad. Conclusions about the ecological effects of sediment contamination should be based on the weight of evidence among the three elements of the triad [36].

Uncertainty

Four principal sources of uncertainty exist about the consensus guidelines. First, the guidelines are based on the concentrations of the 13 parent PAHs and do not include alkylated and other PAH compounds that may contribute to biological effects. The degree to which the distribution of the 13 parent compounds is representative of the distribution of other PAHs is unknown. Second, the laboratory toxicity tests used to develop some of the guidelines from which the consensus values were derived are not sensitive to increased toxicity caused by photoactivation of PAH compounds [31,37]. Thus, effects of PAHs may be greater than expected from the guidelines, although the guidelines do correlate with the species richness of benthic assemblages exposed to ambient light (Figs. 4 and 5). Third, chemical analyses of bulk sediments may greatly overestimate bioavailability in sediments that contain inert (e.g., soot) PAH fractions [38]. In such cases, the consensus guidelines will overestimate toxicity and ecological effects caused by PAHs. Analysis of PAH concentrations in interstitial water can resolve the bioavailability issue when an inert PAH fraction is suspected. Each of these first three sources of error probably contributes to the uncertainty of effects over the broad concentration range between the TEC and EEC. Finally, additional field data, especially for benthic assemblages and other ecological indicators, are needed to validate the consensus guidelines.

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