APPENDIX C: DEFINING INJURIES TO NATURAL RESOURCES IN THE LOWER DUWAMISH RIVER

(Adapted from Appendix D of March 14, 2002 Hylebos Waterway Natural Resource Damage Settlement Proposal Report)

Introduction

The Lower Duwamish River (LDR) Habitat Equivalency Analysis (HEA) evaluates and quantifies natural resource injuries in areas where surface sediments contain Substances of Concern (SOCs) at or above threshold concentrations defined for natural resource injury. The HEA also quantifies how much restoration is required to compensate for these injuries. This appendix describes how injuries are defined and how increasing concentrations of SOCs cause greater injury. It also explains how percent service loss is used in the injury calculations for estimating natural resource damages in the LDR.

Cacela *et al.* (2005) thoroughly discusses the concept of percent service loss. The focus in this appendix is on how service loss supports the HEA, what information is used to determine service loss and how service losses are estimated.[1] All of the processes and results described represent a means to establish groundwork for dialog for reaching NRDA settlements.

Associating Ecosystem Service Loss with Sediment Contamination

The concept of *service* is central to HEA. What is needed is a clear understanding of what service is being evaluated or modeled and how reductions in services are determined (Cacela *et al.,* 2005). Habitats typically provide many and varied types of ecological services (Strange *et al*, 2002) and promote a sustainable ecosystem through complex interactions among plants and animals and their habitat (Holmlund and Hammer, 1999). Examples of ecological services include providing places for shelter, feeding and resting for fish and birds. In addition, human use services include consumptive and non-consumptive uses such as fishing, nature photography, education, etc. Although some human use services are easy to evaluate, for example recreational beach use, others are not. It is difficult to connect services associated with human use with ecological services. Because of this, in the LDR HEA, only ecological services were used to estimate injury.

Ecological service is a term that may embrace several different structural or functional attributes of an ecosystem. In the context of HEA, ecological services are used as an exchange rate for determining how much habitat must be restored to compensate for harm to the environment. Injured and restored habitat is equated by comparing the services provided by each habitat. Although the injured and restored habitats may include human use services as well as ecological services, it is assumed that a focus on restoring ecological services will also support restoring human use services.

[1] Services (or natural resource services) mean the functions performed by a natural resource for the benefit of another natural resource and/or the public. Examples include ecological services such as provision of food, protection from predation, nesting habitat, as well as human services such as fishing, hunting, education, etc.

It is important to consider how an ecological service is lost, how much is lost, and how that loss can be represented. For the purposes of the LDR HEA, ecological services are considered lost when organisms are adversely affected by the presence of a specified concentration of an SOC. Adverse effects can be non-lethal, such as causing changes within the cells of an organism, or lethal (causing the death of the animal or plant). In terms of service losses, these effects would range from small to large. Death may impact the species' population, however it is very difficult to quantify effects at the population level. Consequently, we focus on effects to sample groups of organisms, individual organisms, and processes within an organism.

Organisms live on a finite energy budget. Because energy is limited, any stressor that occurs in addition to natural stressors (i.e., not human-caused) is detrimental to that organism. Organisms must redirect energy to counteract the effects of the stressor (Rowe *et al.,* 1998). Examples of energy redirection induced by stress include fighting any toxicity associated with the stressor and using additional energy to move to avoid unsuitable habitat (Cacela *et al.* 2005). Redirecting energy for these activities comes at the expense of other biological processes, such as growth, reproduction, and avoiding predation. If a particular habitat is more stressful than a reference site, it provides less service, meaning some portions of the habitat's services are lost. The lost portion of service is an injury. Because of the functional role that ecological services play in HEA, service reductions are expressed on a percentage basis. The ecological service index of a unit of habitat is reduced by a fractional amount that reflects the difference in habitat quality at the injured site relative to an uninjured reference location.

One way to evaluate service loss within a habitat is to identify the extent and types of injuries to resources using that habitat. This information is found in scientific literature; however, the breadth of information on injuries varies greatly between chemicals. Two examples of this are described for Hexachlorobenzene (HCB) and Polycyclic Aromatic Hydrocarbons (PAHs). Following the discussion of each of these SOCs is information about other SOCs that are handled in a similar manner.

HCB Injuries and the use of Apparent Effects Thresholds

The only data sets used to evaluate injuries from HCB and several other SOCs are benthic community analyses and bioassay information from the State of Washington's Sediment Management Standards (SMS, Chapter 173-204 WAC, revised 12/95). The State of Washington Department of Ecology maintains a database that determines the apparent effects of particular contaminants to specific organisms. These effects are listed in the Apparent Effects Thresholds[2] (AETs) and are associated with invertebrate bioassays and benthic community data. There are seven AETs considered in this appendix. Five AETs address invertebrate groups and two address the benthic community (Table C1). These include a benthic community analysis and bioassay results for an echinoderm, Microtox™, amphipod, *Neanthes* (*polychaete worm*), "bivalve", and oyster. The bivalve AET is used only when oyster data are not available, because the oyster AET has been more extensively reviewed.

The lowest AET establishes Marine Sediment Quality Standards (MSQS) for Puget Sound that "correspond to a sediment quality that will result in no adverse effects on biological resources…".

[2] An Apparent Effects Threshold is defined as the concentration of a single chemical (or chemical class) in sediments above which a particular biological effect has always been observed in a particular biological test.

Table C 1. Apparent Effects Thresholds (AETs) for a variety of substances of concern. These AETs are derived from data used to promulgate State of Washington (Marine) Sediment Management Standards. All concentrations are expressed at dry weight values.

SUBSTANCES OF CONCERN	***Amphipod Bioassay*** **[1994]**	***Benthic Community Analysis*** **[PSEP, 1988]**	***Bivalve Bioassay [1994]***
Metals (mg/kg or ppm)			
Arsenic	450	57	35
Cadmium	14	5.1	3.6
Chromium	>1,100	260	63.5
Copper	1,300	530	298
Lead	1,200	450	336
Mercury	2.3	2.1	1.7
Silver	6.1	>6.1	3.0
Tributyltin	>180	na	na
Zinc	3,800	410	839
Nonionizable organic compounds (ug/kg or ppb)			
Total LPAHs	29,000	13,000	3,825
2-Methylnaphthalene	1,900	1,400	120
Acenaphthene	2,000	730	660
Acenaphthylene	1,300	1,300	150
Anthracene	13,000	4,400	1,500
Fluorene	3,600	1,000	500
Naphthalene	2,400	2,700	180
Phenanthrene	21,000	5,400	2,000
High molecular weight PAHs (ug/kg or ppb)			
Total HPAHs	69,000	69,000	13,080
Benz[a]anthracene	5,100	5,100	1,100
Benzo[a]pyrene	3,500	3,600	1,000
Benzo[ghi]perylene	3,200	2,600	640
Total benzofluoranthenes	9,100	9,900	na
Chrysene	21,000	9,200	1,600
Dibenzo[a,h]anthracene	1,900	970	250
Fluoranthene	30,000	24,000	3,300
Indeno[1,2,3-cd]pyrene	4,400	2,600	590

SUBSTANCES OF CONCERN	***Amphipod Bioassay*** **[1994]**	***Benthic Community Analysis*** **[PSEP, 1988]**	***Bivalve Bioassay*** ***[1994]***
Pyrene	16,000	16,000	4,100
Chlorinated organic compounds (ug/kg or ppb)			
1,2,4-Trichlorobenzene	51	na	10
1,2-Dichlorobenzene	>110	50	6
1,4-Dichlorobenzene	120	110	97
Hexachlorobenzene	130	22	6

For our analyses, the MSQS for HCB is defined as our threshold for injury (22 parts per billion (ppb)). Within the State's database, all tested sediment samples containing more than 22 ppb of HCB show an adverse effect on benthic communities. This means that *all* analyses indicate a significant reduction in invertebrate population abundance and/or species diversity when compared to a reference location. The initial injury level is defined as relatively insignificant and is estimated as 5% of the ecological service value for any form of marine habitat.[3] In situations where contamination exceeds the threshold level, more AETs are exceeded, resulting in greater injury and greater service loss. We chose three additional injury levels for HCB (and other SOCs where only Washington SMS data are available): a 10% reduction in ecological service value or service loss when at least half of the AETs are exceeded, a 15% service loss when three-quarters of the AETs are exceeded, and a 20% service loss when all invertebrate AETs are exceeded. These additional injury levels are associated with HCB concentrations of 70, 130, and 230 ppb (Table C2).

A 20% service loss is the maximum injury level assigned to HCB because no data were available to indicate effects on biota other than invertebrates. Some may argue that assigning this level of service loss to marine sediments is too low if all tested invertebrate groups are adversely affected. This criticism results from several factors, such as:

[3] Habitats used in the LDR HEA include: marsh, intertidal areas (12 feet (ft) above to 4 ft below Mean Lower Low Water (MLLW); shallow subtidal areas (4 ft below to 14 ft below MLLW); and deep subtidal areas (depths more than 14 ft below MLLW).

- By definition, AETs reflect the *minimum* concentration at which an effect is observed in *ALL* tests. AETs are continually evolving; with associated concentrations usually moving higher simply because all you need to change the AET is to identify a test that shows no effect at that concentration.
- Marine AETs often measure mortality and frequently focus on a 10-day acute test. This usually does not reflect sublethal effects (effects that cause impairment but do not kill the organism). Hence, these AETs are a coarse measure of an organism's ability to survive in contaminated sediment.
- Some AETs only focus on the adult life stage, a period in the life cycle that is often less sensitive to chemical effects.
- None are life cycle tests that determine whether an animal can live, grow, reproduce and maintain their population.
- An invertebrate may ingest, but not metabolize chemicals. Though the invertebrate itself may not be injured, the 'body burden' of the contaminant may provide a source of contamination to predators that eat them, causing impacts to higher level organisms in the food web. For example, a fish may experience injury at a lower concentration than an invertebrate AET (see PCBs).

Although no information is available on HCB effects on animal groups other than invertebrates, mortality to invertebrates and diminished benthic community abundance or diversity should adversely impact higher -level organisms. This would result from diminished quantity or quality of food, requiring animals to expend greater amounts of their limited energy budget to find alternate food resources.

Table C 2. Concentrations of chlorobenzenes estimated to cause injuries to natural resources in Duwamish Waterway, based on Washington State SQS and AET values, expressed in dry weight.

SOC	BIOASSAY	CONCENTRATION		INJURY
Hexachlorobenzene (HCB)				
	"Bivalve" AET	6		(Not used)[1]
	Echinoderm AET	--		
	Benthic Community	22	←	5% Service Loss
	Microtox AET	70	←	10% Service Loss
	Amphipod AET	130	←	15% Service Loss
	Neanthes AET	>120		
	Oyster AET	230	←	20% Service Loss

SOC	BIOASSAY	CONCENTRATION		INJURY
1,2-dichlorobenzene (oDCB)				
	"Bivalve" AET	6		(Not used)[1]
	Echinoderm AET	na		
	Neanthes AET	na		
	Microtox AET	35	←	5% Service Loss
	Benthic Community	50		
	Oyster AET	50	←	20% Service Loss
	Amphipod AET	>110		
1,4-dichlorobenzene (pDCB)				
	"Bivalve" AET	97		(Not used)[1]
	Benthic Community	110	←	10% Service Loss
	Microtox AET	110		
	Echinoderm AET	--		
	Oyster AET	120	←	20% Service Loss
	Neanthes AET	--		
	Amphipod AET	120		
1,2,4-trichlorobenzene (TCB)				
	Echinoderm AET	>4.8		
	"Bivalve" AET	10		(Not used)[1]
	Benthic Community	--		
	Microtox AET	31	←	5% Service Loss
	Amphipod AET	51	←	10% Service Loss
	Oyster AET	64	←	20% Service Loss
	Neanthes AET	--		

[1] The "bivalve" bioassay AET is not used if values are present for the more-accepted Oyster bioassay.

Although there are arguments to suggest a 20% Service Loss is either insufficient or too excessive, based on current information the service losses assigned to invertebrate bioassay data represent an appropriate level without overstating injury.

Injuries for Other SOCs Based Solely on Washington SMS Information—

For several other SOCs only benthic and bioassay data is available from the Washington Department of Ecology. In most instances, *four or more AETs* are present in our analytical database. In those cases, service loss is established in a manner identical to that used for HCB. SOCs in this category include:

Metals	Phenols	Phthalates	Other SOCs
Arsenic	4-methyl phenol	Butylbenzyl phthalate	Hexachlorobutadiene
Cadmium	2,4-dimethyl phenol		
Copper			
Lead			
Mercury			
Silver			
Zinc			

In some instances fewer than four AETs are available, and we identify service loss per SOC based on the following method: *when only three AETs* are available, the lowest concentration is identified as a 5% Service Loss, the second lowest is defined as a 10% Service Loss, and the third is defined as 20% Service Loss (all available AETs are exceeded). For Di-n-butyl phthalate, all three AETs have the same concentration: 1,400 ppb dw. In this instance, only one service loss level (20%) is assigned (Table C5). SOCs in this category include:

Metals	Phenols	Phthalates	Other SOCs
Chromium	Phenol	bis (2-ethylhexyl) phthalate	1,2,4-trichlorobenzene
		Dimethylphthalate	
		Di-n-butyl phthalate	

When *only two AETs* are available, the lowest is identified as a 5% Service Loss, and the highest as a 20% Service Loss. SOCs in this category include the following

Metals	Chlorobenzenes	Phthalates	Other SOCs
None	1,2-dichlorobenzene	Di-n-octyl phthalate	none
	1,4-dichlorobenzene		

Service losses associated with various concentrations of metals are presented in Table C3, and service losses associated with concentrations of phenols, phthalates, and Hexachlorobutadiene are presented in Tables C4, C5, and C6, respectively.

Table C 3. Concentrations of metals estimated to cause injuries to natural resources in Duwamish Waterway, based on State of Washington Sediment Quality Standards and AET values, expressed in parts per million dry weight.

SOC	BIOASSAY	CONCENTRATION (ppm)	INJURY
Arsenic (As)			
	"Bivalve" AET	35	(Not used)[1]
	Benthic Community	57	5% Service Loss
	Neanthes AET	63	
	Echinoderm AET	130	10% Service Loss
	Amphipod AET	450	15% Service Loss
	Microtox AET	700	
	Oyster AET	700	20% Service Loss
Cadmium (Cd)			
	"Bivalve" AET	3.6	(Not used)[1]
	Echinoderm AET	2.7	5% Service Loss
	Neanthes AET	3.0	
	Benthic Community	5.1	10% Service Loss
	Microtox AET	9.6	
	Oyster AET	9.6	15% Service Loss
	Amphipod AET	14	20% Service Loss
Chromium (Cr)			
	"Bivalve" AET	63.5	5% Service Loss
	Neanthes AET	94	10% Service Loss
	Microtox AET	--	
	Echinoderm AET	>96	
	Benthic Community	260	20% Service Loss
	Oyster AET	--	
	Amphipod AET	>110	
Copper (Cu)			
	Neanthes AET	270	5% Service Loss
	"Bivalve" AET	298	(Not used)[1]
	Oyster AET	390	
	Echinoderm AET	390	10% Service Loss
	Microtox AET	390	

SOC	BIOASSAY	CONCENTRATION (ppm)		INJURY
	Benthic Community	530	←	15% Service Loss
	Amphipod AET	1,300	←	20% Service Loss
Lead (Pb)				
	"Bivalve" AET	336		(Not used)[1]
	Neanthes AET	360	←	5% Service Loss
	Echinoderm AET	430		
	Benthic Community	450	←	10% Service Loss
	Microtox AET	530	←	15% Service Loss
	Oyster AET	660		
	Amphipod AET	1,200	←	20% Service Loss
Mercury (Hg)				
	Microtox AET	0.41	←	5% Service Loss
	Oyster AET	0.59		
	Neanthes AET	1.3	←	10% Service Loss
	Echinoderm AET	1.4	←	15% Service Loss
	"Bivalve" AET	1.7		(Not used)[1]
	Benthic Community	2.1		
	Amphipod AET	2.3	←	20% Service Loss
Silver (Ag)				
	"Bivalve" AET	3.0	←	5% Service Loss
	Microtox AET	>0.56		
	Oyster AET	>0.56		
	Neanthes AET	3.3	←	10% Service Loss
	Amphipod AET	6.1	←	15% Service Loss
	Benthic Community	>6.1		
	Echinoderm AET	8.4	←	20% Service Loss
Zinc (Zn)				
	Benthic Community	410	←	5% Service Loss
	Echinoderm AET	460		
	Neanthes AET	530	←	10% Service Loss
	"Bivalve" AET	839		(Not used)[1]
	Microtox AET	1,600	←	15% Service Loss
	Oyster AET	1,600		
	Amphipod AET	3,800		20% Service Loss

[1] The "bivalve" bioassay AET is not used if values are present for the more-accepted Oyster bioassay.

Table C 4. Concentrations of phenols estimated to cause injuries to natural resources in Duwamish Waterway Injuries are based on State of Washington Sediment Quality Standards and AET values, expressed in parts per billion dry weight.

SOC	BIOASSAY	CONCENTRATION (ppb)		INJURY
4-methyl phenol (MP4)				
	"Bivalve" AET	100		(Not used)[1]
	Echinoderm AET	110	←	5% Service Loss
	Oyster AET	670		
	Microtox AET	670	←	10% Service Loss
	Neanthes AET	880		
	Benthic Community	1,800	←	15% Service Loss
	Amphipod AET	3,600	←	20% Service Loss
2,4-dimethyl phenol (DMP)				
	"Bivalve" AET	--		(Not used)[1]
	Oyster AET	29	←	5% Service Loss
	Microtox AET	29		
	Echinoderm AET	55	←	10% Service Loss
	Neanthes AET	--		
	Amphipod AET	77	←	15% Service Loss
	Benthic Community	210	←	20% Service Loss
Phenol				
	"Bivalve" AET	160		(Not used)[1]
	Neanthes AET	180	←	5% Service Loss
	Echinoderm AET	>220		
	Oyster AET	420	←	10% Service Loss
	Microtox AET	1,200		
	Amphipod AET	1,200		
	Benthic Community	1,200	←	20% Service Loss

[1] The "bivalve" bioassay AET is not used if values are present for the more-accepted Oyster bioassay.

Table C 5. Concentrations of phthalates estimated to cause injuries to natural resources in Duwamish Waterway. Injuries are based on State of Washington Sediment Quality Standards and AET values, expressed in parts per billion dry weight.

SOC	BIOASSAY	CONCENTRATION (ppb)		INJURY
bis [2-Ethylhexyl] phthalate (bEPH)				
	Benthic Community	1,300	←	5% Service Loss
	Echinoderm AET	1,700		
	Microtox AET	1,900	←	10% Service Loss
	Oyster AET	1,900		
	Neanthes AET	2,000	←	20% Service Loss
	"Bivalve" AET	2,200		(Not used)[1]
	Amphipod AET	>8,300		
Butylbenzyl phthalate (BBPH)				
	Microtox AET	63	←	5% Service Loss
	"Bivalve" AET	100		
	Echinoderm AET	200	←	10% Service Loss
	Oyster AET	>470		
	Neanthes AET	>580		
	Benthic Community	900	←	15% Service Loss
	Amphipod AET	970	←	20% Service Loss
Di-n-butyl-phthalate (DnBPH)				
	"Bivalve" AET	58		(Not used)[1]
	Microtox AET	1,400	←	20% Service Loss
	Neanthes AET	na		
	Echinoderm AET	>31		
	Oyster AET	1,400		
	Amphipod AET	1,400		
	Benthic Community	>5,100		
Di-n-octyl phthalate (DOPH)				
	"Bivalve" AET	61	←	5% Service Loss
	Microtox AET	na		
	Neanthes AET	na		
	Echinoderm AET	>98		
	Oyster AET	>420		

SOC	BIOASSAY	CONCENTRATION (ppb)	INJURY
	Amphipod AET	>2,100	
	Benthic Community	6,200 ←	20% Service Loss
dimethylphthalate (DMPH)			
	"Bivalve" AET	6	(Not used)[1]
	Microtox AET	71 ←	5% Service Loss
	Echinoderm AET	85 ←	10% Service Loss
	Neanthes AET	--	
	Oyster AET	160 ←	20% Service Loss
	Benthic Community	>1,400	
	Amphipod AET	>1,400	

[1] The "bivalve" bioassay AET is not used if values are present for the more-accepted Oyster bioassay.

Table C 6. Concentrations of hexachlorobutadiene estimated to cause injuries to natural resources in the LDR. Injuries are based on State of Washington Sediment Quality Standards and AET values expressed in parts per billion dry weight.

SOC	BIOASSAY	CONCENTRATION (ppb)	INJURY
Hexachlorobutadiene (HCBD)			
	"Bivalve" AET	6	(Not used)[1]
	Benthic Community	11	5% Service Loss
	Microtox AET	120	10% Service Loss
	Amphipod AET	180	15% Service Loss
	Echinoderm AET	1.3 [2]	
	Oyster AET	270	20% Service Loss
	Neanthes AET	--	

[1] The "bivalve" bioassay AET is not used if values are present for the more-accepted Oyster bioassay.

[2] There is some question about the validity of this number; therefore, it was not used.

PAH Injuries to Vertebrates and Invertebrates

Information on injuries from PAH contamination is more extensive than that for HCB, including effects data for both invertebrates and fishes. Our analysis includes two types of information: biological effects of PAHs on English sole *Pleuronectes vetulu, and AET invertebrate data* from the Washington Sediment Management Standards database.

PAH effects on English Sole are compiled from studies performed by the NOAA Northwest Fisheries Science Center by Johnson et al. (2002). These studies use Total PAHs, a combination of numerous high and low molecular weight PAHs that are listed in Table C7. PAH AETs do not provide a total PAH concentration, only total high molecular weight PAHs (Total HPAHs) and total low molecular weight PAHs (Total LPAHs). The Total HPAHs concentrations are used in this report for effects comparisons between the flatfish and invertebrates. These concentrations are chosen because they represent higher AETs than for LPAHs, and consequently are considered not to overstate injuries.

Table C 7. Polycyclic aromatic hydrocarbons (PAHs) combined to represent Total PAHs in NOAA Northwest Fisheries Science Center studies of PAH effects on English Sole.

Low Molecular Weight PAHs	**High Molecular Weight PAHs**
2-Methylnaphthalene	Benz[a]anthracene
Acenaphthene	Benzo[a]pyrene
Acenaphthylene	Benzo[ghi]perylene
Anthracene	benzofluoranthenes (b+k)
Fluorene	Chrysene
Naphthalene	Dibenzo[a,h]anthracene
Phenanthrene	Fluoranthene
	Indeno[1,2,3-cd]pyrene
	Pyrene

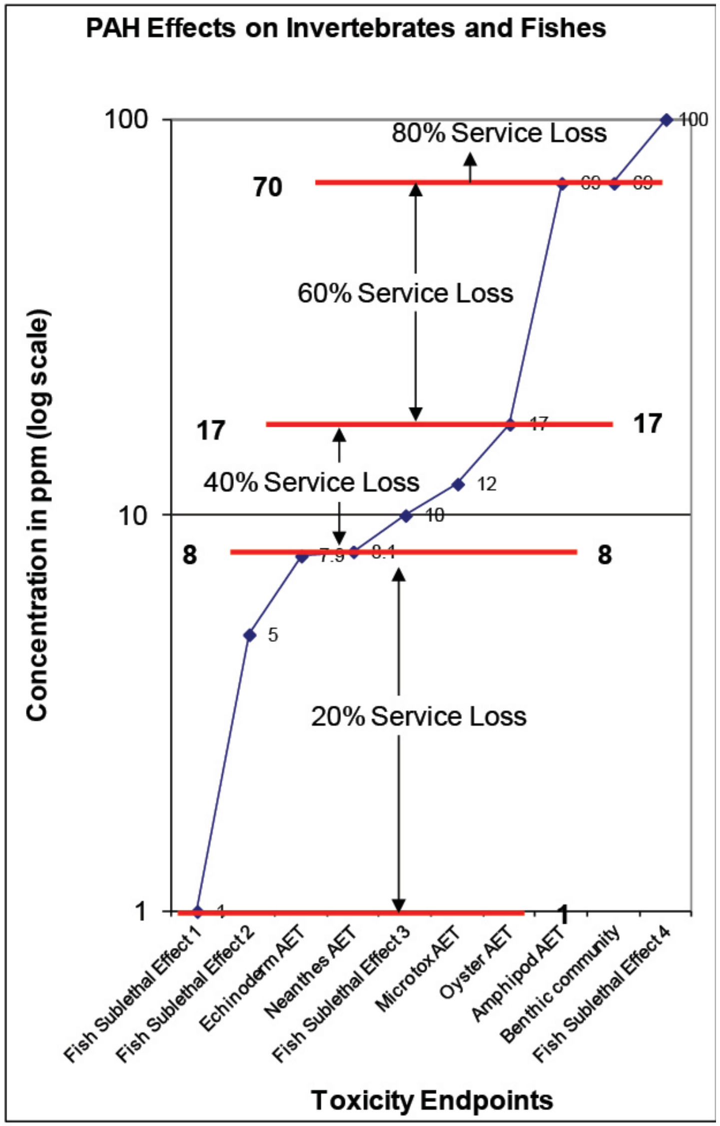
English sole continues to be one of the most extensively studied fish species in pollution monitoring research. Because it is a shallow-water bottom-dwelling flatfish and occurs in urban and non-urban environments along the Pacific Coast of North America, it is particularly likely to take up contaminants in sediment, through direct contact with sediments and through its diet. Since this species is relatively sedentary and spends most of its life in a small area, biological effects in English sole are an accurate reflection of PAH exposure at sites where they are collected. Numerous studies show that English sole from PAH-contaminated areas are highly susceptible to the development of liver cancer and related lesions, and are prone to several other adverse health effects, such as reproductive abnormalities, immune dysfunction, and alterations in growth and development (Myers *et al.* 1994, 1998; Arkoosh *et al.* 1996; and Johnson *et al.* 1998).

Based on a review of the English sole studies and the State of Washington SMS information, the following can be stated about PAH injuries to natural resources. (All PAH concentrations mentioned refer to levels of sediment contamination):

- The first sign of reproductive effects of PAHs on English sole in Puget Sound occurs at about 1 ppm dry weight, and cancerous or pre-cancerous lesions are found fairly frequently. At that concentration, nearly 10% of English sole studied contain 1 or more of a variety of toxicopathic lesions in soft body tissue and nearly 5% of adult females are infertile when compared to female populations in relatively uncontaminated areas.
- By 5 ppm, the number of individuals with lesions has increased three-fold and female infertility has increased to 17% above baseline. By 7.9 ppm, invertebrates also begin to be affected (Table C1).
- By 10 ppm, over 40% of all English sole studied have one or more lesions, nearly 25% of adult females are infertile, and between 10 and 69 ppm, more than half of the invertebrate bioassays show adverse effects.
- By 100 ppm, over 70% of all English sole studied in Puget Sound have some form of toxicopathic lesions, and for adult females, over half have inhibited reproduction capability, over two-thirds do not participate in spawning, and more than three-quarters are infertile. All invertebrate AETs are exceeded.

Information in the previous paragraph describes a significant range of injuries to natural resources from exposure to PAHs in marine sediments. This suggests that a significant range of service losses is associated with these varied injuries. Initial impacts to vertebrates are reported by Johnson et al. (2002) to begin at sediment concentrations as low as 54 ppb, and the variety and extent of injuries to English sole increase markedly with rising PAH concentrations. While this information is from studies focusing on direct exposure to contaminated sediments, these fish indirectly suffer substantial additional exposure through ingestion of invertebrate prey residing in contaminated sediment (Rice *et al.* 1999). In turn, the prey is directly affected by sediment concentrations of PAHs, as low as 7.9 ppm.

To map PAH injuries and identify a range of service losses, impacts on English sole and invertebrate AETs are graphed against PAH concentrations in sediments (Figure C1). The PAH concentrations are represented on the y-axis in (base 10) logarithmic form to permit observing effects details at low concentrations as well as evaluate effects at very high concentrations on the same scale. A 20% threshold service loss is assigned at 1ppm dry weight, with a general grouping of additional flatfish injuries and an invertebrate AET between 1 ppm and 8.1 ppm. This initial service loss is much higher than that assigned for HCB (discussed previously) because it impacts other members of the biological community through the food web.



References	Toxicity Endpoint	Concentration ppm dw
4	Fish Sublethal Effect [1]	1
4	Fish Sublethal Effect [2]	5
1	Echinoderm AET	7.9
1	Neanthes AET	8.1
4	Fish Sublethal Effect [3]	10
1	Microtox AET	12
1	Oyster AET	17
1	Amphipod AET	69
1	Benthic community	69
4	Fish Sublethal Effect [4]	100

References
1 Washington Department of Ecology
4 Johnson et al. 2002

Flatfish Injuries	
Sublethal 1	initial effects on fecundity and occurrence of lesions in soft tissue
Sublethal 2	significant increases lesion occurrence (>30%) and reduced fecundity (>15%)
Sublethal 3	>40% of all individuals with lesions and fecundity reduced by ~25%
Sublethal 4	~75% occurrence of lesions and fecundity reduced by ~50%.

80% Service Loss >70 ppm dry weight	All tested invertebrates affected; flatfish injuries include ~50% reduction in fecundity and ~75% occurrence of at least one lesion/fish
60% Service Loss 17 to 70 ppm	All tested invertebrates affected.
40% Service Loss 8 to 17 ppm	One-half of tested invertebrates affected; significant injuries to flatfish include ~25% reduction in fecundity & 31% occurrence of lesions
20% Service Loss 1 to 8 ppm	Begin to see effects on invertebrates and fishes. Flatfish fecundity reduced by ~5% and up to 10% of all fish with some form of lesion.

Figure C1. Information used to determine injury threshold concentrations for total PAHs and their associated percent Service Losses.

A 40% service loss is assigned to the range of 8 to 17 ppm because both the extent of biological effects on fish and the number of invertebrate AETs that are exceeded at these concentrations. A 60% service loss is assigned to the range of 17 to 70 ppm because of continued substantial increases of biological effects and the incorporation of all invertebrate AETs. Finally, an 80% service loss is assigned to PAH sediment concentrations above 70 ppm.

Other SOCs Handled Similarly to PAHs

Injuries from polychlorinated biphenyls (PCBs), p,p'DDT, p,p'DDE, and p,p'DDD are evaluated in a similar manner. In addition to the Washington SMS data, numerous studies were reviewed for PCBs and the various DDT congeners (forms of DDT that result from the breakdown of the original chemical) (MacDonald 1994). Data from research on PCB effects on several salmonid species were also included (Meador et al. (2002b). As with PAHs, a graph of toxic endpoints and associated concentrations was developed for each SOC. Higher service losses are assigned at points on the graph where there is a notable increase in effect concentration.

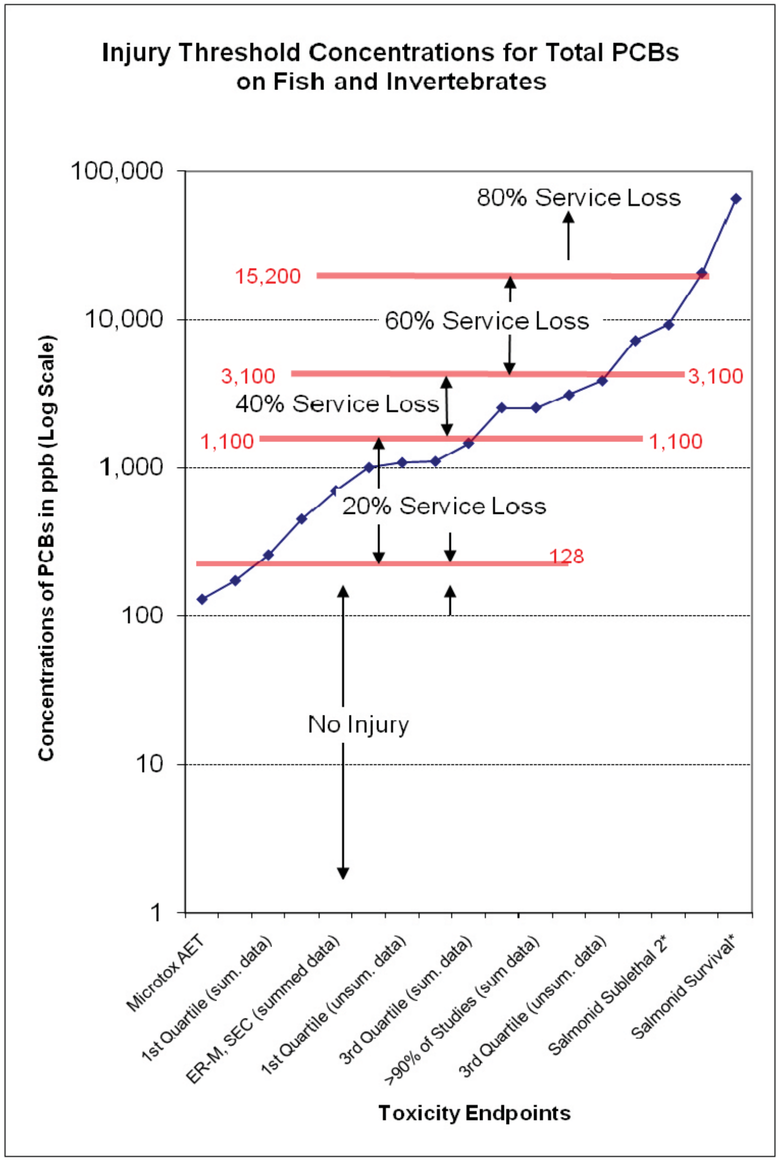
PCBs—The first threshold for PCBs in the LDR HEA was set by the "Sediment Effect Threshold" of "SET" described in Meador et al. (2002b). Since it represents a bioaccumulative effect, it is assigned a 20% service loss. The Trustees used a slightly different total organic carbon (TOC) value to derive the first PCB threshold than the TOC value used by Meador et al. The Trustees calculated an area-weighted average TOC value of 1.7%, based on a more comprehensive set of Duwamish sediment data. Meador et al. used 1.5%. The result is that where Meador et al shows a value of 113 ppb dry weight, the Trustees calculate 128 ppb dry weight. The value of 128 ppb dry weight corresponds to the Washington State Sediment Management Standards Lowest Apparent Effects Threshold, which is 130 ppb dry weight.

PCB injury thresholds are represented by 20-40-60-and 80% Service Losses for four concentration ranges of 128-1,100 ppb (20% Service Loss), 1,100-3,100 ppb (40% Service Loss), 3,100-15,200 ppb (60% Service Loss), and greater than 15,200 ppb (80% Service Loss (Figure C2).

DDT Congeners--DDTs are assigned 10-20-30-40% service losses. These SOCs are assigned a lower service loss range than PAHs and PCBs as most studies only describe injuries to invertebrates. A summary graph and table of service loss information for p,p' DDT is found in Figure C3. It identifies injury ranges as 12-34 ppb (10% Service Loss), 34-340 ppb (20% Service Loss), 340-1,500 ppb (30% Service Loss) and concentrations greater than 1,500 ppb (40% Service Loss).

Figure C4 summarizes toxic endpoint information for p,p' DDE. It identifies injury ranges as 9-65 ppb (10% Service Loss), 65-5,200 ppb (20% Service Loss), 5,200-16,300 ppb (30% Service Loss) and concentrations greater than 16,300 ppb (40% Service Loss).

Figure C5 summarizes toxic endpoint information for p,p' DDD. It identifies injury ranges as 16-70 ppb (10% Service Loss), 70-1,100 ppb (20% Service Loss), 1,100-2,600 ppb (30% Service Loss) and concentrations greater than 2,600 ppb (40% Service Loss).



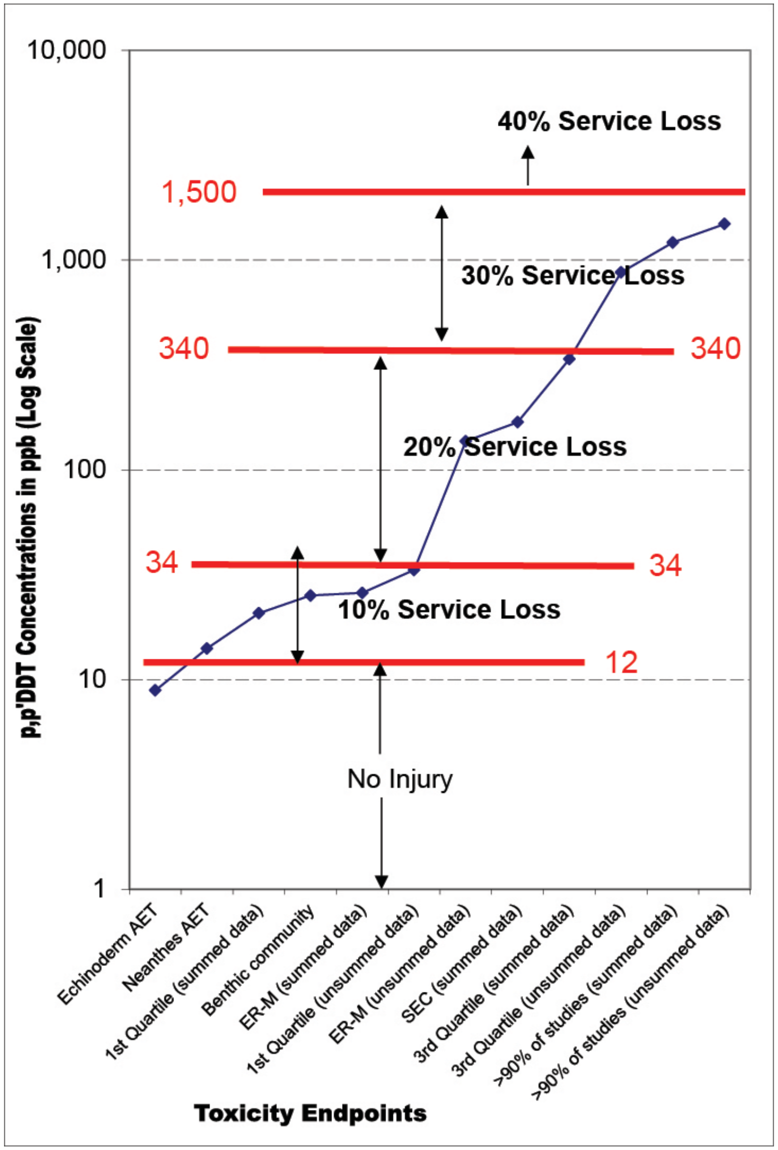
Reference	Toxicity Endpoint	Concentration ppb dw
1	Microtox AET	96
3	Chinook SEC1*	128
2	1st Quartile (sum. data)	191
1	Echinoderm AET	333
2	ER-M, SEC (summed data)	517
1	Benthic Community	739
2	1st Quartile (unsum. data)	798
1	Oyster AET	813
2	3rd Quartile (sum. data)	1,084
2	ER-M (unsum data)	1,870
2	>90% of Studies (sum data)	1,870
1	Amphipod AET	2,291
2	3rd Quartile (unsum. data)	2,856
2	>90% of Studies (unsum)	5,321
4	Salmonid Sublethal 2*	6,800
4	Salmonid Growth*	15,226
4	Salmonid Survival*	47,970

[1]--SEC = Sediments Effects Concentration
[2]--ER-M = Effects Range-Median
* concentrations based on 1.7% TOC

References
1 Washington Department of Ecology
2 MacDonald 1994
3 Meador et al. 2002 (b)
4 NOAA, 2001

80% Service Loss > 15.2 ppm dry weight	All tested invertebrates affected and salmonid growth and survival are affected
60% Service Loss 3.1 to 15.2 ppm	All invertebrates affected and sublethal effects on salmonids such as changes in immuno-suppression and P450 induction
40% Service Loss 1.1 to 3.1 ppm	Most tested invertebrates affected
20% Service Loss 0.128 to 1.1 ppm	First signs of cellular compromise in Chinook salmon; several invertebrates affected

Figure C2. Information used to determine injury threshold concentrations for total PCBs and their associated percent Service Losses.



Ref.	Toxicity Endpoint	Concentration (ppb dw)*
1	Echinoderm AET	9
1	Neanthes AET	14
3	1st Quartile (summed data)	21
1	Benthic community	25
3	ER-M (summed data)	26
3	1st Quartile (unsummed data)	33
3	ER-M (unsummed data)	137
3	SEC (summed data)	169
3	3rd Quartile (summed data)	337
3	3rd Quartile (unsummed data)	874
3	>90% of studies (summed data)	1,214
3	>90% of studies (unsummed data)	1,487

* Concentrations based on 1.7% TOC

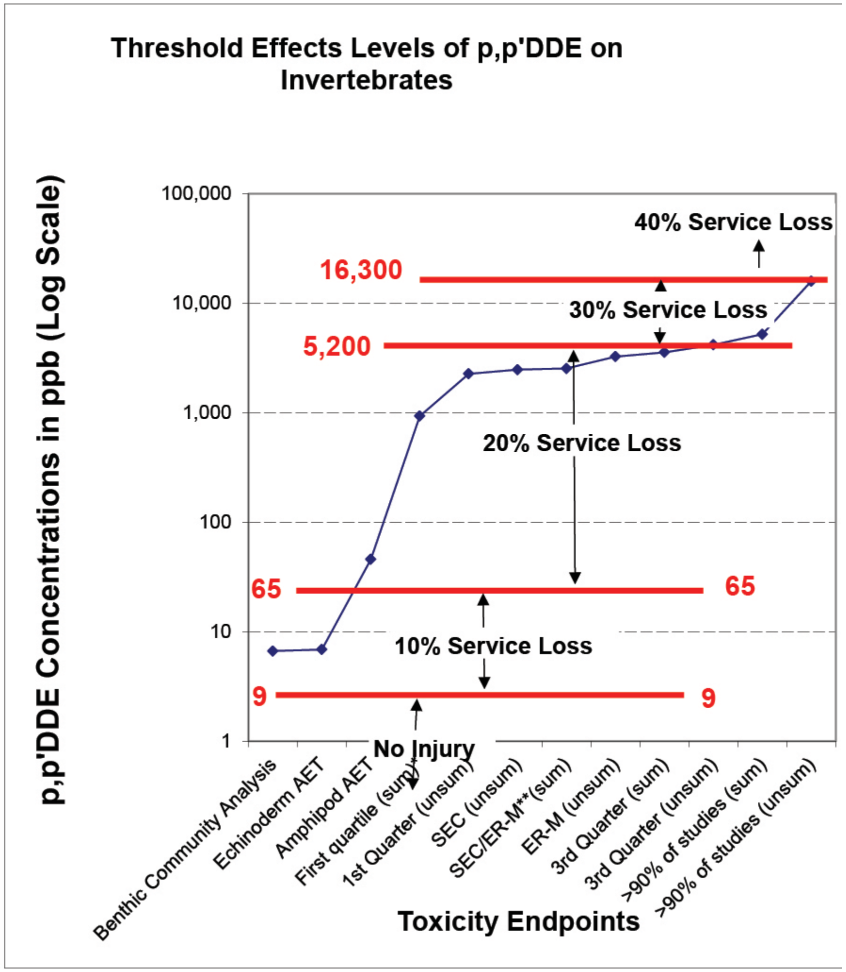
References

1 Washington Department of Ecology

3 MacDonald, 1994

40% Service Loss >1,500 ppb dw	All bioassays show effects.
30% Service Loss 340 to 1,500 ppb	Over 90% of studies reported by MacDonald 1994 show effects by this range.
20% Service Loss 34 to 340 ppb	All State of Washington AETs exceeded; Many studies reported by MacDonald 1994 report effects in this range
10% Service Loss 12 to 34 ppb	Initial level of adverse effects observed in State of Washington AETs.

Figure C3. Information used to determine injury threshold concentrations for p,p' DDT and their associated percent Service Losses.



Reference	Toxicity Endpoint	Concentration (ppb dw)
1	Benthic Community Analysis	7
1	Echinoderm AET	7
1	Amphipod AET	46
3	First quartile (sum)*	931
3	1st Quarter (unsum)	2,267
3	SEC (unsum)	2,473
3	SEC/ER-M**(sum)	2,531
3	ER-M (unsum)	3,254
3	3rd Quarter (sum)	3,554
3	3rd Quarter (unsum)	4,166
3	>90% of studies (sum)	5,196
3	>90% of studies (unsum)	15,899

* Concentrations for MacDonald (1994) data based on 1.7% TOC

** Effects Range-Median Sediment Effects Concentration

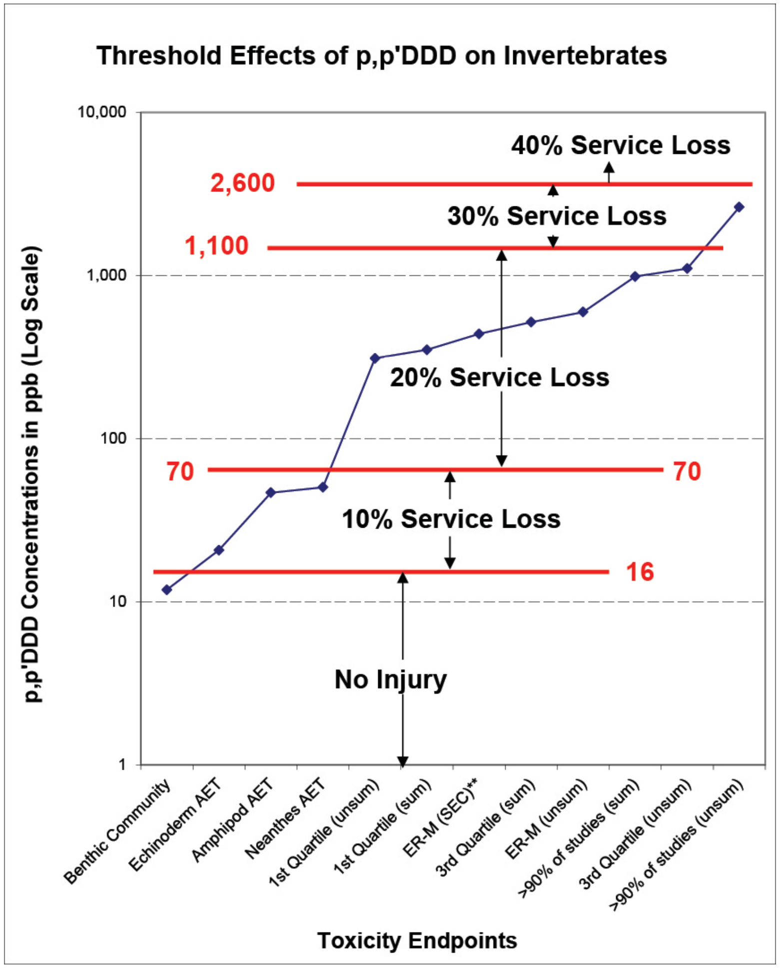
References

1 Washington Department of Ecology

3 MacDonald, 1994

40% Service Loss >16,300 ppb dw	All bioassays show effects.
30% Service Loss 5,200 to 16,300	Over 90% of studies examined by MacDonald 1994 show effects by this range.
20% Service Loss 65 to 5,200	All State of Washington AETs exceeded; Many studies reported by MacDonald 1994 report effects in this range.
10% Service Loss 9 to 65 ppb	Initial level of adverse effects observed in State of Washington AETs.

Figure C4. Information used to determine injury threshold concentrations for DDE and their associated percent Service Losses.



Reference	Toxicity Endpoint	Concentration (ppb dw)*
1	Benthic Community	12
1	Echinoderm AET	21
1	Amphipod AET	47
1	Neanthes AET	50
3	1st Quartile (unsum)	310
3	1st Quartile (sum)	350
3	ER-M (SEC)**	438
3	3rd Quartile (sum)	517
3	ER-M (unsum)	597
3	>90% of studies (sum)	986
3	3rd Quartile (unsum)	1,104
3	>90% of studies (unsum)	2,626

* Concentrations for MacDonald (1994) data based on 1.7% TOC

** Effects Range-Median Sediment Effects Concentration

References

1 Washington Department of Ecology

3 MacDonald, 1994

40% Service Loss >2,600 ppb dw	All bioassays show effects.
30% Service Loss 1,100 to 2,600 ppb	Over 90% of studies reported by MacDonald 1994 show effects by this range.
20% Service Loss 70 to 1,100 ppb	All State of Washington AETs exceeded; Many studies reported by MacDonald 1994 report effects in this range
10% Service Loss 16 to 70 ppb	Initial level of adverse effects observed in State of Washington AETs.

Figure C5. Information used to determine injury threshold concentrations for DDD and their associated percent Service Losses.

Tributyltin Service Losses—There is no MSQS associated with tributyltin (TBT), and more recent AET information is minimal. Consequently, we rely on information compiled from studies elsewhere and the analysis by Meador et al. (2002a) that supports a sediment quality threshold for TBT in Puget Sound to protect prey species for juvenile salmonids that are listed by the Endangered Species Act. In this document, he calculates an effects level of 6,000 ppb OC; a median concentration for all sublethal effects studies which is primarily growth impairment). With a calculated average TOC for the LDR of 1.7%, the previously stated carbon normalized number would translate to 102 ppb dry weight.

For specific studies, TBT concentrations associated with adverse effects range from 100 ppb to 1000 ppb dry weight. Meador (1997) indicates that 329 ppb is a concentration in a range needed to produce a lethal response for a sensitive invertebrate such as the amphipod, *Eohaustorius washingtonianus*. Bryan and Langston (1992), Langston and Burt (1991) and Meador et al. (2002a) have suggested that some populations of bivalves in United Kingdom waters have disappeared in locations with TBT sediment concentrations over 700 ppb. Fent and Hunn (1995) (from ibid) noted that clams have disappeared in other areas where sediment TBT exceeds 800 ppb. Lastly, Meador and Rice (2001) report severe reductions in growth of the polychaete, *Armandia brevis,* for sediment concentrations in the range of 100 to 1,000 ppb.

Based on the above TBT information, the threshold value for injuries from TBT is assigned at 102 ppb dry weight (Table C8). A 5% service loss is associated with this threshold value. A 20% service loss is assigned to concentrations greater than 1,000 ppb.

Table C 8. Concentrations of Tributyltin considered to cause injuries to natural resources in the LDR

SOC	BIOASSAY	Concentration in ppb	INJURY
Tributyltin (TBT)			
Tributyltin (TBT)	NMFS threshold[1]	102	5% Service Loss
	Bivalve abundance[2]	>800	
	Bivalve abundance[3]	>700	
	Polychaete growth[4]	1,000	20% Service Loss

[1] Meador et al.*(2002a*) proposes that a concentration of 6,000 ppb per gram Carbon would be protective for many, but not all prey species. For the average TOC for Duwamish stations, this would translate as 138 ppb DW (average TOC = 1.7%).

[2] Disappearance of clams in areas where TBT exceeded 800 ppb DW, reported by Fent and Hunn 1995.

[3] Populations of bivalves *Macoma balthica* and *Scrobicularia plana* have disappeared in locations with concentrations over 700 ppb--reported by Bryan and Langston (1992) and Langston and Burt (1991).

[4] Severe reductions in growth of *Armandia brevis* for sediment concentrations in the range of 100 - 1,000 ng/g (ppb), reported by Meador and Rice (2001).

Summary

This appendix assigns threshold sediment concentrations for injuries to natural resources from various SOCs. The ecological service losses assigned to each threshold and higher are based on the variety and extent of injuries caused by each SOC. If only invertebrate AET information is used to estimate injury thresholds, the maximum service loss value is determined to be 20%. If information from reports on injuries to fishes is incorporated into our analysis along with the AETs, both initial and maximum service losses are higher, with thresholds at 10-20% and maximum values up to 80%.

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