Sediment Quality in Puget Sound

Changes in chemical contaminants and invertebrate communities at 10 sentinel stations, 1989–2015

February 2018

Publication No. 18-03-005

DEPARTMENT OF ECOLOGY
State of Washington

Publication and contact information

This report is available on the Department of Ecology's website at
https://fortress.wa.gov/ecy/publications/SummaryPages/1803005.html

Data for this project are available at Ecology's Environmental Information Management (EIM) website https://fortress.wa.gov/ecy/eimreporting/.
Click on Marine Sediments Get Data and select Study ID: PSAMP_LT.

The Activity Tracker Code for this study is 01-900.

For more information contact:

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Phone: (360) 407-6764

Washington State Department of Ecology – https://ecology.wa.gov

Location of Ecology Office	Phone
Headquarters, Lacey	360-407-6000
Northwest Regional Office, Bellevue	425-649-7000
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Cover: Puget Sound Sediment Monitoring Program long-term stations.
Map by Sandra Weakland.

Sediment Quality in Puget Sound

Changes in chemical contaminants and invertebrate communities at 10 sentinel stations, 1989–2015

by

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Water Resource Inventory Area (WRIA) and 8-digit Hydrologic Unit Code (HUC) numbers for the study area:

WRIAs
- 1
- 7
- 9
- 10
- 13
- 15

HUC numbers
- 17110002
- 17110004
- 17110018
- 17110019

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Abstract

The sea floor sediment and the benthic (sediment-dwelling) organisms which live there are key components of the Puget Sound ecosystem. Among the ecological functions they serve are the processing, storage, and release of nutrients. Changes in the habitat and organisms can indicate responses of the ecosystem to stressors. Therefore, it is important to know not only current conditions, but also changes over time.

Because benthic organisms are in constant contact with the sediments, and a very large proportion of them ingest sediment to obtain their food, they are a biological endpoint integrating any contamination in the sediments.

This report covers results from 27 years of sampling sediments and benthic invertebrates at 10 long-term stations throughout the greater Puget Sound area every year from 1989 through 2015. These 10 stations represent different habitat types and distinct benthic communities. Overall characteristics of, and trends in, the habitats, sediment chemical contaminants, and benthic invertebrate communities, as well as relationships between them, are presented. Results are placed in context with broader-scale bay and region sediment monitoring results.

Although there were significant increasing or decreasing trends in a few parameters at a few stations, the most common pattern was lack of monotonic (consistently increasing or consistently decreasing) temporal trends.

- Sediments and the invertebrate communities inhabiting them have largely remained stable over time.
- Profound changes in the invertebrate communities occurred at Sinclair Inlet between 2000 and 2001, and at Anderson Island in the late 1990s. More-gradual changes were found at several other stations.
- Little to no relationship was found between invertebrates and measured sediment contaminants.
- Sediment chemistry patterns were generally consistent with those observed at wider spatial scales.
- Changes in benthos seen at wider spatial scales were generally not found at the long-term stations.
- Even though species and abundances may vary considerably over time, in stable systems ecological functions are conserved.

Acknowledgements

The authors of this report thank the following people for their contributions to this study:

- Taxonomic consultants who identified the animals or confirmed taxonomic identifications, especially long-time contributors Jeff Cordell, Steve Hulsman, Gene Ruff, and Susan Weeks.
- Charlie Eaton, Bio-Marine Enterprises, owner and captain of *R/V Kittiwake*, and Tom Putnam and past deckhands.
- Student and citizen volunteers who contributed their time for the sheer love of the critters.
- Reviewers of the draft report, whose editing suggestions improved the report.
- Washington State Department of Ecology staff:
    - Former Marine Sediment Monitoring staff, especially long-time team members Kathy Welch and Ed Long
    - Washington Conservation Corps members who participated in all aspects of the sediment monitoring program, especially Clifton Hermann, Brooke McIntyre, Mattie Michalek, and Nicole Marks
    - Analytical, administrative, and QA staff of the Manchester Environmental Laboratory
    - Current and past Operations Center managers and staff, especially Bernie Strong, Brian Pickering, Tim Zornes, and Tyler Buntain
    - Skippers of *R/V Skookum*: Keith Seiders, Dale Norton, Dave Serdar, Randy Coots
    - Administrative staff of the Environmental Assessment Program who assisted in purchasing and field logistics
    - Members of the Environmental Assessment Program and other Ecology programs who assisted in field sampling

Introduction

The sea floor sediment and the organisms which live there are key components of the Puget Sound ecosystem. Changes in the habitat and organisms can indicate responses of the ecosystem to stressors. Therefore, it is important to know not only current conditions, but also changes over time.

Puget Sound Marine Sediment Monitoring

The Washington State Department of Ecology (Ecology) has been monitoring sediment conditions in the greater Puget Sound area[1] since 1989 as part of the Puget Sound Ecosystem Monitoring Program (PSEMP).[2] There have been two primary thrusts: annual sampling of fixed stations to provide information on temporal trends and rotational sampling of bays and regions of Puget Sound with many random stations to provide information on spatial trends.

Ten sentinel stations for continued long-term monitoring were selected in 1997 from over 70 original PSAMP sediment monitoring stations. The particular stations were chosen because of their proximity to both PSAMP Fish and PSAMP Water Column monitoring stations, as well as to maintain the sampling effort at two stations where long-term benthic invertebrate data had been collected since the 1960s and to represent diverse habitat and benthic community types over a wide geographic area (Dutch et al., 2009, Appendix B).

The regional monitoring program began with 300 stations sampled throughout Puget Sound during 1997-1999 as a joint Ecology and National Oceanic and Atmospheric Administration (NOAA) effort and expanded to a rotating regional probabilistic design, sampling an additional 449 stations over 2002-2014. The 300 PSAMP/NOAA samples plus 81 samples taken in 2002-2003 from embayments of the San Juan Islands, eastern Strait of Juan de Fuca, and Admiralty Inlet form the Puget Sound Baseline. From 2004 through 2014, eight geographic regions of Puget Sound were resampled, one region each year, to form the Second Round survey.

This report summarizes results from 1989 through 2015-2016 at the 10 long-term stations. A companion report (Weakland et al., 2018) summarizes regional- and Sound-scale results from the 1997-2003 Baseline and 2004-2014 Second Round spatial surveys. Each report provides context for the other.

The 10 long-term stations which are the subject of this report (Figure 1, Table 1) have been sampled every year since 1989 for benthic invertebrates, as well as sediment grain size and organic carbon content (Table 2). Chemical contaminants in surface sediments (top 2-3 cm) were measured every year 1989-1996 and about every 5th year since then, an interval sufficient for detecting changes.

[1] Puget Sound proper, plus the embayments of the Strait of Georgia, Strait of Juan de Fuca, and San Juan Islands, collectively called "Puget Sound" for this report.

[2] Originally called the Puget Sound Ambient Monitoring Program (PSAMP).

Key Ecosystem Component

The sediment and benthic (sediment-dwelling) organisms serve key functions, including processing, storage, and release of nutrients needed by other components of the ecosystem. Benthic invertebrates are near the base of the food web that culminates in higher organisms such as salmon, orcas, and humans. Common benthic invertebrates include polychaetes (marine worms), bivalves (clams), and shrimp-like crustaceans.

Because benthic organisms are in constant contact with the sediments, and a very large proportion of them ingest sediment to obtain their food, they are a biological endpoint integrating any contamination in the sediments.

Waterbody depth, sediment grain size, and amount of organic material in the sediment influence the invertebrate community in multiple ways.

- Although many species inhabit a wide range of depths[3], many others are limited to specific or narrow depth ranges.
- Sediment grain size is a limiting factor for feeding, tube-building, and other aspects of life in or on the seafloor.
- The amount of organic carbon in the sediment is related to the processing, burial, or release of nutrients and energy in the ecosystem.
- Both organic matter and chemical contaminants tend to adhere to fine sediments, primarily clay and silt. Therefore, bioavailability of pollutants is partly related to total organic carbon (TOC) and grain size.

Stations

Some of the stations are located in shallow waters close to human development and use, while others are more removed. The Port Gardner, Sinclair Inlet, Thea Foss Waterway, and Inner Budd Inlet stations are close to the heavily industrialized areas of Everett, Bremerton, Tacoma, and Olympia, respectively, whereas the Strait of Georgia, North Hood Canal, and Anderson Island locations are rural. The Bellingham Bay station is located in the outer bay, thus is not as highly influenced by humans as the inner, northern portion of the bay that Ecology monitors as an urban bay.

The Strait of Georgia and central Puget Sound basin stations near Shilshole and Point Pully are 200 or more meters deep, with predominantly silt-clay sediments. The other stations are 25 or fewer meters deep, but represent a range of grain sizes (Table 3).

[3] Puget Sound has higher benthic invertebrate diversity and abundance than many places in the world. So many of the organisms live in so many different habitats across the area that all of Puget Sound can be considered one large benthic community, with some sub-assemblages defined by depth and grain size (Ranasinghe et al., 2013). For simplicity in this report, we refer to the collections of species at these 10 long-term stations as distinct communities.

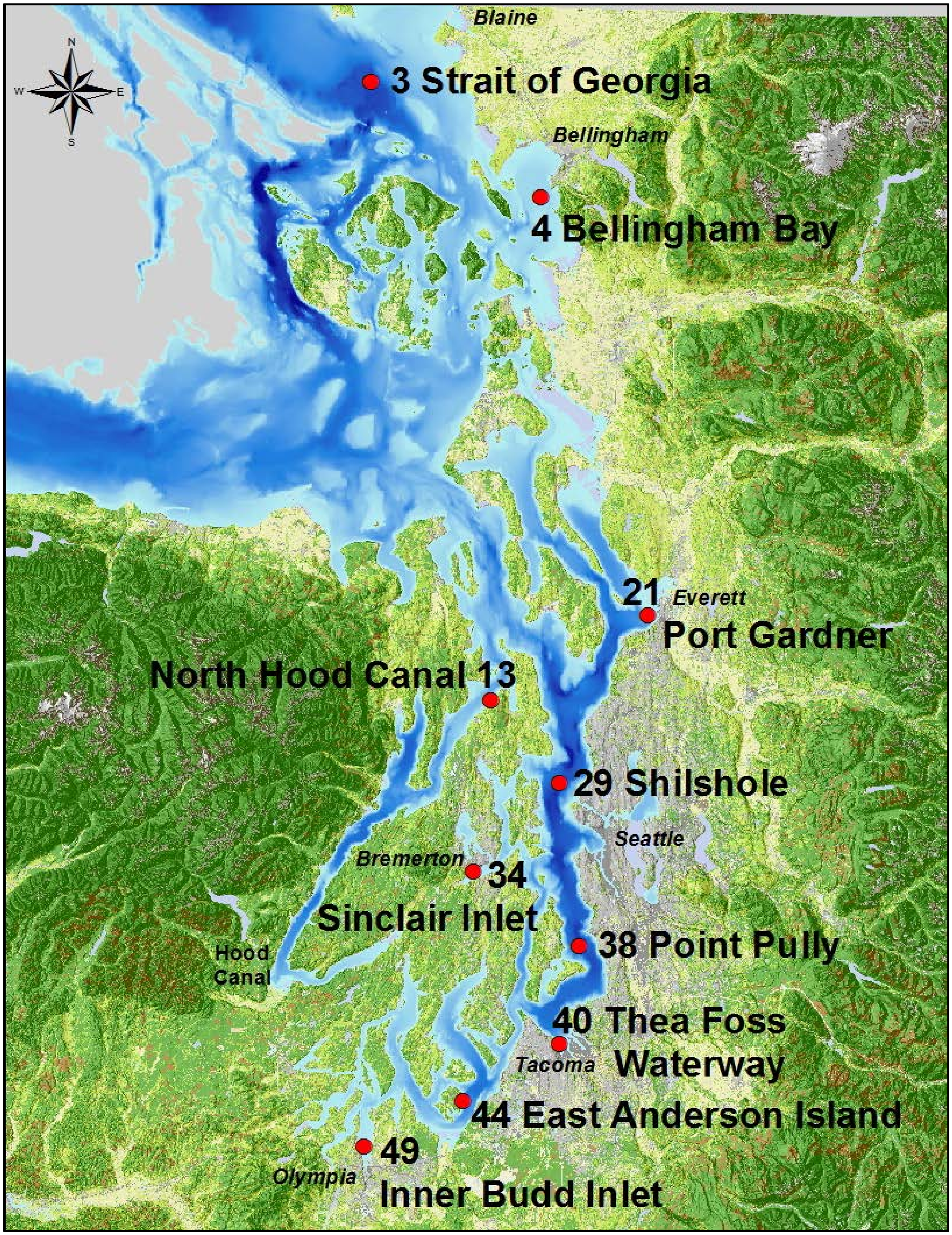


Figure 1. Map of station locations for the Puget Sound Long-Term Sediment Monitoring Program.

Table 1. Station number, location, depth, and sampling schedule of Puget Sound Long-Term Sediment Monitoring Program stations.

Station ID, Location	Latitude (deg min N)	Longitude (deg min W)	Approx. Depth (meters)	Year																
				1989	1990	1991	1992	1993	1994	1995	1996	1997-1999	2000	2001-2004	2005	2006-2009	2010	2011-2014	2015	2016
3, Strait of Georgia (north of Patos Island)	48 52.22	122 58.695	223.0	X	X	X	X	X	X	X		*	X	!	X	!	X	!	^	X
4, Bellingham Bay	48 41.04	122 32.290	24.0	X	X	X	X	X	X	X		*	X	!	X	!	X	!	^	X
13, North Hood Canal (south of bridge)	47 50.26	122 37.740	20.0	X		X			X			*	X	!	X	!	X	!	^	X
21, Port Gardner (Everett)	47 59.13	122 14.575	20.0	X	X	X	X	X	X	X	X	*	X	!	X	!	X	!	^	X
29, Shilshole	47 42.06	122 27.230	199.0	X	X	X	X	X	X	X	X	*	X	!	X	!	X	!	^	X
34, Sinclair Inlet	47 32.84	122 39.725	9.5	X	X	X	X	X	X	X	&	*	X	!	X	!	X	!	^	X
38, Point Pully	47 25.71	122 23.610	199.0	X	X	X	X	X	X	X	X	*	X	!	X	!	X	!	^	X
40, Thea Foss Waterway (Commencement Bay)	47 15.68	122 26.220	10.0	X	X	X	X	X	X	X	+	*	X	!	X	!	X	!	^	X
44, East Anderson Island	47 09.68	122 40.410	20.0	X	X	X	X	X	X	X	+	*	X	!	X	!	X	!	^	X
49, Inner Budd Inlet	47 04.82	122 54.820	5.3	X	X	X	X	X	X	X		*	X	!	X	!	X	!	^	X

X = Sediment chemistry, grain size, and benthic macrofauna
* = Benthos and grain size only
& = Chemistry and grain size only
+ = Chemistry only
! = Benthos, grain size, and TOC only
^ = Benthos, grain size, TOC, sulfides, and ammonia

Table 2. Schematic representation of field replicates collected and processed each year at the Puget Sound Long-Term Sediment Monitoring Program stations.

The symbols represent the separate replicate grabs (for benthos) or composites (for chemistry, grain size, and TOC) taken at each station. Field replicates for physical and chemical analyses are from separate composites; field splits are from the same composite.

	1989	1990	1991	1992-1993	1994	1995	1996	1997-1999	2000	2001-2004	2005	2006-2009	2010	2011-2014	2015	2016
Benthos	●	■	●	■ ■	●	■	♦	● ● ●	●	● ● ● ●	●	● ● ● ●	●	● ● ● ●	●	●
	●	■	●	■ ■	●	■	♦	● ● ●	●	● ● ● ●	●	● ● ● ●	●	● ● ● ●	●	●
	●	■	●	■ ■	●	■	♦	● ● ●	●	● ● ● ●	●	● ● ● ●	●	● ● ● ●	●	●
	●	■	●	■ ■	o	□	◊	o o o	o	o o o o	o	o o o o	o	o o o o		
	●	■	●	■ ■	o	□	◊	o o o	o	o o						
Chemistry	●	■	●	■ ■	●	■	♦		●		●		●		*	●
	+	+	+	+ +	+	+					●		●		*	●
	+	+	+	+ +	+	+					●		●		*	●
	+	+	+	+ +	+	+					+		+		+	+
Grain Size	●	■	●	■ ■	●	X	♦	● ● ●	●	● ● ● ●	●	● ● ● ●	●	● ● ● ●	●	●
	+	+	+	+ +	+	X					●	● ● ● ●	●	● ● ● ●	●	●
	+	+	+	+ +	+	X					●	● ● ● ●	●	● ● ● ●	●	●
	+	+	+	+ +	+	X					+	+ + +	+	+ + + +	+	+
TOC	●	■	●	■ ■	●	■	♦		●	● ● ● ●	●	● ● ● ●	●	● ● ● ●	●	●
	+	+	+	+ +	+	+					●	● ● ● ●	●	● ● ● ●	●	●
	+	+	+	+ +	+	+					●	● ● ● ●	●	● ● ● ●	●	●
	+	+	+	+ +	+	+					+	+ + +	+	+ + + +	+	+

■ No Station 13 o □ ◊ Not processed ♦ Benthos: 21, 29, 38; Chemistry and TOC: 21, 29, 34, 38, 40, 44; Grain Size: 21, 29, 34, 38

+ Field replicates/splits at selected stations X Results unusable * Ammonia and sulfides only

Table 3. Stations-at-a-glance: Physical habitat characteristics, chemical contamination and trends, benthic community characteristics and trends, and correlations between the benthos and environmental variables at the long-term sediment monitoring stations.

Stations are organized by depth-grain size habitat type. Symbol sizes for TOC, Fines, Total Abundance, and Taxa Richness are proportional to the mean values.

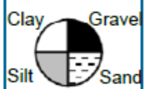
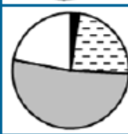
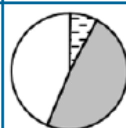
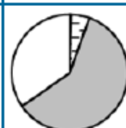
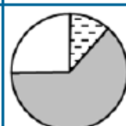
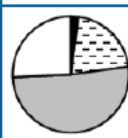
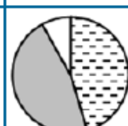
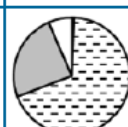
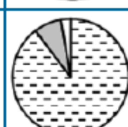
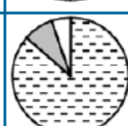
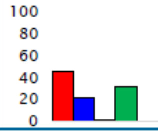
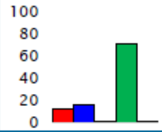
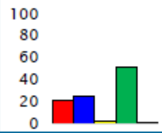
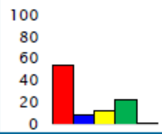
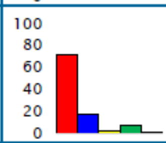
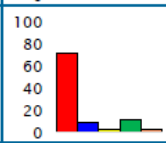
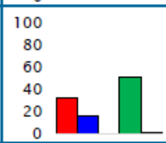
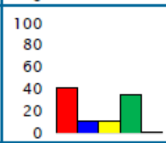
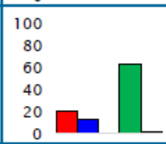
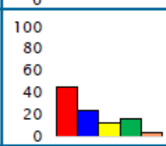
Habitat Type	Station ID, Location (Figure 1)	Depth (meters)	TOC (%) overall mean	Fines (%) overall mean	Grain size	Exceed Sed. Mgmt. Stds.?	Chemistry Index overall mean and trend	Decreasing trends ↓ physical, chemical	Increasing trends ↑ physical, chemical
									
Deep, silty	3, Strait of Georgia	223	1.38	71.0		No	96.5 (*minimum exposure*)	Sand, HPAHs	TOC, Fines, Cr, Cu, Zn
Deep, silty	29, Shilshole	200	1.80	82.6		No	95.5 (*minimum exposure*)	Ag, Pb	none
Deep, silty	38, Point Pully	200	2.32	91.5		Cd: 1992	94.4 ↑ (*minimum exposure*)	Ag, As, Cu, Hg, Pb	none
Shallow, silty	4, Bellingham Bay	25	2.07	94.2		No	95.0 ↑ (*minimum exposure*)	Hg	none
Shallow, silty	34, Sinclair Inlet	11	2.42	89.3		Hg: all years As: 1995	86.7 ↓ (*low exposure*)	Fines, Ag	Cd, LPAHs, HPAHs, PCBs, Butylbenzyl-phthalate
Shallow, silty	49, Inner Budd Inlet	7	2.71	77.7		Hg: 2016	93.1 ↑ (*low exposure*)	Fines, Ag, Pb	As, HPAHs
Shallow, mixed	21, Port Gardner	23	1.21	55.8		Hg: 1991, 2005	95.6 (*minimum exposure*)	Ag, Cd, HPAHs	none
Shallow, mixed	40, Thea Foss Waterway	11	0.98	29.8		PAHs: all years phthalates: 1989	71.1 (*moderate exposure*)	TOC, As, Cu, Hg	Cr
Shallow, sandy	13, North Hood Canal	22	0.27	10.8		No	96.9 (*minimum exposure*)	Clay	Cr, Zn
Shallow, sandy	44, East Anderson Island	22	0.43	13.8		PCBs: 1990, 1992 HCB: 1989	96.6 ↑ (*minimum exposure*)	TOC, Fines, As, Cu, Pb, Zn, LPAHs, HPAHs	Sand, Cr

Table 3 (continued). Abbreviations: Ag = silver, Ann = annelids, Arth = arthropods, As = arsenic, Cd = cadmium, Cr = chromium, Cu = copper, Date = date of sampling, Echin = echinoderms, Fines = % silt+clay, HCB = hexachlorobenzene, Hg = mercury, HPAHs = high-molec-wt PAHs, LPAHs = low-molec-wt PAHs, Moll = molluscs, Pb = lead, Penetration = depth sampler penetrated, rho = Spearman correlation coefficient, Temp = sediment temperature, Zn = zinc

Habitat Type	Station ID, Location (Figure 1)	Total Abundance mean #/0.1 m^2 (min, max)	Taxa Richness mean #/0.1 m^2 (min, max)	Major Taxa % abundance (Ann, Arth, Echin, Moll, Misc)	Trends Abundance, Richness	Benthic Community groups & shifts consecutive years	Correlation of environmental variables with community (rho)	
Deep, silty	3, Strait of Georgia	276 (14, 839)	19 (7, 38)		Abundance ⇧	(1990), (1994-1999), (2001-2003), all other years	0.527	Fines, Temp
Deep, silty	29, Shilshole	338 (75, 613)	31 (20, 42)		no change	(1989), (1990-1998), (1999-2015)	0.397	Date, Temp, Penetration
Deep, silty	38, Point Pully	188 (67, 420)	30 (17, 45)		Richness ⇧	(1989-1994), (1995-2015)	0.420	Date, Salinity, Penetration
Shallow, silty	4, Bellingham Bay	377 (40, 1031)	40 (19, 54)		Abundance ⇧	(1990), (1991), (2005-2014), (2015), all other years	0.377	Date, Temp, Penetration
Shallow, silty	34, Sinclair Inlet	685 (178, 2559)	36 (22, 61)		Richness ⇩	(1989-2000), (2001-2015)	0.488	Date, TOC, Salinity
Shallow, silty	49, Inner Budd Inlet	116 (46, 644)	17 (9, 29)		no change	(1989-2015)	—	none
Shallow, mixed	21, Port Gardner	837 (329, 1251)	47 (33, 60)		Richness ⇧	(1989-1997), (1998-2004), (2005-2015)	0.312	Date, Temp
Shallow, mixed	40, Thea Foss Waterway	700 (67, 1588)	65 (22, 82)		no change	(1989), (1990), (1991-1995), (1997-2015)	0.365	Date, TOC, Fines, Pb
Shallow, sandy	13, North Hood Canal	1350 (253, 4316)	74 (28, 125)		Abundance *cyclical* Richness *mixed*	(1989-1991), (1994-2012), (2011), (2013-2015)	—	none
Shallow, sandy	44, East Anderson Island	837 (329, 1251)	73 (44, 101)		Richness ⇩	(1989-1997), (1998), (1999-2015)	0.507	Date, Penetration

Following are descriptions of the primary physical and biological characteristics of the 10 stations, ordered from north to south.

Station 3, Strait of Georgia

The Strait of Georgia station is located 7 km north of Patos Island (San Juan archipelago), 223 meters deep, within the plume of the Fraser River (B.C.) The sediments are mostly (70-80%) silt-clay, though contained a sizable gravel fraction (up to 30% by weight) the first few years sampled. TOC content is generally just under 1.5%. The benthic community is unlike any other in the long-term and regional sediment monitoring programs, often with large numbers of either medium-sized (~5-cm) *Macoma* spp. clams or the more slender *Yoldia* spp. clams. Other numerically abundant organisms include several polychaetes (*Prionospio* spp., *Pholoe* spp., and *Cossura* spp.) and “pea crabs” (*Pinnixa* spp.). The six taxa listed constitute 69% of the abundance at this station. Mean abundance and richness, about 276 organisms and 19 taxa per 0.1-m^2 sample, are the second-lowest among the 10 long-term stations.

Station 4, Bellingham Bay

The Bellingham Bay station is 24 meters deep, located in central Bellingham Bay near the entrance to Chuckanut Bay. The sediments are consistently >90% silt-clay, with about 2% TOC content. The most characteristic infauna are the burrowing anemone, *Pachycerianthus* sp., small brittle stars (Amphiuridae), the tiny clam *Axinopsida serricata*, and only since 2014, large numbers of the fat, red, cashew-shaped polychaete *Scalibregma californicum*. On average, each 0.1-m^2 sample has 40 taxa and 377 individuals.

Station 13, North Hood Canal

The North Hood Canal station is located in a shallow cove just southeast of the Hood Canal Bridge. It is the sandiest of the 10 stations, the sediments composed of about 90% sand, with <0.25% TOC. The overall mean abundance is 1350 animals/0.1 m^2, but if one excludes the small bivalve *Nutricola lordi*, which was found there in the thousands per sample in 1997-1998 and in the hundreds later on, the mean abundance drops to 718 (Figure 8), still higher than at the other long-term stations except Port Gardner. The community is quite diverse, with an average of 74 taxa/0.1 m^2. Some of the most abundant organisms (aside from *N. lordi*) are the ostracod (“seed shrimp”) *Euphilomedes carcharodonta*, the small snail *Alvania compacta*, the small bivalve *Axinopsida serricata*, “ribbon worms” (phylum Nemertea), and numerous polychaetes.

Station 21, Port Gardner

Located about 20 meters deep on an underwater slope near the city of Everett, the Port Gardner station has a mix of grain sizes, about 50% sand and 50% fines, most of which is silt. TOC levels vary between 1% and 1.5%. Average abundance and richness are 837 animals/0.1 m^2 and 48 taxa/0.1 m^2, respectively. The small clam *Axinopsida serricata* is the most abundant organism, accounting for almost 8% of the total. Two related species of ostracod, *Euphilomedes carcharodonta* and *E. producta*, together account for another 10%. Among other abundant taxa are *Macoma* spp. clams and several carnivorous polychaetes.

Station 29, Shilshole

Located in the deep Central Basin of Puget Sound, northwest of Shilshole, this station has sediments composed of about 50% silt and 30% clay, with about 1.8% TOC content. Taxa richness averages 31 taxa per 0.1-m^2 sample. Small *Macoma* spp. clams contribute 15% of the mean 339 animals/0.1 m^2. Other abundant taxa are the ostracod *Euphilomedes producta* (8.7%), the cumacean ("comma shrimp") *Eudorella pacifica* (6.4%), and the bivalve *Axinopsida serricata* (5.7%).

Station 34, Sinclair Inlet

The Sinclair Inlet station is just 10 meters deep, located southwest of the Naval shipyard at Bremerton. The sediments are about 90% silt-clay, with more silt than clay, and TOC generally ranges between 2% and 2.5%, though sometimes up to 3%. Six taxa account for 40% of the mean 685 organisms/0.1 m^2: the cumacean *Eudorella pacifica*, tiny brittle stars (Amphiuridae), and four polychaetes, including the blue polychaete *Paraprionospio* sp. Two other animals contributing about 4% each are the small bivalve *Axinopsida serricata* and "pea crabs" (*Pinnixa* spp.).

Station 38, Point Pully

At first glance, one might expect the benthic community at the Point Pully station to be similar to that at the Shilshole station, since it also is located 200 m deep in the Central Puget Sound basin, about halfway between Tacoma and Seattle. The clay content, at over 40%, is higher than at Shilshole, or any of the other long-term stations. TOC is generally in the range 2-2.5%, compared to 1.5-2% at Shilshole. Total abundance is relatively low, at 188 organisms/0.1 m^2, and taxa richness is 30 taxa/0.1 m^2. The most visible organism at Point Pully is the smooth sea cucumber *Molpadia intermedia*. The most abundant animals are *Macoma* spp. clams (mostly the fragile *Macoma carlottensis*), the ostracod *Euphilomedes producta*, the cumacean *Eudorella pacifica*, and the small bivalve *Axinopsida serricata*.

Station 40, Thea Foss Waterway

This 10-meter-deep station is located at the mouth of the Thea Foss Waterway in Commencement Bay, just downhill from the "tank farm". Sediments are of mixed grain sizes, about 70% sand. Over the years, TOC levels have varied widely, but average about 1%. This station has the 3^{rd}-highest taxa richness and 3^{rd}-highest total abundance of the long-term stations, at 65 taxa/0.1 m^2 and 700 animals/0.1 m^2, respectively. The top five most abundant taxa are (in order) the bivalve *Axinopsida serricata*, tiny brittle stars in the family Amphiuridae, *Macoma* spp. clams, the polychaete *Prionospio* spp., and the ostracod *Euphilomedes carcharodonta*, together comprising only 20% of the total abundance.

Station 44, East Anderson Island

This station is located 20 meters deep on a steep slope on the eastern side of Anderson Island in South Sound. Sediments are >80% sand, with TOC <0.5%. Taxa richness, at 73 taxa/0.1 m^2, is nearly as high as at the other predominantly sandy station, North Hood Canal, though total abundance is much lower, at 554 organisms/0.1 m^2. Some of the most abundant organisms are the same, including the ostracod *Euphilomedes carcharodonta*, nemerteans ("ribbon worms"), and multiple species of polychaetes, including *Leitoscoloplos pugettensis* and *Mediomastus* spp.

Station 49, Inner Budd Inlet

This is a very shallow station, slightly over 5 meters deep, located just north of Priest Point. The sediments are predominantly silty, and the TOC level, between 2.5% and 3%, is the highest of the long-term stations. Few animals are found at this station: taxa richness, at 17 taxa/0.1 m^2, and total abundance, at 116 organisms/0.1 m^2, are the lowest of these 10 stations. The blue polychaete *Paraprionospio* sp. contributes 15% of the total abundance, followed by another polychaete, *Sigambra bassi*, at 11.5%. Several other spionid polychaetes, nemerteans, "pea crabs", and *Macoma* spp. clams bring the total to 68% of all abundance.

Habitat Types

For this report, the 10 stations are grouped into four general habitat types of depth and predominant grain size (Table 3):

- deep, silty
- shallow, silty
- shallow, mixed
- shallow, sandy

While they do not represent all of the depth-grain size habitat types in Puget Sound, these groupings are relevant to the discussions of the benthic communities later in this report.

Methods

Sampling and laboratory analysis methods are detailed in the Quality Assurance Project Plan (Dutch et al., 2009). All of the data are stored in, and accessible from, Ecology's Environmental Information Management (EIM) database (https://fortress.wa.gov/ecy/eimreporting/), Study ID PSAMP_LT. Links to the case narratives for the laboratory analyses are given in Appendices A and B. This report covers results for biological parameters from 1989 through 2015 and physical and chemical parameters through 2016.

Sample Collection

The North Hood Canal station was initially a rotating station and was sampled only in 1989, 1991, and 1994, until being sampled every year from 1997 on. In 1996, only six stations were sampled, from Port Gardner to Anderson Island, and only a subset of parameters was analyzed at each station (Table 2).

Prior to 2005, only a single sediment sample was taken for grain size, TOC, and chemistry at each station, with the exception of the Point Pully and Anderson Island stations, at which four field replicates or field splits were taken during 1989-1995 (Table 2). No samples were collected for TOC analysis during 1997-1999. From 2005 on, three independent grab samples for all parameters were taken at all stations.

Until 1993, five replicate grabs were taken for benthos at each station and taxonomically identified. Thereafter, only three benthos replicates were identified, even if more had been collected.

Further details of sample collection and analysis are given in the appendices.

Data Preparation

Grain size

- Grain size data were standardized to sum across grain sizes to 100%. Percent fines was recalculated from the standardized silt and clay percentages.
- Data analyses were conducted with gravel, total sand, silt, clay, and fines (silt + clay). Lab duplicates and five classes of sand (modified Wentworth scale) were graphed in the graphical data summaries (Appendix A) but otherwise not used.

TOC

- Lab duplicates were graphed in the graphical data summaries (Appendix A) but otherwise not used.
- Results of laboratory analyses at 104 ^{o}C (Modified PSEP protocol) were virtually identical to those from analyses at 70 ^{o}C (PSEP protocol) and were not used.

Chemistry

- Rejects were excluded from the dataset.
- Lab duplicates were graphed in the graphical data summaries (Appendix B) but otherwise not used.
- Summed Total LPAH, Total HPAH, Total Benzofluoranthenes, and Total Aroclors concentrations were calculated as prescribed in Ecology (2013). When all constituent compounds were nondetect, the value used was the highest reporting limit (per Ecology, 2013), and the value was considered nondetect for analyses for this report.
- SQS Quotients: For those contaminants for which there are Washington State Sediment Management Standards (Ecology, 2013), the SQS quotient, i.e., the ratio of the detected contaminant concentration (TOC-normalized for most organics) to the Sediment Quality Standard (SQS), was calculated.
- Sediment Chemistry Index: The Chemistry Index, a multi-chemical index used to evaluate exposure to complex mixtures of potentially toxic chemicals, was calculated based on the average of SQS quotients of 39 chemicals (Long et al., 2012).

Benthos

Sample selection

For purposes of statistical analyses of the data, only three replicates, usually replicates 1-3, were used, for consistency over the years, even if more replicates had been taxonomically identified. Occasionally a replicate sample was lost or compromised; in such cases, if there were more than three replicates, another one was used instead. In two cases, there were fewer than three replicates used in the statistical analyses:

- In 1994, the Thea Foss station samples had been in formalin too long prior to identification. For two of the three replicates, more than 20% of the molluscs were not identifiable beyond Bivalvia or Gastropoda, hence the data for those samples were excluded, leaving only a single replicate for analysis.
- Due to a lab mix-up during the sorting of the 2001 samples from the Thea Foss and Anderson Island stations, only two replicates from each station could be taxonomically identified.

Taxonomic standardization

Taxonomic identifications changed over the years, due to use of different taxonomists in the early years (1989-1993) than later, increase in skill over time among the consistently-used taxonomists, and ever-changing taxonomy. Name-changes were periodically updated and applied to all relevant identifications in the database (see Data Quality Control Narrative section at the end of Appendix C). While combinations of two species into a single species were easily accomplished, division of one species into two could not be applied to past data. In cases where immature life-stage or physical damage of a specimen made identification to species difficult, if not impossible, animals of a single species were occasionally identified at multiple taxonomic levels.

In order to analyze the data, it was necessary first to standardize the taxonomy. The challenge was to preserve as much detailed information as possible. Ecology's Marine Sediment Monitoring Team developed and adopted the standardization protocol given in Appendix C.

Colonial organisms and hard-substrate organisms such as barnacles were excluded from the dataset for analysis. In phyla (highest taxonomic groups) in which organisms are ordinarily identified to species or genus, organisms which had been identified only to high taxonomic levels (e.g., order or class) also were excluded, except for phylum-level analyses. Because many organisms in less-well-known phyla (e.g., Nemertea) had not been identified beyond phylum in the early years, it was necessary to "roll up" all identifications to phylum for data analyses encompassing the entire range of samples collected.

Univariate benthic measures

Univariate measures of benthic invertebrate community abundance and diversity were calculated (Appendix C).

Functional feeding guilds

Taxa were grouped into functional feeding guilds established by Macdonald et al. (2010, 2012) and abundances summed.

Data Analytical Methods

Nondetects

- Censored boxplots (boxplots obscured for values below the detection limits) were generated for metals, PAHs, and a few other organic compounds frequently detected (Appendix B). Most other organic compounds were detected rarely and therefore were not examined further.
- Because the detection rates for metals and PAHs, including carbazole and dibenzofuran, were usually close to 100%, and the sample sizes were insufficient for maximum likelihood estimation methods, regression and other trend analyses were conducted on detected (including estimated) results, for those chemicals only.

Trends

Because of the lack of replication and gaps in sample collection in the early years, overall trends were determined by weight-of-evidence using two methods: Mann-Kendall test for trend ($\alpha = 0.05$) applied to the yearly means, and fitting curves to the raw results.

Curve-fitting was done by successively running linear, quadratic, and cubic regressions, then selecting the "best fit" curve, based on the significance tests ($\alpha = 0.05$) for each model and coefficient for each regression. In cases in which a higher-order polynomial improved the adjusted R^2 by less than 10%, the lower-order polynomial was used. In most cases, the visual determination of trend direction (increase, decrease, mixed) from the best-fit curve – done for significant regressions only – was obvious; in a few cases, a judgment call was required. Cases of over-fitting (extra curvature to force lines to go through points) were removed from trend consideration.

Results were called "mixed trend" when the quadratic or cubic elements dominated the curve and there was no single direction: increase followed by decrease of approximately equal magnitude, decrease-then-increase, increase-decrease-increase, or decrease-increase-decrease. Results were called "no trend" when the regression slope was not significantly different from zero.

The trend indications from the Mann-Kendall test and those resulting from curve-fitting were usually consistent. Although in some cases one method indicated an increasing or decreasing trend and the other indicated no or mixed trend, thus requiring some judgment to combine, in no cases were the trend indications from the two methods opposite (i.e., one increasing and the other decreasing).

Community analyses

- Bray-Curtis similarity was calculated for every pair of samples at each station, based on 4^{th}-root-transformed abundances of all taxa.
- The centroid (multidimensional mean) of the three replicates for each year was calculated and the distances between the centroids analyzed by ordered ANOSIM (analysis of similarities), hierarchical cluster analysis, and multidimensional scaling (MDS) ordination using PERMANOVA+ and PRIMER v.7 (Anderson et al., 2008; Clarke et al., 2014).

Correlations

TOC, grain size, and chemistry: Pearson correlation coefficients were calculated pairwise between concentrations of individual chemicals (detected only), percent fines, and TOC.

Benthos and environmental parameters: Multivariate correlations between the benthic invertebrate assemblages and suites of habitat-related and chemical contaminant concentrations were calculated as Spearman correlations between similarity matrices for the benthic samples (Bray-Curtis similarities calculated on 4^{th}-root-transformed abundances, all taxa) and distance matrices for the environmental samples (Euclidean distances calculated on normalized variables) using the BioEnv/BEST routine in PRIMER v.7 (Clarke et al., 2014). The correlations were run for all stations combined and for individual stations, for each of multiple scenarios, including:

- Different treatments of nondetects in the chemistry data.
- Inclusion/exclusion of 1994-1996 chemistry data.
- Inclusion/exclusion of salinity, temperature, and grab penetration depth.
- Variance-stabilizing transformations of the environmental-variable data.

The BioEnv/BEST routine determines the selection of variables resulting in the highest correlations for each of one, two, up to a specified maximum number of variables. When inclusion of additional variables improved the correlation by less than 10% over correlations with fewer variables, the smaller set of variables was used.

Results

Conventionals

Grain size

Mean percent fines (silt-clay content) was above 70% at the six silty stations, below 20% at the two sandy stations, and 30%-60% at the two stations with mixed sediments (Figure 2).

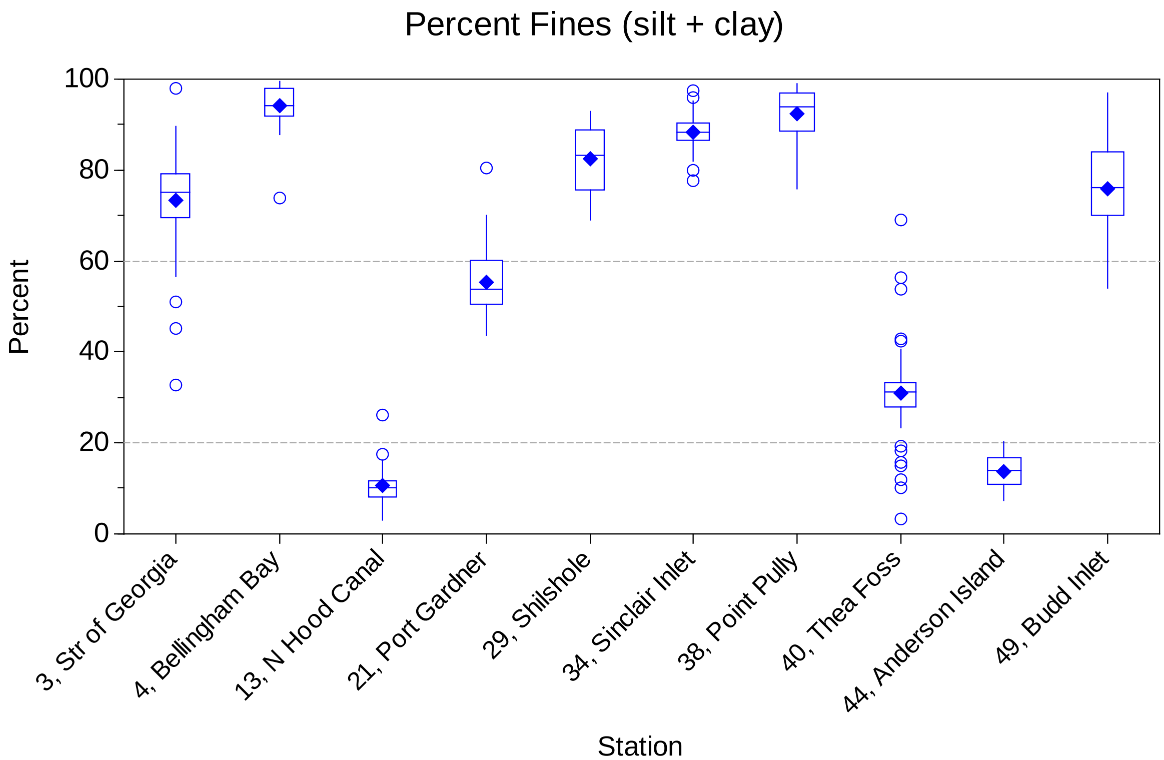


Figure 2. Percent fines (silt + clay), by station, for the Long-Term Sediment Monitoring Program, 1989-2016.

The stations are ordered north to south.

Percent fines remained consistent at six of the 10 stations (Table 5). At Sinclair Inlet, Anderson Island, and Budd Inlet, however, sediments became sandier over time, with less silt at Budd Inlet and less clay at Sinclair Inlet and Anderson Island. Sand content at Port Gardner increased gradually until about 2005, then decreased more rapidly after 2010, with both silt and clay showing the opposite pattern.

Table 4. Correlation between TOC and percent fines, overall and by station.

Station ID, Location	Pearson correlation, *r*	*p*-value
Overall	0.872	<0.0005
3, Strait of Georgia	0.656	<0.0005
4, Bellingham Bay	-0.129	0.384
13, North Hood Canal	0.892	<0.0005
21, Port Gardner	0.658	<0.0005
29, Shilshole	-0.169	0.240
34, Sinclair Inlet	-0.218	0.097
38, Point Pully	-0.196	0.115
40, Thea Foss Waterway	0.160	0.272
44, East Anderson Island	0.663	<0.0005
49, Inner Budd Inlet	0.258	0.051

Sediments from the Strait of Georgia station were coarser, including more gravel, before 1996 than after. Partridge et al. (2005) had speculated a possible connection between silt and high Fraser River runoff in 1996; however, the silt-runoff pattern did not persist after 2000. It is possible that flood-control systems established on tributaries of the lower Fraser River may have mitigated the amount of sediment carried into the Fraser River plume. Another possible explanation for the change in grain size is improvement in accuracy of station-positioning over the years due to evolving navigational technology – the deeper the station, the greater the effect at depth of a small change in boat position at the surface of the water.

Analysis of the 10 stations together did not indicate an overall change in grain size. There was a decrease in silt Sound-wide based on combined regional-scale surveys from 2004-2014 compared to 1997-2003, though clay and total fines (silt + clay) were unchanged. However, the decrease in silt may have been at least partly an artifact of not resampling the same regional stations.

Total organic carbon

Total organic carbon (TOC) content at the long-term stations ranged from under 0.5% at the sandy stations to over 3% at the inner Budd Inlet station (Figure 3). TOC was consistent over the years at most of the stations (Table 5). TOC content did increase over the years, however, at the Strait of Georgia station, and decreased at the Thea Foss and Anderson Island stations. At the Port Gardner station, TOC decreased during the 1990s but continually increased after 2000.

Results from the regional sediment monitoring surveys indicate no statistically significant change in TOC content from Baseline to Second Round. Sediment TOC ranged from less than 0.1% to 7.2% in the regional surveys, with more than 95% of the Sound having TOC levels less than 3%. The long-term station in Budd Inlet had higher TOC content than the surrounding South Sound region. TOC at the North Hood Canal station more closely resembled that of the nearby Admiralty Inlet region than the remainder of Hood Canal.

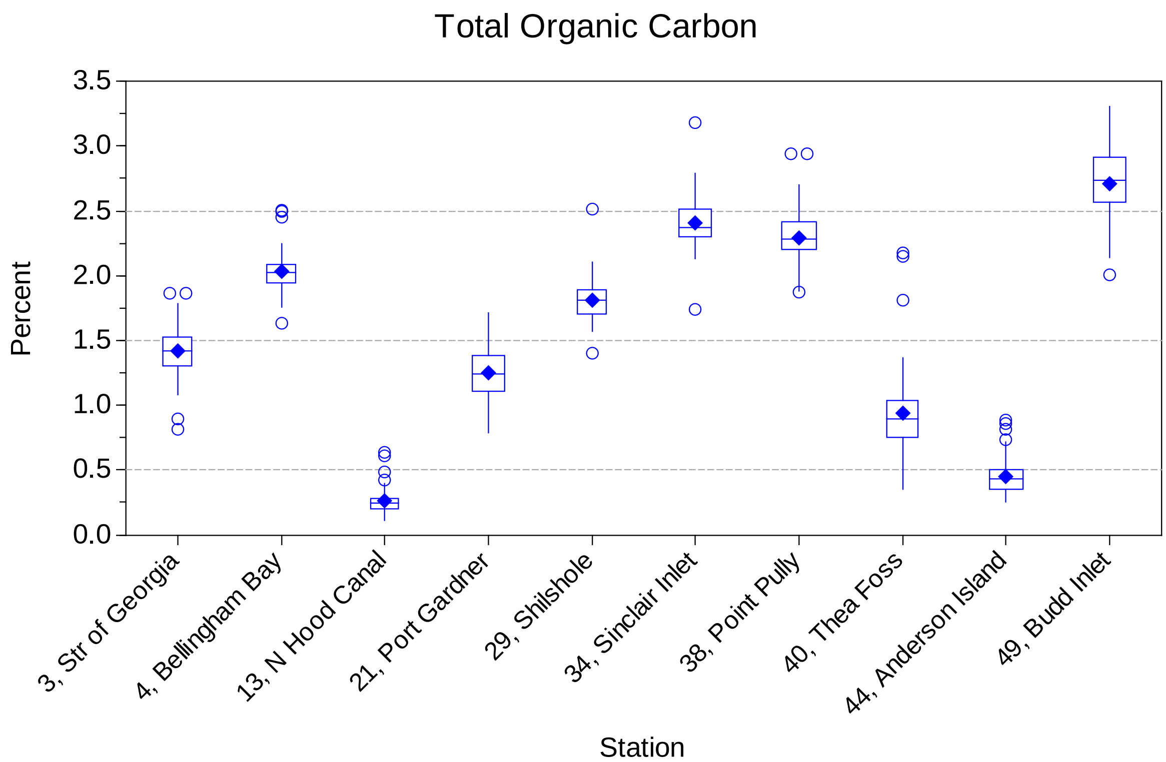


Figure 3. Percent total organic carbon (TOC), by station, for the Long-Term Sediment Monitoring Program, 1989-2016.

The stations are ordered north to south.

Relationship between TOC and grain size

Organic material in and on the sediments is an important food source for many benthic organisms. Furthermore, many organisms are size-selective feeders. The amount of organic material is a function of many processes, including sediment particle size – the smaller the particle, the greater the surface area-volume ratio, and potentially the greater amount of material (food or contaminants) adsorbed onto the surface.

Overall, for all 10 stations combined, TOC and fines were positively correlated. For individual stations, however, TOC and fines were correlated at only four locations: North Hood Canal, Strait of Georgia, Port Gardner, and Anderson Island. Relatively high TOC values at the Thea Foss station in 2010 and the early 1990's resulted in no linear relationship between TOC and fines. TOC was independent of grain size at the siltiest stations, those with >80% fines (Table 4).

Ammonia and sulfides

Ammonia and sulfides are breakdown products from the degradation of organic material, the cycling of nutrients. Furthermore, sulfide is toxic to marine organisms.

Ammonia and total sulfides were measured in both sediment and porewater samples in 2015 (Dutch et al., 2015). Although a single set of measurements is not enough to interpret the biogeochemical condition at a station, relative comparisons among the stations are possible.

Total sulfides were 2-4 times higher at the Point Pully station than at any other station (Appendix A). Porewater ammonia concentrations were highest at Sinclair Inlet and lowest at North Hood Canal. Sediment ammonia at Sinclair Inlet, however, was among the lowest of all stations. The highest sediment ammonia concentrations were at the Strait of Georgia and Budd Inlet stations.

Chemical Contaminants

PSEMP sediment monitoring historically has been focused on toxic contaminants as potentially harmful to the benthos. Sediment samples were analyzed for metals and organic chemicals, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), chlorinated pesticides (e.g., DDT), polybrominated diphenylethers (PBDEs), phthalates, and miscellaneous organic compounds (full list in Appendix B). In 2010, samples were also tested for pharmaceuticals and personal care products — see separate report, Long et al., 2013.

Detection rates

Metals were detected and measurable in almost all samples, though silver was never detected at the North Hood Canal station. The detection rates for PAHs, organic compounds which result largely from incomplete combustion of petrochemical or natural organic matter, climbed over the years to nearly 100%. Other organic compounds were rarely detected, even as the lab's ability to detect them improved over time.

Similar detection rates, concentrations, and patterns of occurrence of contaminants were found in the wider-scale regional sediment monitoring surveys.

Relationships with TOC and fines

Both organic matter and chemical contaminants tend to adhere to fine sediments, primarily clay and silt. Therefore, bioavailability of pollutants is partly related to total organic carbon (TOC) and grain size.

Sediment metals concentrations were positively correlated with fines and TOC for all stations combined, though the correlation strength was weak for mercury, lead, and cadmium (Table 6). PAHs were weakly negatively correlated with fines and TOC. Other organic contaminants were too infrequently detected to determine any correlations.

Table 5. Trends in TOC and grain size over the entire period 1989-2016, by station.

▲ increase ▼ decrease ● mixed trend -- no trend

Parameter	3, Strait of Georgia	4, Bellingham Bay	13, North Hood Canal	21, Port Gardner	29, Shilshole	34, Sinclair Inlet	38, Point Pully	40, Thea Foss Waterway	44, East Anderson Island	49, Inner Budd Inlet
Total Organic Carbon	▲	--	--	●	--	--	--	▼	▼	--
Percent Fines	▲	--	--	●	--	▼	●	--	▼	▼
Gravel	▼	--	--	--	--	--	--	--	▼	--
Total Sand	▼	--	--	●	--	▲	●	--	▲	▲
Total Silt	▲	--	--	●	--	--	--	--	▼	▼
Total Clay	▲	--	▼	●	--	▼	●	--	▼	●

Table 6. Pearson correlation coefficient, *r*, calculated pairwise between concentrations of individual chemicals (detected only), percent fines, and TOC, over all stations and years for which chemical analyses were done.

Bold *signifies correlation significant at individual α = 0.05. The correlation between TOC and fines for this data subset was 0.873 (significant at α = 0.05). For correlations for individual stations, see Appendix B.*

Metals	Fines	TOC	Low-molecular-wt PAHs	Fines	TOC	High-molecular-wt PAHs	Fines	TOC
Arsenic	**0.694**	**0.298**	1-Methylnaphthalene	0.034	0.066	Benzo(a)anthracene	**-0.267**	**-0.147**
Cadmium	**0.403**	**0.550**	2-Methylnaphthalene	-0.033	-0.022	Benzo(a)pyrene	**-0.248**	**-0.139**
Chromium	**0.864**	**0.771**	Acenaphthene	**-0.437**	**-0.253**	Benzo(g,h,i)perylene	**-0.212**	-0.065
Copper	**0.614**	**0.688**	Acenaphthylene	**-0.434**	**-0.281**	Total Benzofluoranthenes	**-0.186**	-0.049
Lead	**0.413**	**0.505**	Anthracene	**-0.367**	**-0.252**	Benzo(b)fluoranthene	**-0.198**	-0.045
Mercury	**0.361**	**0.431**	Fluorene	**-0.364**	**-0.212**	Benzo(k)fluoranthene	**-0.217**	-0.123
Nickel	**0.829**	**0.654**	Naphthalene	**-0.290**	**-0.206**	Chrysene	**-0.250**	**-0.137**
Selenium	**0.688**	**0.664**	Phenanthrene	**-0.247**	**-0.135**	Dibenzo(a,h)anthracene	**-0.412**	**-0.242**
Silver	**0.514**	**0.580**	Retene	0.061	**0.158**	Fluoranthene	**-0.228**	-0.105
Zinc	**0.805**	**0.779**	Total LPAH	**-0.263**	**-0.154**	Indeno(1,2,3-c,d)pyrene	**-0.253**	-0.087
Phthalates	**Fines**	**TOC**	**Other**	**Fines**	**TOC**	Perylene	0.079	**0.187**
Bis(2-ethylhexyl)phthalate	0.081	0.218	Carbazole	**-0.389**	-0.261	Pyrene	**-0.245**	-0.122
Butylbenzylphthalate	-0.112	0.120	Dibenzofuran	**-0.258**	-0.153	Total HPAH	**-0.229**	-0.102

At the level of individual stations, there were no significant correlations of any chemical concentrations with TOC at the Shilshole and Thea Foss stations, and only a few weak negative PAH correlations with TOC at Point Pully (Appendix B). Metals were correlated with TOC at only a few stations, primarily Strait of Georgia and Port Gardner.

Correlations with fines were generally stronger at the mixed-grain-size Port Gardner and Thea Foss stations than for all stations combined. Correlations between HPAHs and fines at the Anderson Island station were positive in direction and moderate in strength, in contrast to the weak negative correlations for the combined stations. A few metals were positively correlated with fines at most of the stations, the mixes of correlated metals varying by station, though a few stations had one or two negative metals-fines correlations.

Patterns and trends

As expected, the concentrations of chemicals were generally much higher at those stations close to industrial areas and low at the stations farther removed from human influence. Furthermore, the stations had different chemical "signatures," i.e., the mixtures of contaminants differed by location. For example, PAH concentrations were much higher at the Thea Foss station in Commencement Bay than at the other stations, while concentrations of metals, particularly mercury, were highest in Sinclair Inlet.

A few patterns and trends emerged over the entire 1989-2016 period (Table 7):

- **Metals:** Silver concentrations decreased at half of the stations, and lead decreased at four of the 10 stations. Chromium levels increased at four stations. Concentrations of other metals remained largely the same overall, though some changed significantly at one to three stations each.
  - Point Pully: Decreased arsenic, copper, lead, mercury, and silver.
  - Strait of Georgia: Increases in several metals, likely related to the increase in finer-grained sediments.
  - Sinclair Inlet: Multiple metals, including mercury, decreased through the 1990s, then increased after 2000. Silver concentrations declined. Except for an anomalously high value in 1995, arsenic levels remained essentially constant.
- **PAHs:** There were no general monotonic trends (overall increase or decrease) across the stations, though trends were evident at a couple of individual stations. However, multiple PAHs at multiple stations showed mixed trends, i.e., increasing <u>and</u> decreasing.
  - Sinclair Inlet: Multiple PAHs increased, though the trends were weak for some high-molecular-weight PAHs (HPAHs). Trends in low-molecular-weight PAHs (LPAHs) were moderate in strength, and either increasing overall or mixed, peaking in 2005 and then decreasing somewhat.
  - Anderson Island: Multiple PAHs decreased.
  - Thea Foss: PAH concentrations varied over the years, with measured levels generally lower in the 1990s and higher in the 2000s. Although PAH concentrations were elevated in 2005 and/or 2010, by 2016 they were similar to the levels in 2000.

Table 7. Trends in Chemistry Index and detected contaminant concentrations over the period 1989-2016, by station.

▲ increase ▼ decrease ● mixed trend -- no trend ND nondetects [green] improvement [red] deterioration

where "improvement" means increased Chemistry Index value or decreased contaminant concentration
and "deterioration" means decreased Chemistry Index value or increased contaminant concentration

	Parameter	3, Strait of Georgia	4, Bellingham Bay	13, North Hood Canal	21, Port Gardner	29, Shilshole	34, Sinclair Inlet	38, Point Pully	40, Thea Foss Waterway	44, East Anderson Island	49, Inner Budd Inlet
	Sediment Chemistry Index	--	▲	●	●	●	▼	▲	--	▲	▲
Metal	Arsenic	--	--	--	●	--	--	▼	▼	▼	▲
	Cadmium	--	--	--	▼	--	▲	--	--	--	●
	Chromium	▲	●	▲	●	●	●	●	▲	▲	●
	Copper	▲	--	--	●	●	●	▼	▼	▼	●
	Lead	--	--	--	●	▼	●	▼	--	▼	▼
	Mercury	●	▼	●	--	--	●	▼	▼	--	--
	Silver	--	--	ND	▼	▼	▼	▼	●	--	▼
	Zinc	▲	--	▲	●	●	●	●	--	▼	●
Low-molecular-wt PAH	2-Methylnaphthalene	●	●	●	●	●	●	●	●	--	●
	Acenaphthene	--	--	--	●	--	▲	--	--	▼	●
	Acenaphthylene	--	--	--	●	●	▲	●	--	▼	●
	Anthracene	●	●	--	--	--	▲	--	--	▼	▲
	Fluorene	●	●	--	●	--	●	●	--	▼	●
	Naphthalene	●	●	--	●	●	●	●	●	●	●
	Phenanthrene	●	●	--	●	●	--	--	--	●	--
	Total LPAH (sum of 6)	●	●	●	●	●	▲	●	--	●	●
High-molecular-wt PAH	Benzo(a)anthracene	●	●	--	--	●	--	--	--	▼	--
	Benzo(a)pyrene	●	●	--	--	●	●	--	--	--	●
	Benzo(g,h,i)perylene	▼	●	--	--	●	▲	--	--	--	--
	Total Benzofluoranthenes	●	--	--	▼	●	▲	--	--	--	--
	Chrysene	●	●	--	--	●	--	--	--	▼	--
	Dibenzo(a,h)anthracene	▼	--	--	▼	●	--	--	--	▼	--
	Fluoranthene	●	●	●	●	--	--	--	--	●	--

	Parameter	3, Strait of Georgia	4, Bellingham Bay	13, North Hood Canal	21, Port Gardner	29, Shilshole	34, Sinclair Inlet	38, Point Pully	40, Thea Foss Waterway	44, East Anderson Island	49, Inner Budd Inlet
	Indeno(1,2,3-c,d)pyrene	▼	●	--	--	●	●	--	--	▼	--
	Pyrene	●	●	●	●	--	●	--	--	--	▲
	Total HPAH (sum of 9)	●	●	●	●	●	▲	--	--	--	▲
Other	Dibenzofuran	●	●	--	●	--	--	●	--	--	●
	Bis(2-ethylhexyl)phthalate	--	--	ND	ND	--	--	--	--	▼	--

Since 2000, some additional patterns have emerged:

- Levels of arsenic, copper, and zinc increased at several stations.
- Concentrations of the majority of HPAHs and one or a few LPAHs generally decreased at half of the stations: Strait of Georgia, Bellingham Bay, North Hood Canal, Shilshole, and Anderson Island. At the Budd Inlet station, PAH decreases after 2000 were mostly LPAHs. The remainder of the LPAHs showed no trend or mixed increase-then-decrease trends.

These patterns are generally consistent with those at the scale of the entire Puget Sound, in which concentrations of most metals and all HPAHs measured declined from the Baseline survey of 1997-2003 to the Second Round survey of 2004-2014, while chromium increased and most LPAHs remained largely unchanged. Although arsenic levels decreased from 1997-2003 to 2004-2014 Sound-wide, arsenic was found to have increased at seven of the 10 long-term stations during a similar period, from 2000 through 2016.

Comparison to standards

Although this sediment monitoring program does not sample for regulatory purposes, and the methods are different, it is still informative to compare contaminant concentrations to Washington Sediment Management Standards (Washington Administrative Code Chapter 173-204; Ecology, 2013) for scale. The Sediment Management Standards were developed to be protective of benthic organisms.[4]

Concentrations were well below, therefore meeting, the standards at four of the 10 stations and were either initially or intermittently above the standards at four other stations. Certain contaminants persistently exceeded the standards over time at two stations: Sinclair Inlet and Thea Foss Waterway (Table 8).

- Total mercury concentrations were above the Sediment Quality Standard (SQS) in Sinclair Inlet except in 1996, and usually also above the Cleanup Screening Level (CSL). Mercury levels were higher after 2000 than in 1989-2000.
- At the Thea Foss station, concentrations of several PAHs were above the respective SQSs multiple years. In 1989 and again in 2005 and 2010, some PAHs also exceeded CSLs. PAH concentrations varied considerably over the years. The number and magnitude of SQS exceedances at that station were smaller in 2016 than in 2005 or 2010, with only benzo(g,h,i)perylene exceeding the CSL.

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[4] The Washington State regulatory sediment criteria (Sediment Management Standards) were derived with the apparent-effects threshold approach, a method of comparing sediment chemical concentrations with both sediment toxicity and adverse effects to the resident benthos (Ecology, 2013).

Two sets of values were derived for each of 47 chemicals or chemical groups:

- The Sediment Quality Standards (SQS) are sediment chemical concentrations below which adverse biological effects are not expected to occur or above which at least minor adverse impacts on benthic invertebrates are expected always to occur.
- The Cleanup Screening Levels (CSL) are concentrations above which at least moderate adverse biological effects are expected to occur. In general, the CSL is higher than the SQS for a given chemical; however, they are the same for some chemicals.

Table 8. Contaminant concentrations higher than Sediment Management Standards Sediment Quality Standards (SQS) and Cleanup Screening Levels (CSL) in surface sediments at six of the 10 long-term sediment monitoring stations.

The other four stations had no contaminant concentrations higher than the standards.

● = exceeds SQS ●† = exceeds CSL (shaded) = not analyzed

Station Location / Contaminant	1989	1990	1991	1992	1993	1994	1995	1996	2000	2005	2010	2016
21, Port Gardner												
Mercury			●							●†		
34, Sinclair Inlet												
Arsenic							●†					
Mercury	●†	●†	●†	●	●	●†	●†		●†	●†	●†	●†
38, Point Pully												
Cadmium				●								
40, Thea Foss Waterway												
2-Methylnaphthalene									●			
Acenaphthene		●									●	
Anthracene									●			
Fluorene	●	●								●	●	●
Naphthalene									●†			
Phenanthrene	●	●				●	●		●	●	●†	●
Total LPAH	●	●								●†	●†	●
Benzo(a)anthracene	●	●							●	●	●	
Benzo(a)pyrene	●									●†	●†	●
Benzo(g,h,i)perylene	●†						●		●	●†	●†	●†
Total Benzofluoranthenes	●									●	●	
Chrysene	●	●							●	●	●	●
Dibenzo(a,h)anthracene	●†	●	●						●	●†	●	●
Fluoranthene	●									●	●	●
Indeno(1,2,3-c,d)pyrene	●†	●							●	●†	●†	●
Total HPAH	●									●	●	●
Bis(2-ethylhexyl)phthalate	●											
Butylbenzylphthalate	●											
Dibenzofuran									●			
44, East Anderson Island												
Hexachlorobenzene	●											
Total Aroclors		●		●								
49, Inner Budd Inlet												
Mercury								X				●

Chemistry Index

The Chemistry Index is a multi-chemical index that is used to evaluate exposure to complex mixtures of potentially toxic chemicals that may accumulate in the sediments. The index is based on the average ratio of 39 chemical concentrations to their respective SQS values. Index values are used to categorize sediments as having *minimum*, *low*, *moderate*, or *maximum* exposure to these chemicals (Long et al., 2012). The Puget Sound Partnership (PSP) adopted the Chemistry Index as one of the Vital Signs indicating the health of Puget Sound (www.psp.wa.gov/vitalsigns) and uses the target value of 93.3, corresponding to the lowest value in the *minimum exposure* category.

Sediments at seven of the 10 long-term stations were in the *minimum exposure* category for all but a few samples (Figure 4), and more than 70% of the samples at the Point Pully station were classified as *minimum exposure*. All but one of the sediment samples from Sinclair Inlet were in the *low exposure* category. Sediments in the Thea Foss Waterway of Commencement Bay were in the *high exposure* category 42% of the time and the *moderate exposure* category 37% of the time. No samples from either Sinclair Inlet or Thea Foss were classified as *minimum exposure*.

On average over the years, the PSP target was met at all of the stations except three: Sinclair Inlet, Thea Foss, and Budd Inlet. The mean Chemistry Index value at the Budd Inlet station was close to meeting the target, at 93.1.

Chemistry Index values improved (increased) over the years at the Bellingham Bay, Point Pully, Anderson Island, and Budd Inlet stations, and deteriorated (decreased) at the Sinclair Inlet station (Table 7).

Inner harbor areas and several urban bays in the Puget Sound-area regional and bay-scale sediment surveys did not meet the PSP target, though all did improve over time. The Chemistry Index results for the long-term stations within urban bays are consistent with the respective bay-wide results. The Bellingham Bay long-term station, which met the PSP target, is located outside the northern, urban portion of Bellingham Bay, which did not meet the PSP target.

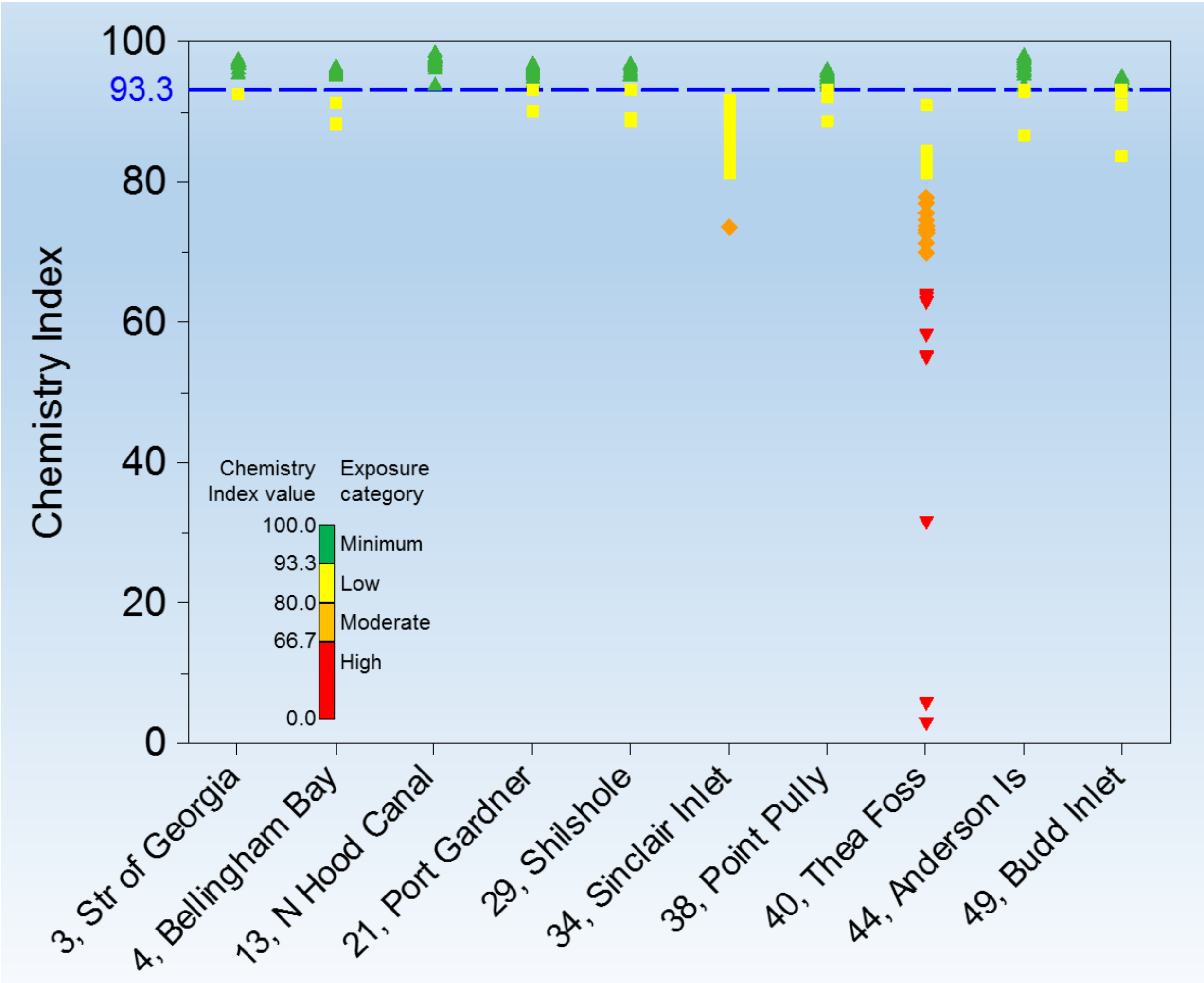

Figure 4. Chemistry Index values for the 10 long-term sediment monitoring stations, 1989-2016.

Each symbol represents a sample. The stations are ordered north to south.

The Puget Sound Partnership (PSP) target value of 93.3, which corresponds to the lowest value in the minimum exposure level, is indicated by the dashed blue line.

Benthic Invertebrates

The sediment-dwelling (benthic) invertebrates are the most important biotic endpoint for conditions in the sediment, whether stressors be human-caused (e.g., contaminants) or natural events. One of the benefits of annual monitoring at these 10 stations is to understand trends in benthic invertebrate communities over time and identify relationships with habitat, contaminant, and other variables.

Benthic invertebrate organisms (benthos) were identified and counted for all samples. After taxonomic standardization across years and stations, there were 396 taxa[5] in the 772-sample dataset.

Occurrence, abundance, and diversity

Occurrence of a given species ranged from a single sample to 711 samples, with anywhere between one individual to over 3600 in a sample. Total abundance of all species in a single sample ranged from 14 to 4320 individuals (Table 9). Occurrence, abundance, and type of invertebrates varied considerably by station.

Table 9. Occurrence and abundance of benthic invertebrates at the 10 long-term sediment monitoring stations, 1989-2015.

Measure	Minimum	Maximum	Mean	Median
Occurrence of a single taxon (# of samples)	1	711	52	8
Abundance of a single taxon in a single sample	1	3603	12	2
Total abundance of all taxa in a single sample	14	4320	528	407
Taxa richness (# of taxa) in a single sample	7	125	41	36

Although the mean abundances in the major taxonomic groups differed from station to station (Figure 5a), as did the number of taxa (Figure 5b), the average proportions of the major taxa were similar across the stations. More species of annelids were found than other types of species (Figure 5b). The majority of the stations had higher counts of annelids per sample than of other taxa, though four stations were dominated by molluscs: North Hood Canal, Port Gardner, and the two deep Central Basin stations, Shilshole and Point Pully (Figure 5a).

[5] Lowest-level taxonomic identification practicable, often species, but sometimes a higher level (e.g., genus, family).

Benthic community diversity is measured several ways. Taxa richness is the number of taxa; higher richness, i.e., more taxa, is generally associated with greater diversity. Evenness is a measure of how equitably species are represented in a community; the higher the evenness index, the more equitable (even) the abundance of the taxa. Dominance, on the other hand, is a measure of inequitability — the fewer taxa accounting for 75% of the abundance (lower dominance index), the less diverse the community is.

The North Hood Canal station had the highest total abundance, while the Budd Inlet station had the least (Figure 6a). However, close to half (47%) of the mean abundance at North Hood Canal was due to a single small bivalve, *Nutricola lordi*. Total abundance was low also at the deepest stations, located in the Strait of Georgia and in the central Puget Sound basin.

Taxa richness was highest at the sandiest stations, North Hood Canal and Anderson Island, and lowest at the northern and southern extremes of Puget Sound: the Strait of Georgia and Budd Inlet stations, respectively (Figure 6b). The mixed-grain-size stations at Port Gardner and the mouth of the Thea Foss Waterway (Commencement Bay) had the next-highest abundance and richness.

The evenness index was relatively high at half of the stations, across multiple habitat types: Bellingham Bay, Point Pully, Thea Foss, Anderson Island, and Budd Inlet (Figure 6c). The Shilshole station had both the lowest evenness and lowest dominance. Dominance was low also at Budd Inlet and Strait of Georgia. The Anderson Island station had the highest dominance (Figure 6d).

The habitats are quite similar at the Point Pully and Shilshole stations, both in the Central Puget Sound basin, 200 meters deep, with high percent fines, and similar mixes of species are found there. Curiously, however, the evenness and dominance index values for those two stations are substantially different, indicating different distributions of those species, with fewer species accounting for a higher percentage of the total abundance at Shilshole than at Point Pully.

Community composition

The 10 stations represent distinct benthic invertebrate communities. While there were some year-to-year changes in the benthic community at a given station, the communities remained distinct from each other (Figure 7). Furthermore, the similarities of the invertebrate assemblages reflect the similarities of depth and grain size in the habitats.

Patterns of abundance of several commonly-occurring species (Figure 8) illustrate not only differences among stations, but also habitat preference, cycles, increasing or decreasing trends, or all of the above.

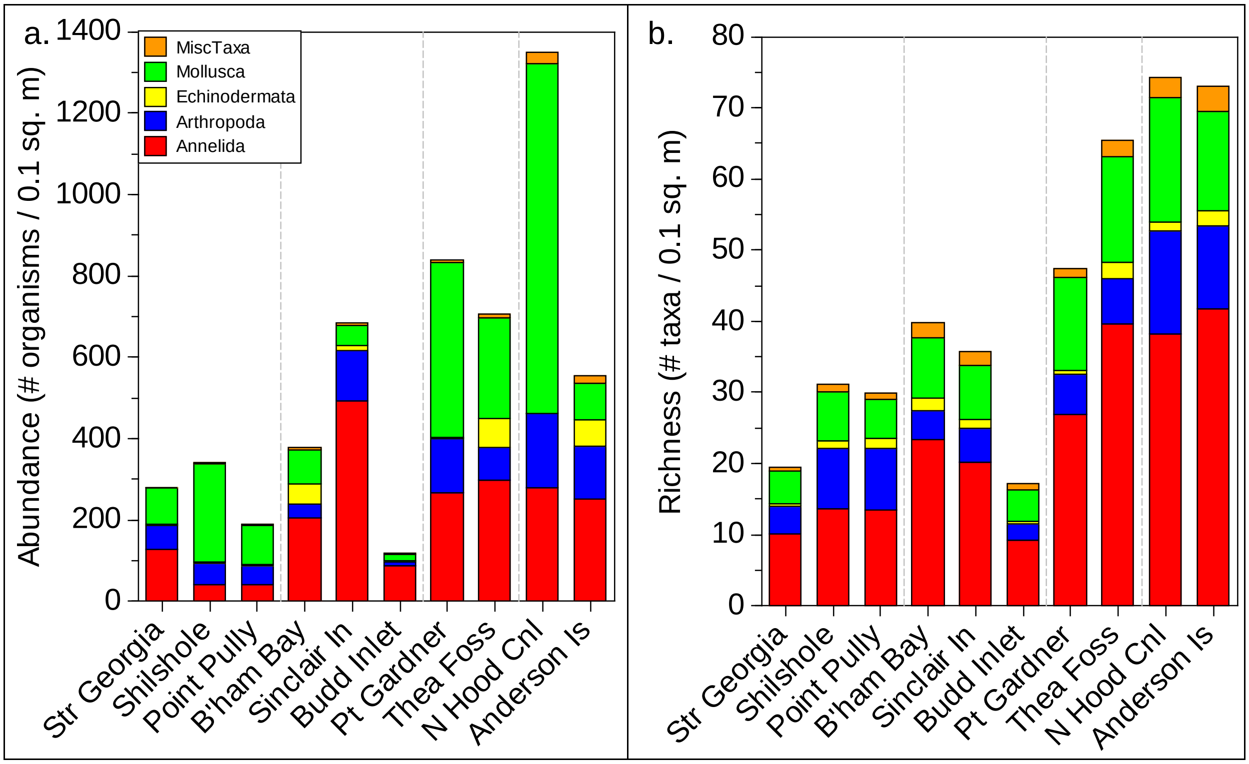

Figure 5. (a) Mean total abundance and (b) mean taxa richness (number of taxa) of benthic invertebrates by phylum (major taxonomic group) for each of the 10 long-term sediment monitoring stations.

The stations are grouped by habitat type, as in Table 3.

Common vs. occasional taxa

Of the 396 taxa found, 65 occurred at least once at all 10 long-term stations and/or in every year from 1989 to 2015. Collectively, they constituted only about 16% of the taxa, but over 85% of the total abundance. Tables and graphs of the mean abundance of these 65 taxa are given in Appendix C.

The similarity of the benthos across stations based on only these 65 "common" taxa shows the same general pattern as in Figure 7 for all taxa (Appendix C). If anything, the distinctness of the stations is accentuated, including distinguishing between the two otherwise similar-looking stations in the deep central basin of Puget Sound, near Shilshole (north of Seattle) and Point Pully (halfway between Seattle and Tacoma). Thus, the "common" taxa represent the primary information in the benthic communities.

Interestingly, the other 331 "occasional" taxa also provide a picture similar to that in Figure 7, though with more overlap between close stations (Appendix C). It is these "occasional" taxa that distinguish 1989-2000 vs. 2001-2015 at the Sinclair Inlet station.

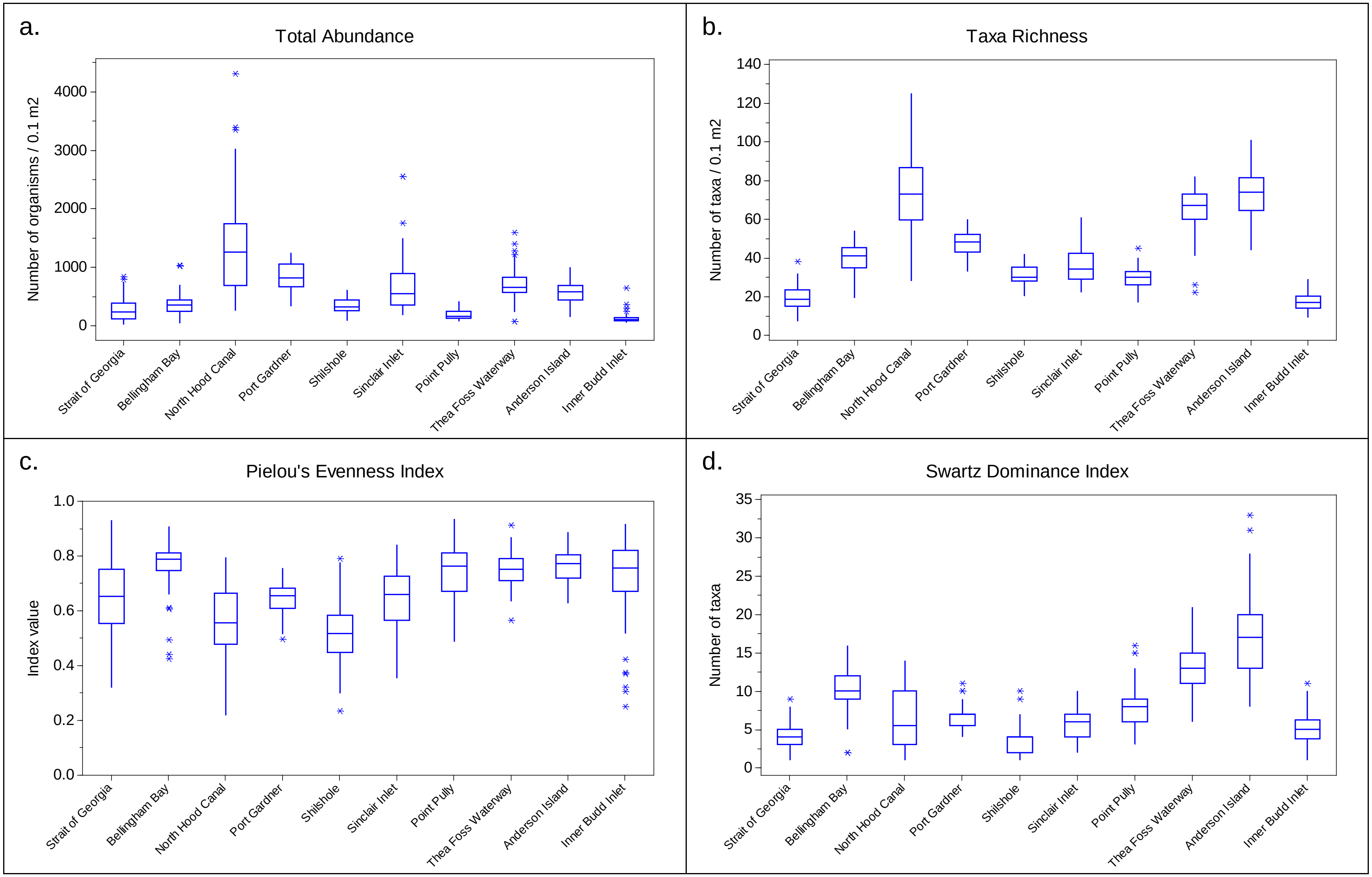

Figure 6. Univariate benthic measures, by station: (a) Total abundance, (b) Taxa richness, (c) Pielou's evenness, (d) Swartz dominance index.

The stations are ordered north to south.

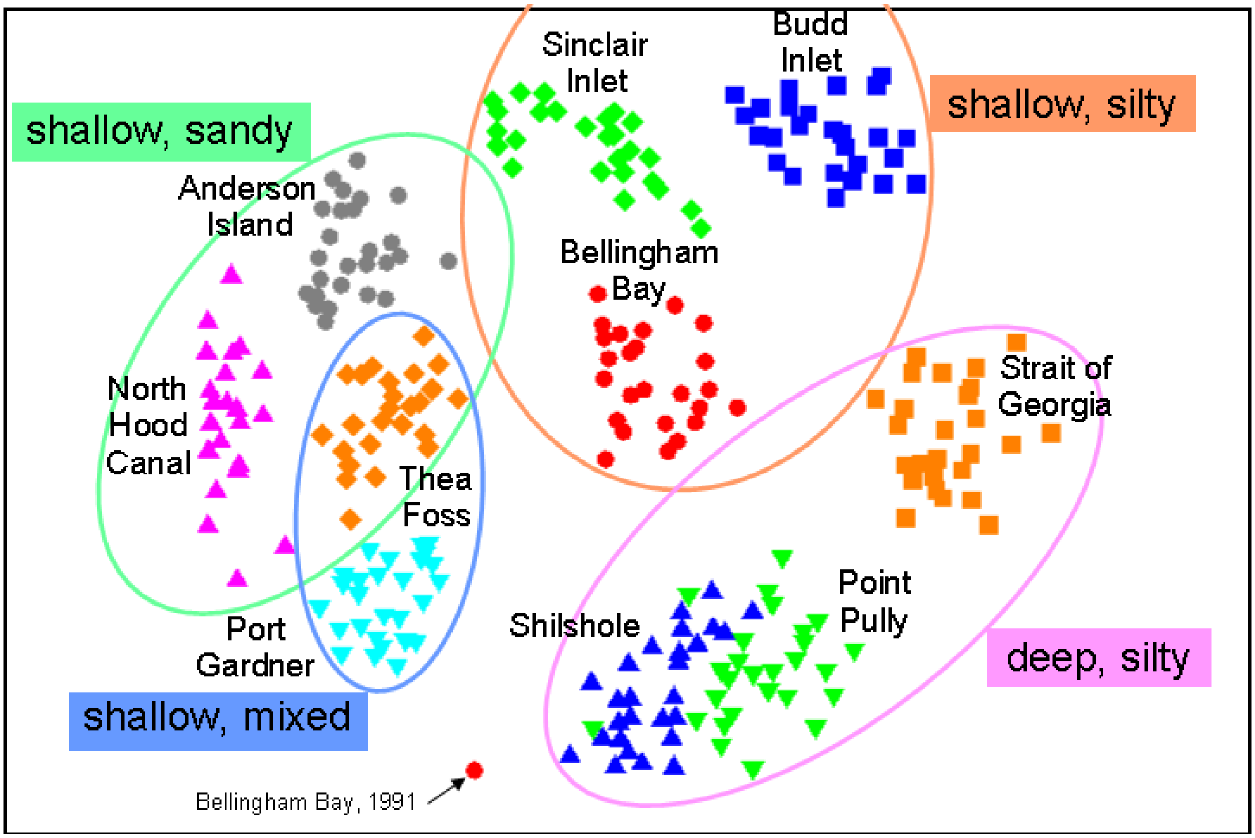

Figure 7. Nonmetric multidimensional scaling ordination diagram indicating the degree of similarity of the species mixes and abundances at the 10 long-term stations over the years.

Each station has a separate symbol, repeated for each year. The closer the symbols are, the more similar the assemblages are. The ovals group stations by habitat type. For example, the benthos of the deep Central Basin stations (Shilshole and Point Pully) are similar, but very different from that in northern Hood Canal, all quite different from that in Budd Inlet. The unusually located point for the Bellingham Bay station for 1991 is largely an artifact of representing a high-dimensional dataset in two dimensions.

Figure 8. Mean abundance (number of individuals/0.1 m^2) of some of the common benthic invertebrate species found at all 10 stations and throughout Puget Sound: (a) *Prionospio* spp., a polychaete; (b) *Axinopsida serricata*, a small bivalve; (c) *Parvilucina tenuisculpta*, a small bivalve; (d) *Heterophoxus* spp., an amphipod; e) *Euphilomedes producta*, an ostracod ("seed shrimp").

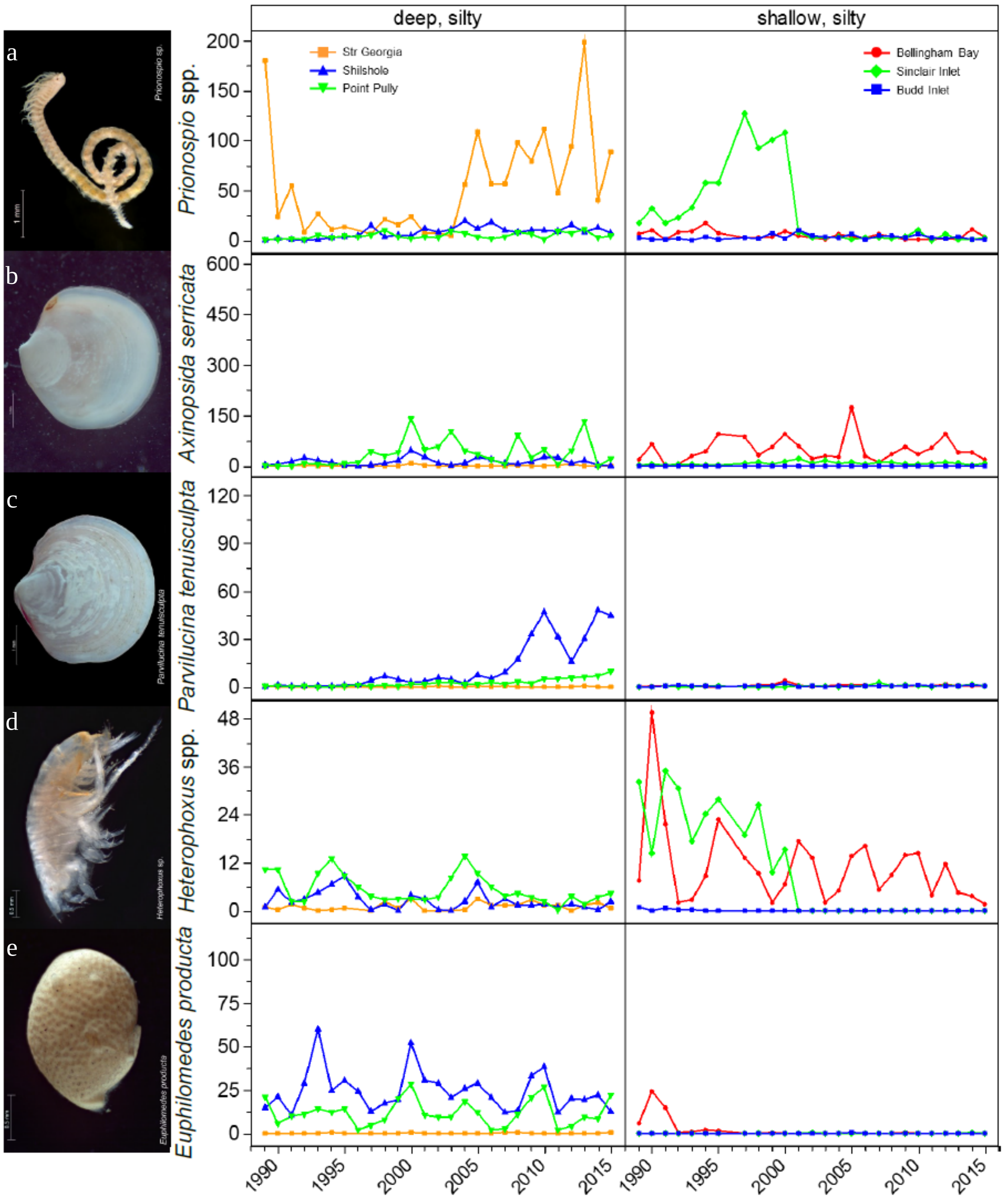

Figure 8 (continued). *The stations are arranged by habitat type. All of the species are in the facultative detritivore feeding guild except Heterophoxus spp., which is a facultative carnivore. Abundances of these animals over the years at each of the 10 stations illustrate a number of patterns, including habitat preference (A. serricata, E. producta), differences among stations (Prionospio spp.), cycles (E. producta, Heterophoxus spp.), decreasing trends (E. producta, Heterophoxus spp.), increasing trends (P. tenuisculpta), mixed trends (Prionospio spp.), or multiple patterns.*

Trends in abundance and diversity

Abundance

Overall, total abundance of benthic invertebrates increased at the Strait of Georgia and Bellingham Bay stations and was unchanged at six other stations (Table 10). At the Sinclair Inlet station, benthic abundance peaked in 1995, then decreased precipitously between April 2000 and April 2001, followed by a slow and uneven increase to near-1989 levels, though with different mixtures of organisms. Abundance at the North Hood Canal station was considerably higher in 1997-1998, due primarily to the small bivalve *Nutricola lordi*, than in the rest of the 27-year time studied, and has been declining since around 2008. Total abundance at several stations displayed a cyclical-type pattern with an approximate 10-year period.

Taxa richness

Taxa richness increased at the Port Gardner and Point Pully stations, and decreased in Sinclair Inlet and Anderson Island (Table 10). The number of taxa at the North Hood Canal station peaked in the late 1990's and has been declining since then. At the Sinclair Inlet station, taxa richness was highest in the early 1990's, decreased for about 10 years, then leveled off. Taxa richness at the Anderson Island station decreased from 1990 to about 2003, then increased slightly and leveled off. Taxa richness was unchanged at the other five stations.

Evenness and dominance

Including all taxa, Pielou's evenness index appears to have increased strongly at the North Hood Canal station. That trend resulted from the decreasing abundance of *Nutricola lordi* – excluding that species, evenness values at North Hood Canal were unchanged over the years (Appendix C). The Swartz dominance index decreased from 1989 to about 2005 at the Anderson Island station, indicating lower diversity because fewer taxa were accounting for ever-greater proportions of the abundance, but then the dominance index increased somewhat. No trends in either dominance or evenness were found at the other stations.

Major taxa

Among the major taxonomic groups, the most consistent change was decreased amphipod abundance at four stations: Port Gardner, Point Pully, Thea Foss, and Budd Inlet (Table 10). Arthropod abundance did increase at the Strait of Georgia station. Echinoderms (specifically, brittle stars) increased in abundance at three stations (Strait of Georgia, Sinclair Inlet, and Thea Foss).

Results from the regional surveys indicate that total abundance decreased from the Baseline 1997-2003 survey to the Second Round survey of 2004-2014 in the regions encompassing the embayments of the Strait of Georgia and Admiralty Inlet, though not in other regions of Puget Sound. The primary changes in the Strait of Georgia region occurred in the northern, urban portion of Bellingham Bay, not in the outer bay, where the long-term Bellingham Bay station is located, at which total abundance increased. (The Strait of Georgia long-term station is outside the regional boundaries.) None of the long-term stations is located in the Admiralty Inlet region, so no direct comparison can be made.

Table 10. Trends in univariate benthic measures over the period 1989-2015, by station.

Changes in abundance not categorized as improvements or deteriorations involve mixtures of both sensitive and tolerant species.

▲ increase ▼ decrease ● mixed trend -- no trend ND nondetects improvement deterioration

Parameter	3, Strait of Georgia	4, Bellingham Bay	13, North Hood Canal	21, Port Gardner	29, Shilshole	34, Sinclair Inlet	38, Point Pully	40, Thea Foss Waterway	44, East Anderson Island	49, Inner Budd Inlet
Total Abundance	▲	▲	●	--	--	●	--	--	--	--
Taxa Richness	--	--	●	▲	--	▼	▲	--	▼	--
Pielou's Evenness	--	--	▲	--	--	●	--	--	●	--
Swartz Dominance Index	--	●	▲	▲	--	--	--	--	▼	--
Annelid Abundance	--	--	--	▲	--	●	●	--	▼	--
Arthropod Abundance	▲	--	--	▼	--	--	▼	▼	--	▼
Echinoderm Abundance	▲	●	--	--	--	▲	--	▲	●	--
Mollusc Abundance	--	--	▼	--	--	--	●	--	▲	--
Misc. Taxa Abundance	--	--	--	--	--	●	--	--	--	--

Total abundance decreased from the regional Baseline to Second Round surveys in four of the five geomorphological/anthropogenic-use strata[6], though not in the Basin stratum. Taxa richness remained unchanged from Baseline to Second Round by region, but decreased significantly in the Harbor, Passage, and Urban strata. The trends, or lack thereof, at the long-term stations are not consistent with the wider-scale results.

Changes in individual taxa over time

For the most part, there were no trends in the common individual taxa across stations. In a few cases, abundances increased or decreased over time at more than one station, generally in the animals' preferred habitats. These trends are illustrated in Figure 8.

- The small bivalve *Parvilucina tenuisculpta* increased at half the stations. The increase was exponential at Port Gardner.
- The ostracods ("seed shrimp") *Euphilomedes carcharodonta* and *Euphilomedes producta* both decreased at both the Port Gardner and Thea Foss stations.
- The amphipod *Heterophoxus* spp. disappeared after 2000 at the Sinclair Inlet station and has been decreasing in abundance in Budd Inlet.
- For a small polychaete, *Prionospio* spp., found in 71% of samples at the long-term stations, trends were mixed and patterns varied by station.
- Another small white clam, *Axinopsida serricata*, the most common species of all Puget Sound benthos, tends to peak in abundance every 2-3 years at individual long-term stations, though not in sync across stations. Its abundance has been decreasing since 1998 at the Thea Foss station.

Puget Sound-wide, abundances of several species – including *Parvilucina tenuisculpta* and *Prionospio steenstrupi* – thought to be moderately tolerant to pollution, hypoxia, and/or nutrient enrichment (Gillett et al., 2015) increased from the Baseline 1997-2003 survey to the 2004-2014 Second Round survey. Such patterns were seen only occasionally among the long-term stations, however, with the exception of *Parvilucina tenuisculpta*, which increased in abundance at five of the long-term stations, most notably at Port Gardner, Anderson Island, and Shilshole (Figure 8).

Euphilomedes carcharodonta was listed among the species whose decline contributed to decreased total abundance in the Admiralty Inlet and Strait of Georgia regions of Puget Sound. Among the long-term stations, that species decreased, but primarily at Port Gardner and Thea Foss. *E. carcharodonta* also is thought to be moderately pollution-tolerant (Gillett et al., 2015).

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[6] Basin, Harbor, Passage, Rural, Urban (Dutch et al., 2009)

Changes in communities over time

At three stations, Sinclair Inlet, Anderson Island, and Thea Foss, the communities changed substantially during the 27 years. By contrast, the Budd Inlet benthic community has remained largely unchanged. At the other stations, there were shifts in the benthos over time, with sets of successive years having generally similar taxa and abundance (Appendix C).

Sinclair Inlet: The species mixes and abundances at the Sinclair Inlet station were quite different before and after 2000. Several species at the Sinclair Inlet station disappeared after 2000, e.g., the amphipod *Heterophoxus* sp. and the polychaete *Phyllochaetopterus prolifica*; and others suddenly appeared or greatly increased in abundance, e.g., the polychaete *Pholoe* sp. and the bivalve *Nutricola lordi* (Figure 9). Multiple species declined precipitously between 2000 and 2001, not just the two shown in Figure 9; likewise, more than just two species increased after 2001.

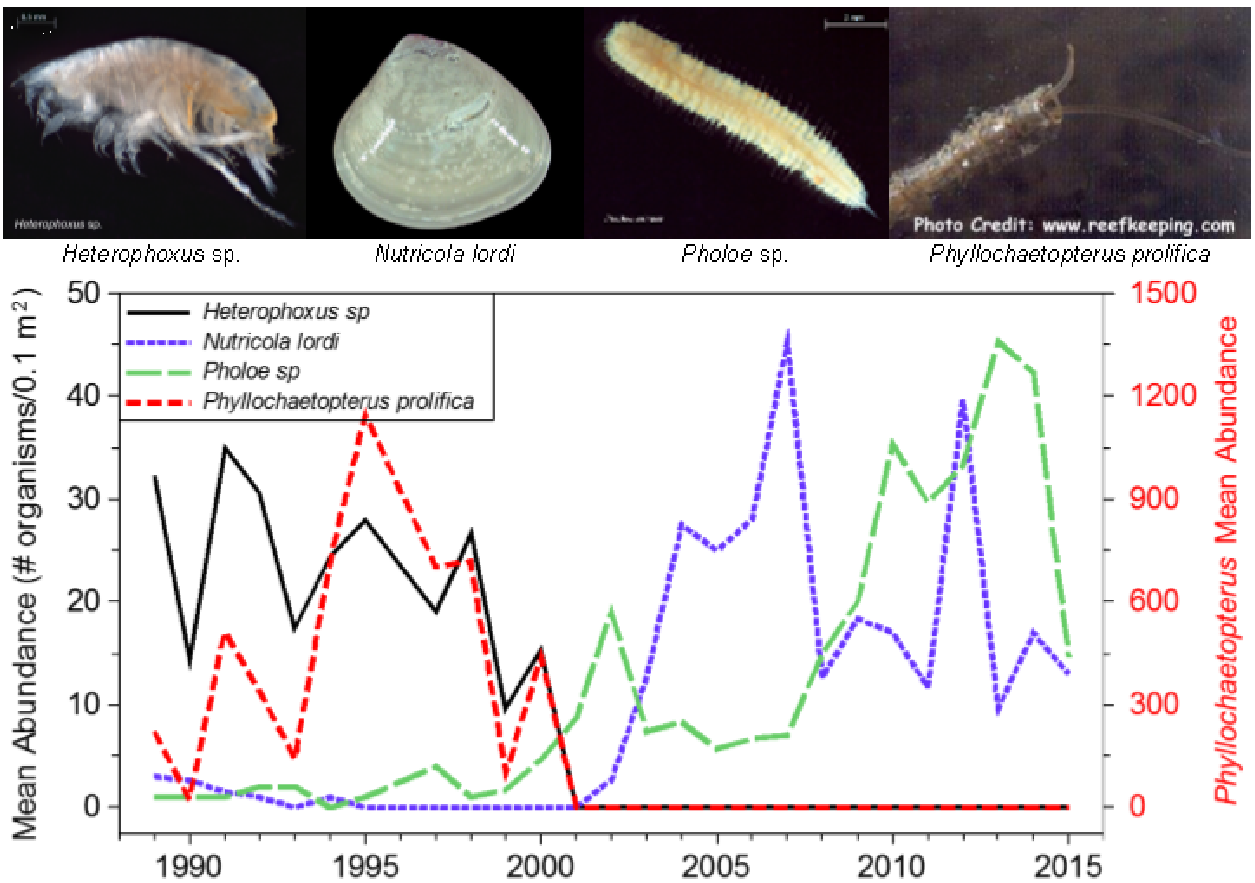


Figure 9. Changes in abundance of several species over time at the Sinclair Inlet station.

Note the separate scale for abundance of Phyllochaetopterus prolifica.

Anderson Island: The Anderson Island station benthos also underwent rapid change, around the year 1998 — the assemblages were distinct in 1989-1997 vs. 1998 vs. 1999-2015. The sediment grain size changed around that time, to comprise more sand and less clay.

Two of the same species that declined so abruptly at the Sinclair Inlet station also did so at Anderson Island, specifically the polychaetes *Phyllochaetopterus prolifica* and *Spiochaetopterus costarum* Cmplx. But the species which increased at Anderson Island after 1998 were not the same as those that increased so strongly after 2000 in Sinclair Inlet.

Thea Foss: At the Thea Foss station, the 1989-1992 assemblages were distinct from those in 1993-2015. Species which appeared or disappeared in the Thea Foss Waterway were different from those in Sinclair Inlet or at Anderson Island. What made 1989-1992 distinct from later years at the Thea Foss station were frequently species that were in low numbers in the early years and tended to increase gradually over time. That pattern, combined with the decrease in PAHs at the same time, suggests that cleanup of the Thea Foss Waterway may have improved conditions enough that those species could flourish.

Feeding guilds

How, where, and what organisms eat serve different functions in the ecosystem. Functional feeding guilds determined by Macdonald et al. (2010, 2012) integrate not only what organisms eat, but also where and how they obtain their food (Figure 10). Characterizing the benthos by feeding guilds gives perspectives into ecological conditions.

Grouping taxa into those functional feeding guilds demonstrates that while feeding guild abundances differ by station (Figure 11a), the proportions of taxa in the feeding guilds are similar across stations (Figure 11b). Furthermore, although the abundance—and even the *type* of organisms—by feeding guild varies considerably from year to year within a single community, the percent abundance remains almost constant (Appendix C). In other words, the functions that the organisms serve in the community are preserved, unless something happens to unbalance the community, as in Sinclair Inlet in 2000-2001.

ANOSIM similarity analysis of the benthos summed up to the feeding guilds for these 10 stations combined over 27 years reveals that the feeding guild structure in 2000, was statistically significantly different compared to about half the other years. One factor in the difference was total abundance, which was higher in 2000 than in all other years, 10-30% higher in 2000 than in the years for which the feeding guild structure was significantly different from 2000. Further investigation reveals that there were more obligate suspension-feeders – a small fraction (4-6%) of the soft-bottom benthos – in 2000 than in other years. Surface deposit feeders was the only feeding guild which did not have more organisms in 2000 than other years.

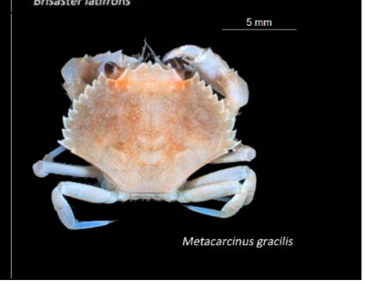
Feeding Guild Type	Examples	
Benthic Carnivore • eats live animals only		
Facultative Carnivore • eats live animals when available, but capable of switching feeding modes		
Facultative Detritivore • ingests particulate matter (without sediment), but capable of switching feeding modes		
Surface Deposit Feeder • ingests sediment at surface, digests edible organic matter, excretes inedible particles		
Subsurface Deposit Feeder • ingests sediment below surface, digests edible organic matter, excretes inedible particles		
Other: Suspensivore • filter feeder Herbivore • eats plants Macro-omnivore • eats plants and animals Planktivorous Carnivore • eats zooplankton		

Figure 10. Functional feeding guilds (Macdonald et al., 2012) and a few representative organisms.

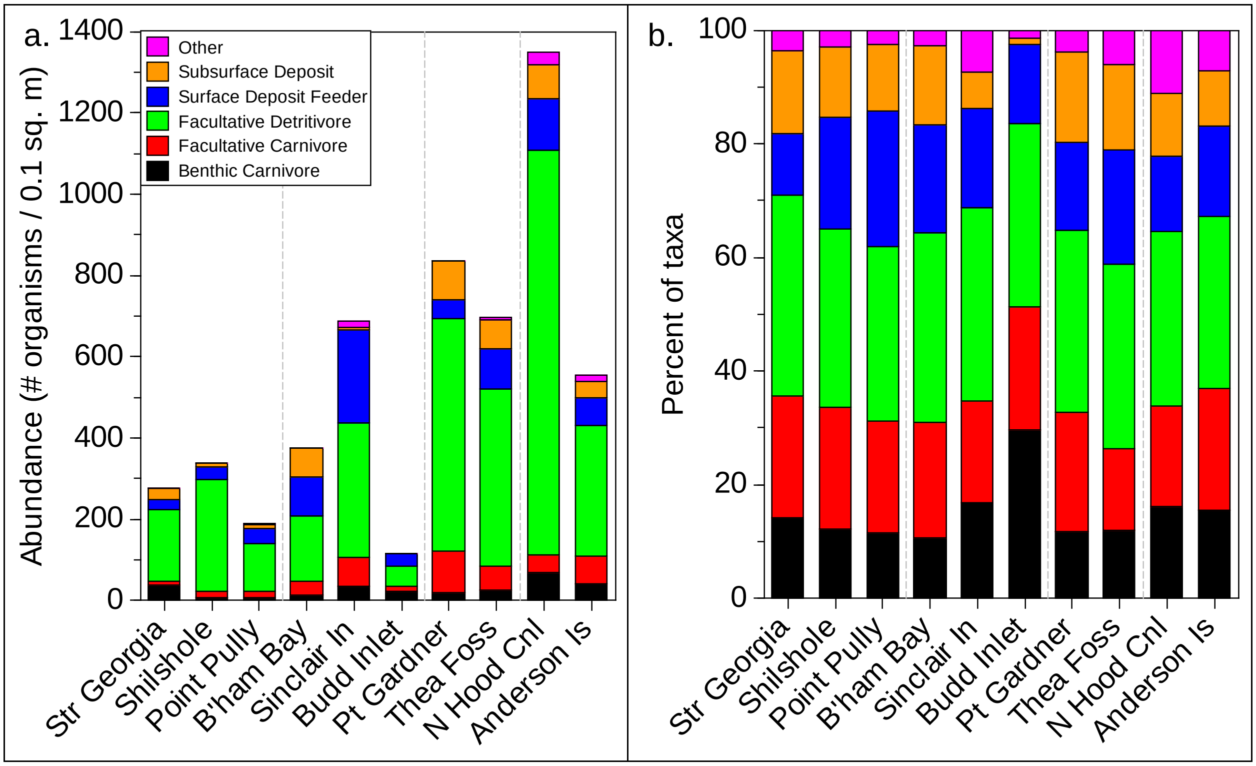


Figure 11. (a) Mean abundance and (b) mean percent taxa of benthic invertebrates by functional feeding guild for each of the 10 long-term sediment monitoring stations.

The stations are grouped by habitat type.

Changes in feeding guilds

Changes in the feeding guilds are described by habitat type below. See Table 11 and the graphs in Appendix C.

Deep, silty

Strait of Georgia: The community structure was very different prior to 2000 than since. The numbers of subsurface deposit feeders increased from 10-15% of abundance in 1989-1993 to about 75% in 1997, then about 50% in 1998-1999. In 2000-2001, more than 80% of the animals were facultative detritivores. There have been increases in surface and subsurface deposit feeders and decreases in benthic carnivores since 2004, when over 40% of the benthos were carnivorous.

Shilshole: The year 1989 stands out as being different from all others, with about 25% of the animals being subsurface deposit feeders, compared to <5% in other years.

Point Pully: The proportions of subsurface deposit feeders decreased from over 15% to less than 10% over the years, with facultative detritivores increasing. In 2007 and again in 2014, the proportions of facultative detritivores dropped from about 60% to about 25% of total abundance.

Shallow, silty

Bellingham Bay: The numbers of subsurface deposit feeders, specifically *Scalibregma californicum*, increased suddenly in 2014, with the numbers of *S. californicum* alone doubling the total abundance that year. With that increase in subsurface deposit feeders and with the 2013 large increase in numbers of surface deposit feeders, the proportions of facultative detritivores dropped from 40-50% of abundance to 10-20%.

Sinclair Inlet: Between 2000 and 2001, the benthic community shifted from one largely dominated by facultative detritivores to one dominated by surface deposit feeders. The numbers of obligate benthic carnivores also increased after 2000.

Budd Inlet: In addition to almost no subsurface deposit feeders, there also are almost no herbivores, macro-omnivores, planktivores, or suspensivores. There appears to be an almost cyclical pattern to the relative abundances of the obligate and facultative detritivores and the obligate and facultative carnivores at that station. The balance of surface deposit feeders to facultative detritivores was reversed in 2007 and especially in 2013.

Shallow, mixed

Port Gardner: There has been a steady increase in subsurface deposit feeders and decrease in facultative detritivores since 2004.

Thea Foss: In 1989-1990, there were relatively more surface deposit feeders and fewer subsurface deposit feeders than in other years.

Shallow, sandy

North Hood Canal: The proportion of facultative detritivores has decreased from over 80% during 1989-1998 to 60-70%, likely due to the decrease in abundance of *Nutricola lordi*, a facultative detritivore. The two groups which increased the most were surface deposit feeders and benthic carnivores.

Anderson Island: The change in benthic taxa before-during-after 1998 was not strongly represented in relative abundances of the feeding guilds, though the proportion of facultative detritivores did increase slightly. In 1997 there were relatively more surface deposit feeders and fewer facultative detritivores than in other years.

Table 11. Trends in feeding guild abundances over the period 1989-2015, by station.

▲	increase	▼	decrease	●	mixed trend	--	no trend

Feeding Guild	3, Strait of Georgia	4, Bellingham Bay	13, North Hood Canal	21, Port Gardner	29, Shilshole	34, Sinclair Inlet	38, Point Pully	40, Thea Foss Waterway	44, East Anderson Island	49, Inner Budd Inlet
Benthic Carnivore	--	●	--	--	--	▲	▲	--	--	--
Facultative Carnivore	--	--	--	▲	--	▼	--	▲	--	--
Facultative Detritivore	▲	--	▼	--	--	▼	--	--	●	▼
Surface Deposit Feeder	▲	--	--	--	--	▲	--	▼	--	--
Subsurface Deposit Feeder	--	--	--	▲	▼	--	▼	--	▼	--
Other	--	--	●	--	--	▼	--	--	▼	--

Relationships Between Environmental Variables and Benthos

Of the environmental variables measured, those with the greatest correlation to the benthic invertebrate communities were habitat variables (location, depth, salinity, temperature, grain size, TOC), grab penetration depth, and time of year (date of sampling) (Table 12). At the North Hood Canal and Budd Inlet stations, no statistically significant correlations were found with any of the environmental variables.

The chemical contaminants that were measured were generally uncorrelated with the benthos, or added at most a few percent to the correlation. There were weak correlations between the benthic communities and lead or PAHs at Thea Foss, and mercury at Sinclair Inlet (Table 12).

All of the sampling was done in the spring, in April in most years, but occasionally in March or even early May. Climatic and oceanographic conditions vary by year, and environmental cues for reproduction include temperature and food availability. Size and stage of development would affect whether juveniles would be retained on the 1-mm mesh sieve which would catch the adults. Thus some of the variability among the benthos found was likely due to when they were collected.

Table 12. Multivariate correlations between benthic invertebrate communities (all taxa) and environmental variables.

Correlations not statistically significant at α = 0.05 are not shown.

Station(s)	Spearman rho	Variables
All stations and years together	0.451	TOC, Fines
All stations within years	0.448	TOC, Cd
	0.474	Cd, Ag, Zn
All years within stations	0.329	Julian, Temp, Pen
3, Strait of Georgia	0.527	Fines, Temp
4, Bellingham Bay	0.377	Julian, Temp, Pen
13, North Hood Canal	--	none
21, Port Gardner	0.312	Julian, Temp
29, Shilshole	0.397	Julian, Temp, Pen
34, Sinclair Inlet	0.488	Julian, TOC, Sal
38, Point Pully	0.420	Julian, Sal, Pen
40, Thea Foss Waterway	0.365	Julian, TOC, Fines, Pb
44, East Anderson Island	0.507	Julian, Pen
49, Inner Budd Inlet	--	none

Ag = silver (ug/g); Cd = cadmium (ug/g); Fines = silt-clay content (%); Hg = mercury (ug/g);
HPAH = Total HPAH (sum of 9 compounds) (ng/g); Julian = Julian date of sampling; Pb = lead (ug/g);
Pen = grab penetration depth (cm); Sal = salinity of overlying water in the grab (ppt);
Temp = temperature of surface sediment in the grab (^{o}C); TOC = total organic carbon (%); Zn = zinc (ug/g)

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Discussion

The nearly three decades' worth of benthic invertebrate community information is a unique and very important dataset for science and for understanding the Puget Sound ecosystem. This information provides insights into benthic community structure and life cycles of individual species that can only be obtained by a continuous set of consistent measurements from a long-term monitoring program.

Chemistry

Other than metals and PAHs, few contaminants were measurable above detection limits. Four of the 10 long-term stations are located in urbanized bays and have higher chemical contaminant concentrations than the six stations which are more distant from industrial influences. Sediment contaminant concentrations exceeded Washington Sediment Management Standards (SMS) at two stations: mercury at Sinclair Inlet and PAHs at Thea Foss. The sediment chemistry results for the long-term stations are consistent with those of the regional-scale monitoring program.

Concentrations of organic contaminants in sediments, and toxicity of such contaminants, have been found to “correlate well” with TOC (Michelsen, 1992). The partition of organic contaminants into the organic fraction of sediments is the basis for the requirement for TOC-normalization of organic contaminants for the Sediment Management Standards. Michelsen (1992) also states that others have found poor correlations between TOC and the dry weight concentrations of organic contaminants, while still finding toxicity and TOC to be correlated. Among the Puget Sound long-term sediment monitoring stations, moderate, positive correlations between TOC and PAHs were found only at the sandy, low-TOC Anderson Island station. At all the other stations, TOC-PAH correlations were either nonexistent or weak and negative.

Benthos

Except where some disturbance destabilized the habitats and communities, the sediments at the long-term stations, and the invertebrate communities inhabiting them, have largely remained stable over time, though with some drift and cycles in species composition and abundance. A few of the stations, however, experienced profound change.

- At the Sinclair Inlet station, there was a sudden loss of some species in 2001 and sudden increase in others.
- The benthos at the Anderson Island station shifted in the late 1990s for unknown reasons—the changes in species and abundance were more abrupt and of larger magnitude than would be expected for the slight shift in clay and sand content that occurred.
- Gradual changes in the benthos in the early years of sampling at the Thea Foss station may have been related to sediment cleanups in Commencement Bay.
- The grain size at the Strait of Georgia station in 1989-1994 was considerably coarser than from 1997 on. Whether grain size was influenced by Fraser River flow or perhaps reflected inaccuracy in navigational positioning is not known. The dominant benthic organisms at that station did change with the grain size.

Feeding guilds summarize some of the functions of benthic invertebrate communities. In stable conditions, such as at the bottom of the deep Central Basin of Puget Sound, the feeding guilds were essentially constant proportionally, even though the species and abundances in each guild varied from year to year. Thus, the ecological function of the feeding guilds is conserved. In impacted communities, such as Sinclair Inlet, however, there was considerable variability in the feeding guilds over time. The pattern of stable feeding guild proportions is consistent with that reported by Macdonald et al. (2012) for the Strait of Georgia.

Correlations

On the whole, there was little to no relationship between the sediment contaminant variables measured at these 10 stations and the benthic communities. However, at the two stations with persistent contaminant concentrations higher than the SMS, those particular contaminants were weakly correlated with the benthos. The primary determinants of invertebrate communities were found to be habitat variables, such as depth and grain size. Secondarily, the date of sampling had a small effect on the benthos found.

The lack of correlation between contaminants and the benthos likely relates to several factors:

- Cleanups and source control of point-source pollution.
- Increasing importance of nonpoint-source pollution from stormwater.
- Other contaminants or stressors not yet measured.

Patterns at different spatial and temporal scales

Although some of the patterns in sediment chemical contamination at the long-term stations were generally similar to those at bay-, region-, or Sound-wide scales, the same was not true of patterns in the benthos. The general lack of strong trends in the benthos at the long-term stations over 27 years continuously, whether individual species or univariate measures of abundance and diversity, suggests that some of the changes reported at wider scales at only two points in time may actually be within the normal range of temporal variability. Furthermore, some of the changes observed between the Baseline and the Second Round surveys could potentially be due to having not resampled the same locations.

Conclusions and Recommendations

Conclusions: Lessons Learned and Moving Forward

These 10 stations were chosen from a larger set in 1997 for continuation of annual monitoring to represent different types of habitats and distinct benthic communities. Because they were hand-picked, these stations cannot be used to make inferences about larger areas (geographic regions or bays).

The random-sampling designs of the regional and urban bays sediment monitoring programs provide spatial coverage and enable estimation of conditions for broad areas, but logistically and economically could be sampled only one region and one bay per year. Thus, there was a gap of 5-11 years between the first and second surveys for any given region or bay. Such an interval is sufficient for measuring changes in sediment contamination, but insufficient for characterizing the benthos. Because oceanographic conditions differ year-by-year, external forces affecting the benthos (e.g., water temperature, salinity) differed from one region or bay to the next within the 10-year regional surveys or 6-year urban bays surveys, and between the first and subsequent samplings of any given region or bay. Hence there was both temporal and spatial confounding in the regional and urban bays sediment monitoring programs.

The continuity of the 10 long-term stations have provided insights for the temporal gaps in the regional and urban bays surveys, and the spatial monitoring programs have provided broad-scale context for the long-term program. Instead of continuing the segregated long-term and spatial surveys, Ecology is combining the best of both. Beginning in 2017, Ecology is now sampling annually at 50 stations throughout Puget Sound. The 10 long-term stations will be continued as part of those 50. Twelve stations coinciding with long-term Marine Waters monitoring program stations and 28 random stations chosen from a probabilistic design complete the set. From 2018 forward, the same 50 stations will be resampled every year. Thus, the combination of spatial and temporal coverage will enable Ecology to make annual estimates of sediment quality for all of Puget Sound.

The sediment monitoring program has met the original goals of documenting the status and trends of sediment contamination and benthic invertebrate communities. With knowledge gained from almost three decades of sampling, improvements from environmental management (e.g., toxics source control and cleanup), and the accelerating pace of climate change, it is time to broaden the focus.

Although legacy contaminants at levels known to be harmful to benthic organisms are largely confined to more highly urbanized and industrialized areas of Puget Sound and tend to be decreasing over time, adverse effects on benthic communities in the regional surveys have increased and do not correlate with sediment contamination. Furthermore, certain contaminants, such as PCBs, are not disappearing from the environment, but are concentrated and biomagnified up the food chain (West et al., 2017).

Benthic invertebrates are critical components of the entire Puget Sound ecosystem, providing crucial functions such as nutrient renewal, as well as sequestration and/or biomagnification of toxics. Thus, we must take an ecosystem approach to understanding the health of Puget Sound.

Toward that end, Ecology is enhancing the Puget Sound sediment monitoring program and collaborating with other monitoring programs to provide information on connections with the rest of the ecosystem, while continuing the important toxics work. In addition, since 2016, Ecology has been collaborating with the long-term Marine Waters monitoring program to jointly sample particulate nutrients in near-surface and near-bottom waters at 20 co-located sediment and waters stations, including 9 of the 10 long-term sediment stations (all but the Strait of Georgia station). This and other collaborations planned for 2018 and beyond are detailed in Dutch et al. (2018).

Recommendations

Results of this study support the following recommendations, which have already been implemented in the redesign of the Puget Sound Sediment Monitoring program (Dutch et al., 2018):

- Expand the set of long-term stations sampled annually to a set which can be used for making inferences about sediment conditions for the entire Puget Sound every year.
- Add biogeochemical parameters.
- Collaborate with other researchers in order to understand ecosystem-level processes.

In addition, understanding of shifts in ecological functioning with shifts in hydrological and nutrient dynamics with climate change will require seasonal sampling of the habitat and benthic inhabitants.

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Appendices

Appendices A, B, and C are available online linked to this report at:
https://fortress.wa.gov/ecy/publications/SummaryPages/1803005.html

Appendix A. Physical Sediment Characteristics Data Summary

Appendix B. Sediment Chemistry Data Summary

Appendix C. Benthic Invertebrates Data Summary

Appendix D. Glossary, Acronyms, and Abbreviations

Glossary

Adjusted R^2: A measure of how well a regression curve fits the data, adjusted for the inclusion of all terms; specifically, in a polynomial regression, inclusion of higher-order polynomial terms.

Anthropogenic: Human-caused.

Cleanup Screening Level: Sediment chemical concentrations above which at least moderate adverse biological effects are expected to occur.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Parameter: A physical, chemical, or biological property whose values determine environmental characteristics, or a calculated index whose values describe environmental or biological characteristics.

Point source: Sources of pollution that discharge at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites where more than 5 acres of land have been cleared.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Sediment Quality Standard: Sediment chemical concentrations below which adverse biological effects are not expected to occur or above which at least minor adverse impacts on benthic invertebrates are expected always to occur.

Acronyms and Abbreviations

CSL	Cleanup Screening Level
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System software

HPAH	high-molecular-weight polycyclic aromatic hydrocarbon
LPAH	low-molecular-weight polycyclic aromatic hydrocarbon
MEL	Manchester Environmental Laboratory
PAH	polycyclic aromatic hydrocarbon
PBDE	polybrominated diphenyl ether
PCB	polychlorinated biphenyl
PBT	persistent, bioaccumulative, and toxic substance
SQS	Sediment Quality Standard
USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WRIA	Water Resource Inventory Area

Units of Measurement

°C	degrees Centigrade
cm	centimeter
dw	dry weight
g	gram, a unit of mass
kg	kilogram, a unit of mass equal to 1,000 grams
km	kilometer, a unit of length equal to 1,000 meters
m	meter
mg	milligram
mg/Kg	milligrams per kilogram (parts per million)
mm	millimeter
ng/g	nanograms per gram (parts per billion)
psu	practical salinity units
ug/g	micrograms per gram (parts per million)
ug/Kg	micrograms per kilogram (parts per billion)