Herrera Environmental Consultants, Inc.

Memorandum

To Dan Cheney, Trina Wellman, Betsy Peabody, Joth Davis, Bobbi Hudson, Peter Becker, Susan Burke

From Peter Steinberg and Julie Hampden, Herrera Environmental Consultants

Date February 25, 2010

Subject Nitrogen Removal with Shellfish Harvest in Oakland Bay and Puget Sound

Low dissolved oxygen levels in portions of Puget Sound have prompted recent large scale studies in south Puget Sound (Roberts et al. [2008]) and Hood Canal (Hood Canal Dissolved Oxygen Program [www.hoodcanal.washington.edu]). Since nitrogen is the nutrient that most likely limits phytoplankton productivity, and phytoplankton productivity partially determines dissolved oxygen depletion, most research has focused on estimating the magnitude of nitrogen sources including watersheds, wastewater, the atmosphere, and exchange with the Pacific Ocean.

This memorandum summarizes an assessment of the potential for nitrogen removal from Oakland Bay and Puget Sound through shellfish harvest. The assessment of nitrogen removal is based on review of publicly available harvest data and a literature review on common nitrogen concentrations in shellfish. For perspective and scaling, quantities of nitrogen removal through shellfish harvest in Oakland Bay and Puget Sound are compared to atmospheric, watershed, and marine nitrogen loads to the surface mixed layers of these water bodies.

The sections below present analytic methods and analysis results for Oakland Bay and Puget Sound, highlighting areas of uncertainty.

Methods

Shellfish Harvest Nitrogen

All shellfish harvest data collected by the Washington Department of Fish and Wildlife were compiled, including harvest estimates for 14 major shellfish species for 2000 to 2008. Average annual shellfish harvests were determined by averaging the most recent (2000 to 2008) years of data in metric tons wet weight. The shellfish nitrogen concentration was assumed to be 1 percent of the total wet weight, a value well supported by the literature (Rice 2001; Ojea et al. 2004; Linehan et al. 1999) and by local ongoing tissue concentration studies in oysters (Henderson Inlet) and Manila clams (in Oakland Bay) (Davis 2010 unpublished data).

Nitrogen Loadings

This section describes the process of obtaining dissolved nitrogen loading estimates for Oakland Bay and Puget Sound. Loading estimation methods were different for Oakland Bay and Puget

Sound, with the former depending on a steady-state water and salinity balance model and the latter relying on a literature review without original calculations.

Oakland Bay

Since no known detailed nitrogen budgets were found for Oakland Bay, publicly available data were used to develop dissolved nitrogen loading estimates for watershed, wastewater, atmospheric and marine sources.

Watershed Nitrogen Loadings

The USGS StreamStats website (http://streamstats.usgs.gov/wastreamstats/index.asp) was used to develop flow estimates for the watershed. This application allows selection of any point on a map to reveal the drainage area to the point and mean annual precipitation within that drainage area. The StreamStats process was repeated around the perimeter of Oakland Bay to determine the waterbody's total drainage area and average watershed precipitation. Partitioning of this precipitation into evaporation, streamflow, and groundwater flow via hydrologic modeling was beyond the level of detail needed for this study. Instead, it was assumed that 80 percent of the precipitation falling on the watershed each year would be discharged as stream water or groundwater.

This total volume of stream water and groundwater entering Oakland Bay each year was multiplied by a single total dissolved nitrogen (TDN) concentration. Dissolved nitrogen was used in place of total nitrogen because dissolved nitrogen is more bioavailable than particulate nitrogen. TDN was used in place of dissolved inorganic nitrogen (DIN) because organic nitrogen is an appreciable portion of dissolved nitrogen in streams of the region. The stream water TDN concentration used was a flow-weighted mean concentration of the TDN concentrations of 32 Hood Canal tributaries, measured monthly over 2 years. The Hood Canal tributaries dataset was used because it is exhaustive and currently being published (Steinberg et al. *in press*), and it is considered to be representative of the Oakland Bay watershed because it comes from tributaries with land use distributions similar to those of Oakland Bay's tributaries.

Wastewater Nitrogen Loadings

Nitrogen loads entering Oakland Bay from the Shelton Wastewater Treatment Plant were estimated using flow data provided in the South Puget Sound Dissolved Oxygen Study – Interim Report (Roberts et al. 2008) and concentration data provided by City of Shelton (2009). Flow data included permitted maximum monthly average discharge. Concentrations provided by City of Shelton were the "typical" effluent concentrations of 10 to 12 mg/L DIN.

Atmospheric N Loadings

The atmospheric nitrogen loadings to Oakland Bay's water surface was estimated using the area's average rainfall amount, provided by the StreamStats program and the long-term volume-weighted mean DIN concentrations in rainwater at four regional National Atmospheric

Deposition (NADP) monitoring sites (Olympic National Park – Hoh River, La Grande, North Cascades National Park – Marblemount, and Mount Rainier National Park – Tahoma Woods) (NADP 2008). DIN concentrations, rather than TDN or TN concentrations, were used in the analysis because, as is common for precipitation chemistry data, only DIN data were available. Loads associated with dry nitrogen fallout were not estimated. Steinberg et al. (*in press*) presented calculations based on Clean Air Status and Trends dry fallout data that showed dry nitrogen fallout in the area was a minor source at 15 times smaller than nitrogen in precipitation.

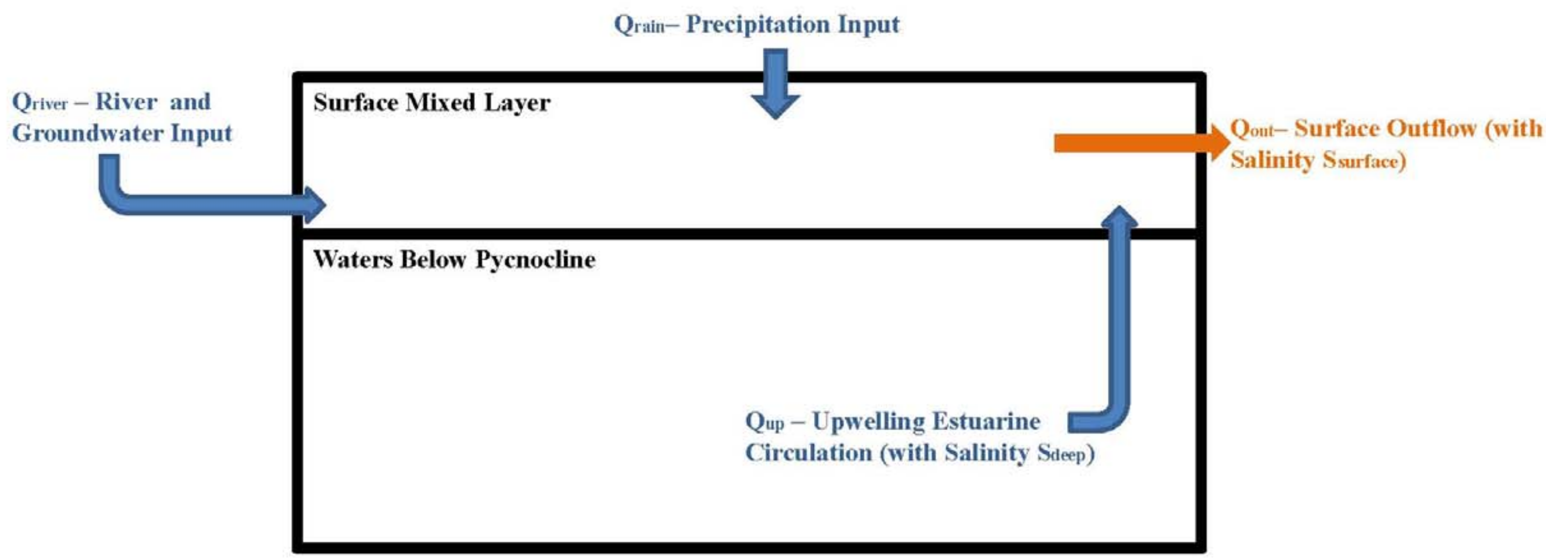
Marine Nitrogen Loads

Nitrogen loadings to the surface layer of Oakland Bay from estuarine circulation were estimated with steady state salinity and water balance equations, similar to calculations performed by Mackas and Harrison (1997) for all of Puget Sound. These equations and a diagram of the major components are presented in Figure 1. As shown in Figure 1, Oakland Bay is first divided into two boxes: one above its pycnocline (depth where maximum density gradient is found) and one below its pycnocline. Then, the measured average annual salinities for the surface and deep boxes, in combination with estimated freshwater flows entering Oakland Bay, are used to estimate the annual volume of water upwelling due to two-layer estuarine circulation flow. This upwelling volume is then multiplied by the DIN concentration at depth to arrive at the nitrogen loading due to estuarine circulation (referred to as the marine nitrogen loading for the rest of this text). Again, DIN data were used in place of TDN data because there were no measurements of organic nitrogen available.

The salinity and DIN concentration data for Oakland Bay that were used came from a representative monitoring station maintained by the Washington Department of Ecology (see station OAK004 in Figure 2). All data available (1989 to 2008) were downloaded from the web (Washington Department of Ecology 2009). The median pycnocline depth was found using a Matlab script to process all 193 available salinity profiles and find in each the depth at which the density gradient was greatest. All available salinity and DIN data for the station were then classified as surface or deep samples, and the median values were used for loading calculations.

Puget Sound

A literature review (rather than original calculations) was used to estimate inorganic nitrogen loadings to Puget Sound, because of the complexity and scale of the system and the existence of detailed loading estimates. Loading rates for marine inputs, sewage, and atmospheric inputs came from Mackas and Harrison (1997). That study analyzed potential for eutrophication in Georgia Basin and Puget Sound. It compared river and anthropogenic nitrate nitrogen loadings to loadings from estuarine circulation, with estuarine flow calculated in a salinity balance equation. DIN loading rates for rivers came from a USGS nutrient loading review for Puget Sound (Embrey and Inkpen 1998). DIN loading rates were used because TDN loading rates were not calculated.



1. **Water Balance Equation (Steady State)**

Inflow = Outflow

$$Q_{river} + Q_{rain} + Q_{up} = Q_{out}$$

2. **Salinity Balance Equation (Steady State)**

Upwelling Flow * Salinity at Depth = Outflow * Salinity at Surface

$$Q_{up} * S_{deep} = Q_{out} * S_{surface}$$

3. **Solving for Upwelling Flow Based on Known Salinity Profile and Water and Salinity Balance Equations**

$$Q_{up} = S_{surface} / S_{deep} * (Q_{up} + Q_{river} + Q_{rain})$$

Figure 1. Diagram of the salinity balance equation used to estimate estuarine circulation.

Legend

Monitoring station

Figure 2. Monitoring station location.

N

0 2,500 5,000 10,000 Feet

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Results

Tables 1 and 2 present the major components of the nitrogen cycles for Oakland Bay and Puget Sound, respectively. The Oakland Bay nitrogen cycle is also presented in Figure 3. Annual shellfish harvest data for Oakland Bay and Puget Sound are available in Appendix A.

Table 1. Major components of the Oakland Bay nitrogen cycle.

Nitrogen Input/Removal	Annual Loading (MT/year)	Annual Loading (Percent)
Input		
Sewage (DIN)	61.1	4.5%
Rivers and Groundwater (DIN)	168	12.4%
Atmospheric (DIN)	3.39	0.3%
Marine loading into Oakland Bay (DIN)	1,120	82.8%
Total Input	1,352	100%
Removal		
Shellfish Harvest (TN)	11.7	

DIN = Dissolved inorganic nitrogen
TN = Total nitrogen

Table 2. Major components of the Puget Sound nitrogen cycle.

Nitrogen Input/Removal	Annual Loading (MT/year)	Annual Loading (percent)	Source
Input			
Sewage (DIN)	5,658	3.3%	Mackas and Harrison (1997)
Rivers (DIN)	11,000	6.4%	Embrey and Inkpen (1998)
Shoreline Groundwater Input (DIN)	3,650	2.1%	Mackas and Harrison (1997)*
Atmospheric (DIN)	3,103	1.8%	Mackas and Harrison (1997)*
Marine loading into Puget Sound (DIN)	148,920	86.4%	Mackas and Harrison (1997)
Total Input	172,331	100%	
Removal			
Shellfish Harvest (TN)	62	--	This study's summary of WDFW harvest data for 2000 - 2008

* Estimates include Georgia Basin and Puget Sound
DIN = Dissolved inorganic nitrogen
TN = Total nitrogen

Oakland Bay Nitrogen Cycle

The most important source of nitrogen to the surface layer of Oakland Bay is upwelling caused by estuarine circulation, totaling an estimated 1,120 metric tons/year (MT/year). Loadings from the watershed (168 MT/year), wastewater (61.1 MT/year), and precipitation (3.39 MT/year) are

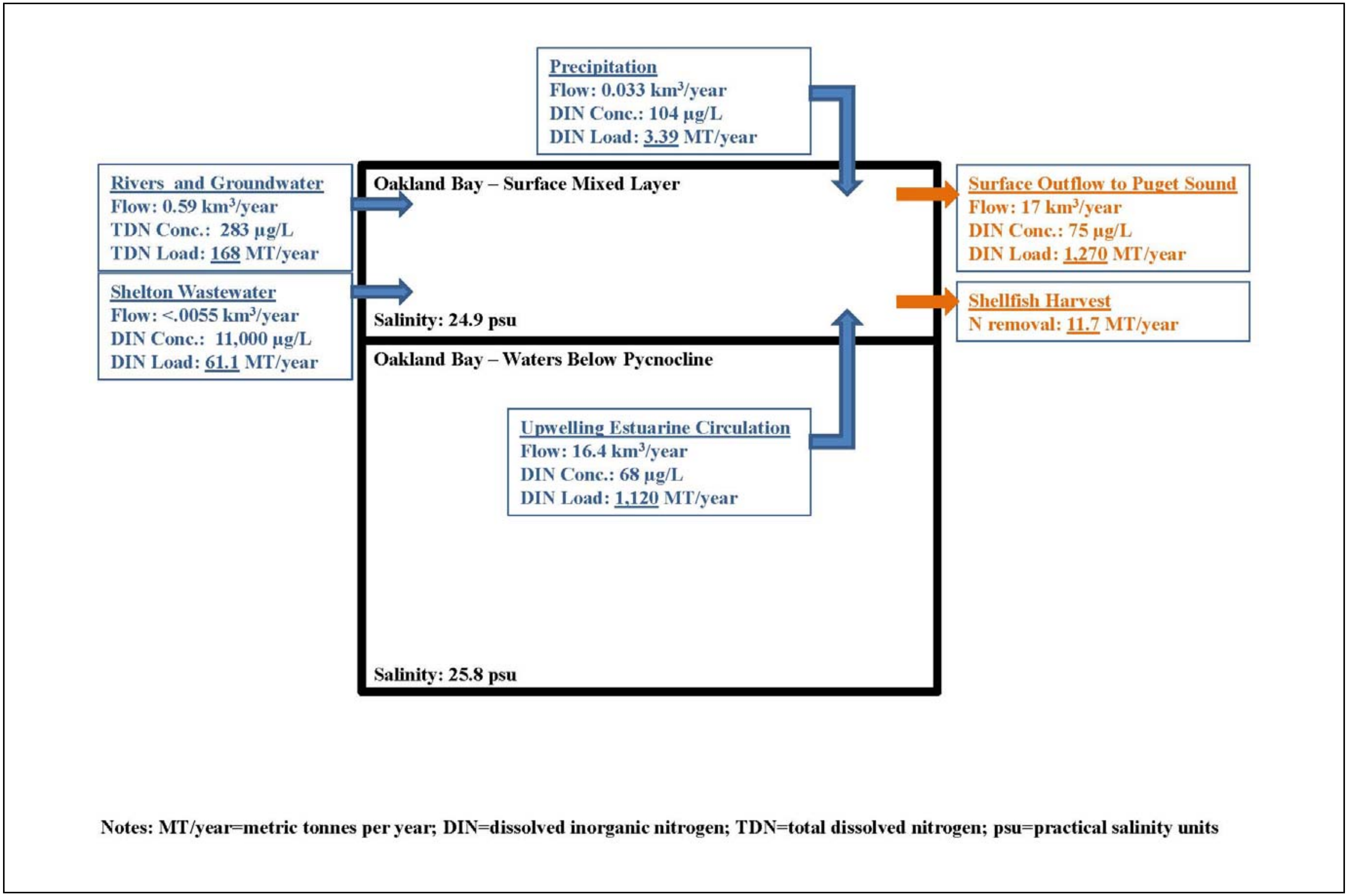

Figure 3. The Oakland Bay nitrogen cycle.

considerably smaller. Nitrogen removal through shellfish harvest sums to 11.7 MT/year, which represents 0.87 percent of the total nitrogen loading from all sources (i.e., the watershed, wastewater, marine, and precipitation) or 5.0 percent of the total load from sources excluding marine (i.e., the watershed, wastewater, and precipitation).

Puget Sound Nitrogen Cycle

Like Oakland Bay, the dominant nitrogen source in Puget Sound's nitrogen cycle is marine loading. Marine nitrogen loading is approximately 86 percent of the total nitrogen load from sewage, rivers, shoreline groundwater input, atmospheric loading, and marine loading. Shellfish nitrogen removal was 62 metric tons/year (0.04 percent of the total N load), or 0.26 percent of the total load from sewage, rivers, shoreline groundwater input, and atmospheric sources.

Discussion

Shellfish harvest removes more of the nitrogen input to Oakland Bay than Puget Sound, but it removes no more than 1 percent of the dissolved nitrogen load in either location. In Oakland Bay, shellfish harvest was 5.0 percent of the load from terrestrial sources, excluding the marine nitrogen load. Shellfish harvest represents a larger proportion of dissolved nitrogen load to Oakland Bay than Puget Sound because the average depth is lower in Oakland Bay and, thus, the shellfish harvest rate per volume of water is greater in Oakland Bay.

In part, shellfish nitrogen removals appear small because marine nitrogen loads in both Puget Sound and Oakland Bay are relatively high. Waters outside of the Strait of Juan de Fuca exhibit a strong correlation between salinity and nitrate concentrations, i.e., the nitrate concentration increases with depth. Upwelling of these deep waters off the Strait of Juan de Fuca is the largest nitrogen source to Puget Sound (Mackas and Harrison 1997). Within Puget Sound, areas having relatively uniform salinities with depth experience vertical mixing and overturning circulation that contributes additional nitrogen loads to surface waters.

Importantly, this set of calculations does not include shellfish impacts on water quality, other than through harvest. For example, shellfish may reduce the release of ammonium resulting from sediment diagenetic processes and also favor the conversion of ammonium to nitrate, an essential step before denitrification (Cerco and Noel 2005). These difficult-to-quantify higher order water quality effects are neglected in looking only at nitrogen removal through harvest. A deterministic shellfish and water quality modeling study in the northern Adriatic Sea found nitrogen loss to sediment processes could be a flux twice as large a nitrogen removal from harvest (Brigolin et al. 2009). If this pattern were realized in Puget Sound, the combined nitrogen removal due to aquaculture and harvest would be closer to 3 percent of the total input nitrogen load.

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APPENDIX A

Shellfish Harvest Data

Table A-1. Recent shellfish harvest in Oakland Bay recorded by WDFW.

Species	Year	Shellfish Harvested (kg/year)	Nitrogen Removed (kg/year)	Average Annual N Removed (kg/year) (2000 - Present) [a]
Manila Clam	2000	969,192	9,692	
	2001	1,017,285	10,173	
	2002	1,109,875	11,099	
	2003	874,849	8,748	
	2004	954,740	9,547	
	2005	1,083,670	10,837	
	2006	2,090,808	20,908	
	2007	1,104,085	11,041	11,506 [b]
Kumamoto Oyster	2002	2,338	23.4	
	2003	2,391	23.9	5.9
Mussels	2000	664	6.6	
	2001	3,103	31.0	
	2003	523	5.2	
	2004	3,273	32.7	
	2005	935	9.4	
	2006	4,394	43.9	
	2007	45,470	454.7	
	2008	58,209	582.1	145.7
Pacific Oysters	2003	604	6.0	
	2004	397	4.0	
	2005	846	8.5	
	2006	197	2.0	
	2007	695	6.9	
	2008	584	5.8	4.2
Geoduck	2002	3,729	37.3	
	2008	803	8.0	5.7

[a] Average annual N removal quantities are based on the rows of data shown, except years with no reported harvest are assigned zero.

[b] Manila Clam harvest data for 2008 were not available at time of compilation. This year was excluded from harvest averages (i.e., it was not counted as a zero harvest).

Table A-2. Recent shellfish harvest in Puget Sound recorded by WDFW.

Species	Year	Shellfish Harvested (kg/year)	Nitrogen Removed (kg/year)	Average Annual N Removed (kg/year) (2000 - Present) [a]
Blue Mussel	2000	850,792	8,508	
	2001	755,329	7,553	
	2002	487,179	4,872	
	2003	765,325	7,653	
	2004	969,419	9,694	
	2005	1,145,964	11,460	
	2006	1,759,883	17,599	
	2007	1,078,530	10,785	
	2008	1,048,338	10,483	9,845
Butter Clam	2000	25,462	255	
	2001	26,307	263	
	2002	27,795	278	
	2003	8,437	84	
	2004	8,828	88	
	2005	6,342	63	
	2006	14,150	142	
	2007	10,890	109	
	2008	7,507	75	151
Cockle Clam	2000	258	3	
	2003	523	5	
	2004	1,314	13	
	2005	823	8	
	2006	516	5	
	2008	322	3	18
Geoduck Clam	2000	8,705	87	
	2001	123,851	1,239	
	2002	235,650	2,357	
	2003	220,619	2,206	
	2004	349,887	3,499	
	2005	436,599	4,366	
	2006	526,116	5,261	
	2007	452,099	4,521	
	2008	433,364	4,334	3,097

Table A-2 (continued). Recent shellfish harvest in Puget Sound recorded by WDFW.

Species	Year	Shellfish Harvested (kg/year)	Nitrogen Removed (kg/year)	Average Annual N Removed (kg/year) (2000 - Present) [a]
Horse Clam	2000	258	3	
	2001	2,256	23	
	2002	3,749	37	
	2003	6,088	61	
	2004	4,965	50	
	2005	1,708	17	
	2006	2,074	21	
	2007	1,647	16	
	2008	4,208	42	30
Manila Clam	2000	2,388,226	23,882	
	2001	2,696,185	26,962	
	2002	2,728,295	27,283	
	2003	2,797,984	27,980	
	2004	2,958,417	29,584	
	2005	3,490,719	34,907	
	2006	5,189,334	51,893	
	2007	3,366,999	33,670	
	2008	2,382,875	23,829	31,110
Mud Clam (Macoma)	2000	7,325	73	
	2002	225	2	
	2003	83	1	
	2006	6	0	
	2007	4	0	
	2008	324	3	13
Native Littleneck Clam	2000	56,890	569	
	2001	64,000	640	
	2002	64,330	643	
	2003	31,485	315	
	2004	34,915	349	
	2005	45,402	454	
	2006	39,335	393	
	2007	39,183	392	
	2008	27,802	278	448

Table A-2 (continued). Recent shellfish harvest in Puget Sound recorded by WDFW.

Species	Year	Shellfish Harvested (kg/year)	Nitrogen Removed (kg/year)	Average Annual N Removed (kg/year) (2000 - Present) [a]
Softshell Clam	2001	102,087	1,021	
	2002	293,491	2,935	
	2003	509,513	5,095	
	2004	316,812	3,168	
	2005	421,351	4,214	
	2006	392,936	3,929	
	2007	232,830	2,328	
	2008	440,717	4,407	3,387
Eastern Oyster	2000	6	0	
	2002	9	0	
	2004	1,638	16	
	2005	11,744	117	
	2006	15,050	151	
	2007	12,667	127	
	2008	32,990	330	106
European Oyster	2000	6,951	70	
	2001	5,417	54	
	2002	4,268	43	
	2003	5,487	55	
	2004	5,332	53	
	2005	5,737	57	
	2006	6,151	62	
	2007	7,574	76	
	2008	1,374	14	54
Kumamoto Oyster	2000	3,181	32	
	2001	8,578	86	
	2002	24,985	250	
	2003	32,766	328	
	2004	37,551	376	
	2005	38,630	386	
	2006	48,402	484	
	2007	31,102	311	
	2008	18,169	182	270

Table A-2 (continued). Recent shellfish harvest in Puget Sound recorded by WDFW.

Species	Year	Shellfish Harvested (kg/year)	Nitrogen Removed (kg/year)	Average Annual N Removed (kg/year) (2000 - Present) [a]
Olympia Oyster	2000	1,695	17	
	2001	25,865	259	
	2002	1,536	15	
	2003	1,390	14	
	2004	1,187	12	
	2005	3,375	34	
	2006	1,398	14	
	2007	27	0	
	2008	17	0	41
Pacific Oyster	2000	1,358,576	13,586	
	2001	1,235,330	12,353	
	2002	1,404,349	14,043	
	2003	1,304,600	13,046	
	2004	1,344,085	13,441	
	2005	1,719,283	17,193	
	2006	1,498,077	14,981	
	2007	1,151,276	11,513	
	2008	803,979	8,040	13,133

[a] Average annual N removal quantities are based on the rows of data shown, except years with no reported harvest are assigned zero.