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Quantifying Benthic Nitrogen Fluxes in Puget Sound, Washington—A Review of Available Data

Scientific Investigations Report 2014–5033

U.S. Department of the Interior
U.S. Geological Survey

Cover photographs: Top and bottom photographs taken on September 1, 2010, by Curtis DeGasperi, King County Water and Land Resources Division; and center photograph taken on October 30, 2007, by Washington State Department of Ecology Environmental Assessment Program personnel.

Top: Benthic chamber filled with water prior to deployment in Quartermaster Harbor, Washington.

Bottom: Image of deployed benthic flux chamber from remotely operated camera, Quartermaster Harbor, Washington.

Center: Simple benthic flux chambers used in South Puget Sound Dissolved Oxygen Study by the Washington State Department of Ecology.

Cover background: Diagram showing spatial relation of processes in the sediment nitrogen cycle (see report figure 1).

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
	Mass	
microgram (µg)	3.527	ounce (oz)
centimeter squared per second (cm^2/s)	0.1550	inch squared per second (in^2/s)
	Areal rate	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Acronyms and Abbreviations

C	carbon
DIN	dissolved inorganic nitrogen
Do	molecular diffusion coefficient
Ds	whole sediment diffusion coefficient
F	flux
HDPE	high-density polyethylene
N	nitrogen
N_2	nitrogen gas
NH_4^+	ammonium
NO_3^-	nitrate
NO_2^-	nitrite
SOD	sediment oxygen demand

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Abstract

Understanding benthic fluxes is important for understanding the fate of materials that settle to the Puget Sound, Washington, seafloor, as well as the impact these fluxes have on the chemical composition and biogeochemical cycles of marine waters. Existing approaches used to measure benthic nitrogen flux in Puget Sound and elsewhere were reviewed and summarized, and factors for considering each approach were evaluated. Factors for selecting an appropriate approach for gathering information about benthic flux include: availability of resources, objectives of projects, and determination of which processes each approach measures. An extensive search of literature was undertaken to summarize known benthic nitrogen fluxes in Puget Sound. A total of 138 individual flux chamber measurements and 38 sets of diffusive fluxes were compiled for this study. Of the diffusive fluxes, 35 new datasets were located, and new flux calculations are presented in this report. About 65 new diffusive flux calculations are provided across all nitrogen species (nitrate, NO_3^-; nitrite, NO_2^-; ammonium, NH_4^+). Data analysis of this newly compiled benthic flux dataset showed that fluxes beneath deep (greater than 50 meters) water tended to be lower than those beneath shallow (less than 50 meters) water. Additionally, variability in flux at the shallow depths was greater, possibly indicating a more dynamic interaction between the benthic and pelagic environments. The overall range of bottom temperatures from studies in the Puget Sound area were small (5–16 degrees Celsius), and only NH_4^+ flux showed any pattern with temperature. For NH_4^+, flux values and variability increased at greater than about 12 degrees Celsius. Collection of additional study site metadata about environmental factors (bottom temperature, depth, sediment porosity, sediment type, and sediment organic matter) will help with development of a broader regional understanding benthic nitrogen flux in the Puget Sound.

Introduction

Open water (pelagic) and bottom water (benthic) processes of organic matter and nitrogen cycling are inherently coupled in marine environments. Particulate matter, which can result internally from primary production or externally from terrestrial process (that is, runoff), is transported to bottom sediment surfaces from settling within the water column. During the transport of particulate matter to marine bottoms, several processes can take place to break down material into various forms of nitrogen (N). This N takes many forms, both organic and inorganic and becomes available for uptake by marine biota. Particulate matter that is not decomposed in the water column will ultimately settle out onto the sediment surface where it can decompose further or be permanently buried. In deep waters, settling times are longer resulting in more time for particulate matter decomposition before reaching the sediment surface (Boynton and Kemp, 2009; Bronk and Steinberg, 2009). The opposite is true in shallow embayments and estuaries where particulate matter deposition is greater and therefore plays a potentially larger role in nutrient and oxygen dynamics. As particulate matter breaks down on the sediment surface, the forms of N regenerated can undergo a wide variety of transformation processes (fig. 1). Three primary microbial processes influence the type and amount of regenerated N: ammonification, nitrification, and denitrification: (1) ammonification produces ammonium (NH_4^+) from the breakdown of organic matter and provides a direct link from organic matter deposition to N regeneration from the sediments; (2) nitrification converts NH_4^+ to nitrate (NO_3^-) under aerobic conditions; and (3) denitrification converts NO_3^- to nitrogen gas (N_2) under low oxygen conditions in the presence of organic carbon. These three processes can cause concentration gradients between the overlying water and sediment resulting in exchanges between two compartments (fig. 1). This exchange of N across the sediment-water interface is referred to as a benthic flux, which can operate in two directions with a release of N into the bottom water

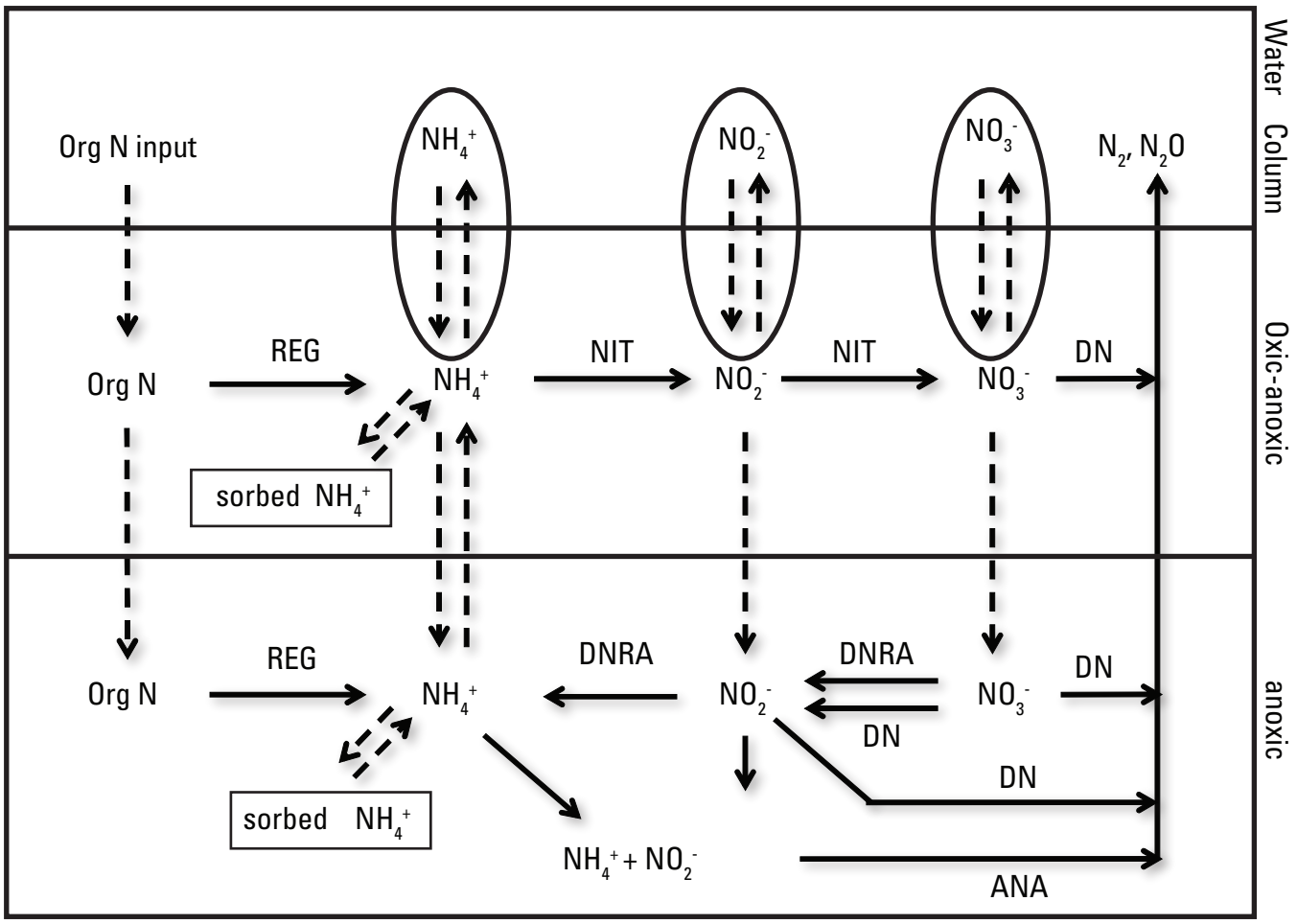

Figure 1. Spatial relation of processes in the sediment nitrogen cycle for ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-). Dashed lines represent process exchanges by diffusion, advection, or surface-sediment exchange. The circled sediment nitrogen cycle pathways are the focus of this report. (Org N, organic nitrogen; N_2, nitrogen gas; N_2O, nitrogen oxide gas REG, regeneration; NIT, nitrification; DN, denitrification; ANA, anaerobic ammonium oxidation; DNRA, dissimilatory nitrate reduction to ammonium).

(positive flux) or the removal of N from the bottom water (negative flux). Environmental factors, such as temperature, can influence flux rates. A detailed description of N cycling in marine sediments is available from Joye and Anderson (2009).

Understanding benthic fluxes is important for understanding the fate of materials that settle to the seafloor and the role these fluxes they have on the chemical composition and biogeochemical cycles of marine waters (Klump and Martens, 1981; Berelson and others, 1987; Tengberg and others, 1995). Organic and inorganic forms of N can be regenerated during the breakdown of particulate organic matter. However, most studies have focused on inorganic N (NH_4^+ and NO_3^-) fluxes because these forms are tightly coupled to primary productivity, which in turn, can alter water column oxygen concentrations and provide energy sources to high trophic levels. The source of N species to overlying waters from benthic fluxes can be comparable, or exceed, other external sources to a water body (Kuwabara and others 2009a, 2009b).

In Puget Sound, Washington, ignoring or underrepresenting benthic flux as a source of N to marine waters can result in ineffective management actions and can lead to chronic water quality problems in sensitive areas. Shallow areas near the shores of Puget Sound are most likely to experience low levels of dissolved oxygen because of the combination of low relative circulation, warm summer water temperatures, and proximity to watershed nutrient contributions; sediment nitrogen fluxes may also dominate in these shallow areas. Benthic nutrient fluxes have been quantified in very few areas in the Puget Sound: Budd Inlet, Dabob Bay, Quartermaster Harbor, and several South Puget Sound inlets in the late summer only. More sediment flux data are needed, particularly in sensitive shallow areas, because they are expected to be an important local cycling source. Model development taking place at the Washington State Department of Ecology includes sediment-water exchanges (M. Roberts, Washington State Department of Ecology, written commun., 2013), and as more is learned about the

role of benthic N fluxes in Puget Sound, this information can be incorporated into coupled sediment and biogeochemical models to better capture nutrient and oxygen dynamics, and to provide improved information for managers of Puget Sound resources. This report will provide Washington State Department of Ecology with additional information to better incorporate benthic fluxes into their models in the future.

Purpose and Scope

This report provides a review of the available scientific literature related to benthic nitrogen fluxes in Puget Sound. All known sediment nitrogen fluxes in areas around Puget Sound are summarized to identify factors controlling benthic fluxes and data gaps for future research.

Description of Study Area

The study area for the review of existing benthic nitrogen flux data was focused in Puget Sound, Washington. Puget Sound is an estuary of the Pacific Ocean in western Washington state and is characterized by a deep (200 m), north-south trending glacial trough fringed by shallow embayments and river deltas (fig. 2). The southern area of Puget Sound is a complex of islands and inlets that are much shallower than the main basin. Circulation is dominated by large tidal flow (mean 10,000 to 20,000 m^3/s) compared to freshwater inflow (mean 1,000 m^3/s) (Khangaonkar and others, 2012). Circulation of tidal water is limited in south Puget Sound and other embayments that are relatively long and narrow. Strong vertical gradients in biogeochemical processes (primary production concentrated in the upper photic zone and benthic decomposition of organic material) combined with differences in lateral and vertical mixing lead to local variation in temperature, nutrients, and dissolved oxygen.

Factors Influencing Benthic Nitrogen Flux

Numerous physical and environmental factors can influence the rate (and direction) of N flux in the marine environment. Comprehensive reviews of these factors have been compiled and include: the amount and type of organic matter delivered to the sediment, temperature, depth, light, time of the year (season), wind induced suspension, substrate characteristics, sediment oxygen consumption rates, and the presence and amount of vegetation and benthic fauna (Boynton and Bailey, 2008; Bronk and Steinberg, 2009; Kuwabara and others, 2009b).

The amount and quality of organic matter delivery to the sediment surface determines the amount and form of N mineralized from the sediment as well as the sediment oxygen demand (SOD). Research suggests that the amount and quality of organic matter delivery is the overarching factor regulating sediment biogeochemistry and N exchange across the sediment-water interface (Boynton and Kemp, 2009). Organic matter can be from terrestrial sources and pelagic or benthic primary producers. Secretion of dissolved organic matter from roots and rhizomes of benthic macrophytes also can take place. Once particulate material settles, several potential sources of N are in the water column from the benthos, including excretion from meiofauna, macrofauna, nitrogen fixation, and N remineralization of the organic matter (Bronk and Steinberg, 2009). Numerous studies show a positive correlation between increases in organic matter delivery and sediment N regenerations (Bronk and Steinberg, 2009). In shallow waters, potentially more organic material reaches the sediment-water interface because of faster transit times (Boynton and Kemp, 2009). Therefore, the depth of overlying water is another factor that can influence the amount of N flux from sediments as it is related to how much organic matter is delivered to the sediment. For example, SOD, which is important to the deposition and digenesis of organic carbon and N cycling, has been shown to decrease as depth increases, especially at depths greater than 25–50 m (Bailey and Boynton, 2007; Boynton and Bailey, 2008).

The quality of the organic matter source also can influence the amount of sediment N regeneration. For example, phytoplankton can have a lower carbon to nitrogen (C:N) ratio than other types of marine vegetation; therefore, more N regeneration occurs from the breakdown of phytoplankton than sea grass (Bronk and Steinberg, 2009). Depth of overlying water also can influence the quality of the organic matter deposited as long transit times in deep waters result in more pelagic decomposition. These long transit times can preferentially decompose the labile part of the organic matter during sedimentation, resulting in delivery of a more recalcitrant form to the sediment (Boynton and Kemp, 2009). Therefore, substrate type, which is related to locations of sediment deposition and resuspension (erosion), also can contribute to the amount to N flux from the sediment (for example, see King County, 2012).

Seasonality, temperature, and amount of light are all related and can influence N regenerated from sediments in multiple ways. For example, fluxes can change seasonally in magnitude and direction (into or out of the sediment) or shift in the form of dissolved inorganic nitrogen (NH_4^+ or NO_3^-) produced from sediments in response to light and temperature changes (Boynton and Bailey, 2008; Bronk and Steinberg, 2009). In estuaries, the shallow depths allow more light penetration and result in closely connected areas of N remineralization and benthic-pelagic coupling (Boynton and Kemp, 2009). In a review of estuarine NH_4^+ fluxes, temperature and depth played an important role, with greater flux at depths less than 10 m and temperatures greater than 20 °C (Boynton and Kemp, 2009).

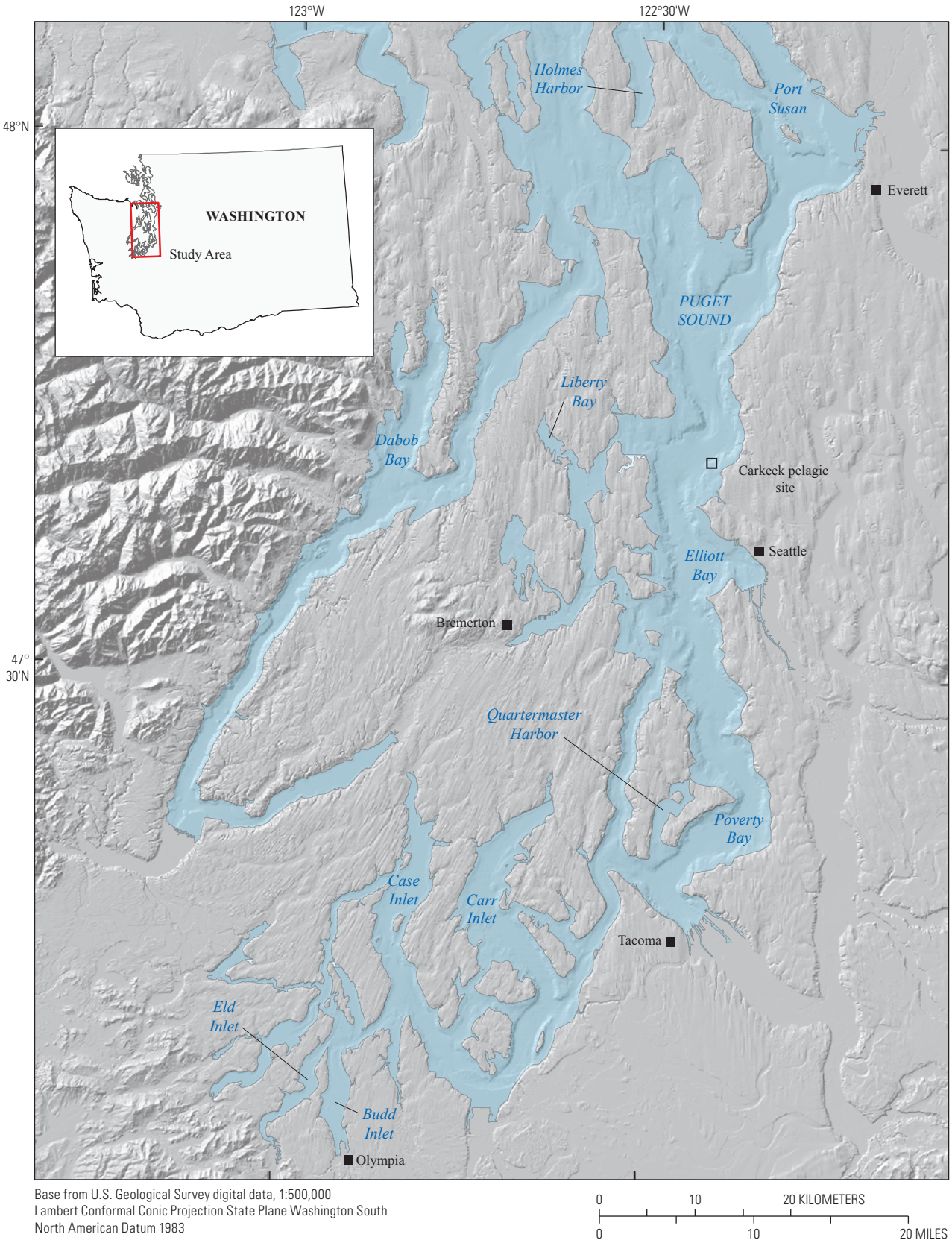

Figure 2. Location of embayments with existing benthic nitrogen flux data, Puget Sound, Washington.

In addition to light and temperature, season can have an indirect influence by potentially increasing terrestrial organic matter delivery to the marine system during rainfall events. In marine environments where terrestrial runoff is a valuable component of the water budget, such as in shallow embayments, the time of year can be an important factor to consider.

The oxygen status of the sediment also is an important factor dictating the magnitude, direction, and form of N release from the sediment. Most of the processes in the sediment N cycle are microbially mediated and dependent on the amount of oxygen present in the sediment porewater. For sediment with high organic matter content, oxygen penetration into the sediments is low and NH_4^+ and N_2 fluxes usually dominate (Pedersen and others, 1999). The efflux of NO_3^- also is heavily dependent on the amount of oxygen penetration (Bronk and Steinberg, 2009). The presence or absence of primary producers can influence the form of N released from the sediment, with positive relations between N mineralization and the amount of sediment chlorophyll (Boynton and Kemp, 2009). Phytoplankton, with their low C:N ratios, can fuel rapid decomposition reducing oxygen levels in sediment. This decomposition can in turn cause a decrease in sediment denitrification through a lack of NO_3^- production from nitrification, which needs high oxygen levels to convert NH_4^+ to NO_3^-. The overall result of these coupled processes is a release of NH_4^+ from the sediment. In contrast, seagrasses and other benthic microalgae can increase sediment oxygen concentrations through photosynthesis, and oxygen transport to the root zone, reversing this process (Caffrey and Kemp, 1990; Risgaard-Petersen and Jensen, 1997). Rates of ammonification (production of NH_4^+ from organic matter) and release of NH_4^+ from the sediment tend to be higher in sediments colonized by seagrasses compared to bare sediments (Boon and others, 1986; Caffrey and Kemp, 1990). Nitrification and denitrification also tend to increase in the presence of vegetation (Bronk and Steinberg, 2009). Oxygen released from roots favors nitrification of NH_4^+ to NO_3^- and the increase in NO_3^- leads to increases in denitrification, illustrating the importance of nitrification-denitrification coupling in the sediment N cycle. As important as oxygen is on the release of N from sediments, the influence on water column nitrogen concentration tends to decrease with depth (Boynton and Bailey, 2008), pointing toward shallower waters as important areas to study.

Another important factor influencing the amount of N flux from the sediment is the amount of biological activity related to benthic fauna. Benthic fauna can alter N flux through excretion of N-containing compounds, bioturbation, and bioirrigation (Grundmanis and Murray, 1977; Murray, 1982; Grundmanis, 1989; Bronk and Steinberg, 2009). Bioturbation is a process where surface sediments can be physically mixed by organisms burrowing and moving around in the sediment. Bioirrigation is the direct exchange of overlying water into the sediment through burrows and tubes of benthic fauna, and indirect exchange by diffusion through tube and burrow walls (Christensen and others 1984; Aller and Aller, 1998; Na and others, 2008, Brand and others, 2013). Overall, bioturbation and bioirrigation can facilitate oxygen penetration deep into sediments (Grundmanis and Murray, 1977) that is a crucial factor controlling the many processes on the sediment N cycle, and which form of N is released from the sediment. For example, the oxic layer in sediments often is on the order of millimeters deep (Brandes and Devol, 1995), and bioirrigation and bioturbation can have an effect to 10 cm deep or greater (Grundmanis and Murray, 1977). Bioirrigation has been shown to be important in deep water, where benthic biomass tends to be lower (Christensen and others, 1984; Devol and Christensen, 1993). However, the importance of biological effects on benthic flux generally decreases with increased depth of the water column (Grundmanis, 1989; Chang and Devol, 2009).

Benthic fluxes generally are expected to be heterogeneous in the environment because many of the factors that influence flux also are heterogeneous. Therefore, this variability should be considered when designing benthic flux studies and when using this information for incorporation into water quality models.

Methods for Measuring Benthic Nitrogen Fluxes

Two approaches generally are used to measure benthic fluxes in marine environments: (1) direct methods that isolate part of the sediment where changes in concentrations in overlying water are measured over time, and (2) indirect methods that use measurements of porewater nutrient concentrations to calculate a diffusive flux into or out of the sediment. Numerous methods within each of these two approaches have been historically used by researchers.

Direct Methods

Direct methods isolate the sediment-water interface and overlying water and calculate fluxes by measuring concentration changes in the overlying water over time. Direct methods can be undertaken in situ, using benthic chambers, or using sediment incubations onboard a ship or in a laboratory.

Benthic Chambers

In situ benthic chambers range in sophistication and cost from large deep sea ocean landers (see Tengberg and others [1995]) to small and less expensive chambers made from inverted aquaria (Roberts and others 2008, King County, 2012). Fluxes are calculated from benthic chambers

by taking the change in concentration of a solute over time (slope of concentration versus time curve), multiplying this by the overlying water volume, and dividing by the area of sediment covered by the chamber. Fluxes determined from benthic chambers are the most direct estimate of true benthic fluxes because they incorporate all of the processes affecting the flux, including advection, diffusion, bioturbation, and bioirrigation. Additionally, benthic chambers include any change in nitrogen in the overlying water due to processing of organic substrates on the sediment surface and any reaction of nitrogen taking place in the overlying water from nitrogen released from the sediment (Archer and Devol, 1992). The method of sampling the overlying water also can vary from remotely or automatically triggered sample collection at set times (Tengberg and others, 1995) to sampling overlying water from the surface using a peristaltic pump (Roberts and others, 2008). Benthic chambers often include a one-way valve where replacement bottom water is pulled into the chamber during sample collection. Overlying water concentrations are then corrected for dilution before determining the rate of change during the operation of the chamber. If sample volumes are small compared to the total overlying water volume, then correction for dilution may not be necessary. In order for benthic chambers to represent the bulk environment, some amount of stirring is needed. However, the need to stir is an active area of research with strong disagreements. For example, some studies have shown that the amount (speed and duration) of stirring is not too important as long as some stirring takes place (Berelson and others, 1987; Tengberg and others, 2004). Whereas other studies show a clear link between stirring rates and SOD (Boynton and others, 1981). The main goal of stirring is to replicate water movement and boundary layer thickness outside the chamber, because if ambient conditions are not met, measured fluxes from the sediment will differ from actual fluxes. Additionally, a well-stirred chamber allows samples that are collected over time to be well mixed and to better represent the solute concentration during the time of sample collection. Benthic chambers typically are operated from 12–24 hours, depending on how quickly solute concentrations change in the overlying water.

There are several benefits to using benthic chambers for determining fluxes: (1) they incorporate multiple processes that can influence exchange of solutes across the sediment-water interface (diffusion, advection, bioturbation, bioirrigation); (2) they incorporate a larger area of measurement than other methods; (3) fluxes are measured in situ and minimize disturbance from collection and extraction of sediment cores for onboard or laboratory analyses; and (4) they maintain in situ temperatures and pressures. In more sophisticated chamber setups, incorporation of tracer injections can be used to further analyze overall mass balances, and depth of penetration of solutes during the measurement period (Berelson and others, 1987; Tengberg and others, 1995). Some disadvantages include: (1) potential long term deployment where exchange rates are slow, leading to increased costs for personnel and time on ship and increased power requirements; (2) disturbance of sediment surface from bow waves as chambers approach the sediment surface, which is particularly important for maintaining the upper flocculent layer of sediments; and (3) maintenance of stir rates at levels low enough to not resuspend surface sediments, yet still maintaining hydrodynamics representative of the outside chamber. However, disturbances to the sediment surface can be minimized by using scuba divers for the placement of chambers in shallow environments, or through lander designs such as dampening equipment prior to landing and insertion of the chamber into sediment after the lander has settled (Tengberg and others, 1995). Another consideration for chamber deployments is the potential for a non-steady state change in solute concentration in the overlying water. This can result from changes in solute gradients as constituents decrease or increase in the overlying water during the deployment time. To counteract this effect, researchers sometimes based flux measurements on the first several points in the concentration curve where rates are still linear (Devol and Christensen, 1993). Finally, knowing the overlying water volume of the chamber is crucial to calculating accurate fluxes; remote cameras or scuba divers often are needed to verify depth of placement of chambers (Tengberg and others, 1995; King County, 2012).

Core Incubations

Direct flux measurements can be made from intact cores collected at depth and analyzed either on board the research vessel or in the laboratory. Cores can be collected remotely using a coring device, or directly using scuba divers. Similar to benthic chambers, fluxes are determined from knowing the area of the core, volume of overlying water, and rate of concentration changes in the overlying water. Some degree of stirring generally should be incorporated and experiments carried out at in situ temperatures to simulate ambient conditions. Core incubations can be simple batch experiments (Beutel and others, 2008; Chang and Devol, 2009), or more detailed flow-through systems that try to accurately emulate conditions at depth (Miller-Way and others, 1994). In flow-through incubations, a reservoir of bottom water is pumped into the overlying water of the core, where it is stirred and pumped out to maintain the overlying water volume, and samples of the outlet are collected over time. It is important to maintain in situ conditions of the bottom water, particularly with respect to dissolved oxygen concentrations, or large errors can result in calculated fluxes (Miller-Way and others, 1994).

Advantages of core incubations include the ability to control environmental variables such as: (1) the temperature; (2) the ability to run many replicates to increase statistical power of the results; (3) the relatively simple and low cost,

which allows for more sites to be sampled over time; (4) the collection of cores not limited by logistical barriers such as weather, costs for ship time, need for divers; and, (5) the similarity to "actual" fluxes, determined using benthic chambers under the right conditions (Miller-Way and others, 1994). The biggest limitation of core incubations are the potential effects on fluxes determined at non-ambient temperature and pressures, and disturbances from the collection and retrieval of cores. Temperatures often are controlled, but pressures cannot be simulated at depth very easily. Additionally, stirring rates might over or underestimate true fluxes. Finally, collection of cores might not capture the flocculent layer accurately, resulting in erroneous fluxes; however, this can be minimized with scuba divers and careful collection of cores.

Indirect Methods

The most common indirect method for determining benthic fluxes in the environment is by measuring porewater profiles in the sediment and using this information to calculate concentrations across the sediment-water interface to estimate a diffusive flux. Typically the calculated flux (F) is based on Fick's law of diffusion and represents diffusional flux into or out of the sediment:

$$F = Ds \times \theta \times \frac{dC}{dz} \quad (1)$$

where

F is the calculated flux;
Ds is the whole sediment diffusion coefficient, which is the molecular diffusion coefficient (Do) corrected for bottom water temperature (Li and Gregory, 1974) and tortuosity (Ullman and Aller, 1982);
dC/dz is the concentration gradient at z=0, the sediment-water interface; and
θ is the sediment porosity.

For most marine sediments, porosity at the sediment water interface can be quite high (greater than 0.80). For sediments with porosity of 0.7 or greater, the relation between Ds and Do has been approximated by $Ds=\theta^2 Do$.

The Fick's law model does not incorporate the contributions to the flux from wind resuspension or benthic fauna and therefore are considered underestimates of the true flux (Kuwabara and others 2012). Porewater profiles can be influenced by radial diffusion from vertical burrows and short circuiting from moving overlying water directly to deeper depths in the sediment profile. Despite this limitation, the diffusional flux can be a good screening tool for comparison to other nutrient sources in a given region to determine the relative proportion of nutrients from this process. Researchers have developed an expanded version of the Fick's law model that incorporates effects from biological irrigation by including a non-local exchange term to the equation:

$$F = Ds \times \theta \times \frac{dC}{dz} + \alpha \times \left(Cz - Co\right) \quad (2)$$

where

F is the calculated flux
Ds is the whole sediment diffusion coefficient, which is the molecular diffusion coefficient (Do) corrected for bottom water temperature (Li and Gregory, 1974) and tortuosity (Ullman and Aller, 1982);
dC/dz is the concentration gradient at z=0, the sediment-water interface;
θ is the sediment porosity;
α is an empirically derived irrigation coefficient;
Cz is concentration at depth z; and
Co is concentration of the bottom water.

In this non-local exchange model, biological irrigation is considered a direct exchange of interstitial waters with equal amounts of overlying bottom water. Non-local exchange refers to the ability of fauna to exchange material from nonadjacent points between overlying water and points in the sediment removed from the interface (Emerson and others, 1984). In some cases, the flux related to biological irrigation can far exceed that of simple diffusion (Emerson and others, 1984; Grundmanis, 1989; Archer and Devol, 1992).

Determining the concentration gradient at the sediment-water interface is the most important step for estimating fluxes using porewater data. The gradient can be determined in the simplest form by comparing the concentration of solute in the overlying water to the concentration at the first subsurface sample, which gives the linear gradient across the interface (Murray, 1982; Devol, 1987; Grundmanis, 1989). However, this approach can lead to errors because the overlying water concentration is influenced by the whole water column, and likely does not represent the concentration at the sediment-water interface (Klump and Martens, 1981). A linear gradient also can be determined from three or more adjacent porewater concentrations in the profile near the sediment-water interface (Klump and Martens, 1981; Archer and Devol, 1992). Because solute gradients tend to be nonlinear, numerical and curve-fitting methods also have been used to estimate exponential gradients near the sediment-water interface to better estimate benthic fluxes (Klump and Martens, 1981; Berg and others, 1998).

Numerous methods have been used to sample porewater either in situ or ex situ (shipboard or in a laboratory). The most common ex situ method for extracting porewater samples from the sediment is to collect a sediment core, section the core at desired intervals into sealed containers, and then centrifuge the sediment for 10–30 minutes at high speeds (Christensen

and others, 1984; Chang and Devol, 2009). The supernatant liquid is then removed and filtered for chemical analysis. A variation of this method has been used where small horizontal sediment plugs are removed from a larger core; where the holes, covered with electrical tape, are placed at premeasured depths and these sediment plugs are then centrifuged for extraction of porewater (Emerson and others, 1984; Petersen and Carpenter, 1986). These core-section-centrifuge methods are simple to use, cost effective, and allow for many sites and replicates to be collected in a short period of time. When possible, in situ sampling of porewater is recommended because it does not require the collection and extraction of sediment cores prior to porewater sampling, therefore it minimizes disturbance to natural porewater gradients. In situ sample methods include the use of a 'harpoon' sampler, where porewater is pulled from various depths at the same time (Grundmanis and Murray, 1977; Murray, 1982; L. Miller, U.S. Geological Survey, written commun., 2013), and recently an in situ porewater sampler, designed to extract samples from multiple depths into attached syringes while being filtered inline, has been successful (Kuwabara 2009a, 2009b). Equilibration methods for collecting porewater also have been used (Emerson and others, 1984; D'Angelo and Reddy, 1994; Moore and others, 1998) including passive diffusion samplers commonly termed "peepers." In this approach, a pipe or a tube with prefilled cavities of deoxygenated, deionized water covered with a permeable membrane is installed into the sediment and allowed to equilibrate with the surrounding environment for weeks or longer. At the end of the deployment period, the peeper is removed and water in the cavities is collected for chemical analysis. The materials used to make up the equilibration device must be deoxygenated because they often are made of high-density polyethylene (HDPE), which is semi-permeable. This approach is simple; however, the long deployment times and the amount of sediment disruption during placement and retrieval are drawbacks to the approach (Environmental Consulting and Technology, Inc., 2007).

The spatial resolution of all methods for porewater extraction is on the order of centimeters in the vertical direction. Only a few techniques can provide a finer, millimeter-scale resolution in porewater, and include microelectrodes (Binnerup and others, 1992; Jensen and others, 1994) and 'core squeezing' (Bender and others, 1987; Brandes and Devol, 1995). Microelectrodes use oxygen and other ion-specific probes that are lowered into the sediment at fine spatial scales to refine solute gradients, especially near the sediment-water interface where gradients often are steepest. The core squeezing technique involves the compression of a sediment core through a fritted disc on the sediment surface, and water is collected at discrete intervals for analysis. The finer control on this squeezing allows for the smaller scale resolution often needed for estimating accurate solute gradients.

Limitations of calculating diffusive flux from porewater data are related to potential errors in estimating the concentration gradient at the sediment surface and estimating the correct value for the diffusion coefficient. Other physical and logistical limitations occur from disturbance during collection and sampling of cores; pressure effects if cores are collected from great depths; limits on vertical resolution of samples; difficulty in separating out active flocculent layer; and the inability to incorporate effect from benthic fauna (Christensen and others, 1984; Emerson and others, 1984; Berelson and others, 1987; Devol, 1987; Berg, and others, 1998). However, in areas of the deep sea with low flow (tidal) energies, low oxygen and benthic faunal activity, and low depositional rates, the porewater technique can be reliable (Miller-Way and others, 1994).

Comparison of Methods

Few studies have used multiple methods of flux determination to compare the estimates from each. Devol (1987) compared chamber (lander) fluxes and porewater diffusive fluxes in Alaska and Mexico, and determined that chamber fluxes were better than porewater diffusive fluxes at incorporating biological effects. Similarly, on the Washington state continental shelf, benthic NO_3^- flux from chambers was about 3 times greater than diffusive fluxes, likely a result of bioirrigation (Devol and Christensen, 1993). Miller-Way and others (1994) compared flow-through core incubations and flux chambers and showed that processes not sensitive to oxygen levels were in agreement, but those more sensitive to oxygen were not in agreement. This comparison was complicated because incubation water used by Miller-Way and others (1994) was not maintained at in situ oxygen concentrations. In deep water (about 200 m), Murray (1982) showed good agreement between lander chamber fluxes and in situ porewater sample derived flux, possibly a result of limited biological activity and water movement, which can influence the magnitude of benthic fluxes. Emerson and others (1984) determined benthic flux at a site in Puget Sound using porewater and either a diffusive (Fickian) flux or a flux derived from a non-local bioirrigation model. For solutes with a strong gradient at the sediment-water interface, the bioirrigation model resulted in larger fluxes when compared to a simple diffusive flux. This importance of bioirrigation flux in Puget Sound also was shown in deep water (about 200 m) by Grundmanis (1989) where simple diffusive fluxes typically were less. In this same study, bioirrigation fluxes were compared to 'actual' flux from a lander chamber, and agreement was good for oxygen consumption rates, and not good for other solutes (for example, NH_4^+). A summary of different approaches to determine flux concluded that core incubation well represents actual fluxes under controlled conditions, and has the advantage of lower costs and the ability to cover a large geographical area (Environmental Consulting Technology, Inc., 2007). However, results are not consistent and the accuracy of a given method or methods varies depending on site-level conditions and specific study questions.

Benthic Nitrogen Fluxes in Puget Sound

Benthic nitrogen fluxes were compiled from an extensive search of the literature including scientific journals and state, county, and university reports. In all, nitrogen fluxes from various methods were compiled for eight sites for at least one type of nitrogen species (NO_3^-, NO_2^-, or NH_4^+) (fig. 3*A*). Additionally, benthic fluxes were calculated for other sites where publications presented porewater data in either a table or in a figure, but a flux was not calculated. Furthermore, fluxes were calculated following direct contact with original researchers who had unpublished porewater data in old reports, field notes, and paper copies of tabulated data. In all, about 30 additional data sets were found for the Puget Sound (fig. 3*B*; appendixes A–C). Many of these data were from sites in deep waters of Puget Sound, which allowed for comparison to recent flux data focused in more shallow estuarine waters. Phosphate data available during the data compilation are provided in appendix D for further consideration, although phosphate fluxes were not analyzed.

Chamber Flux Measurements

Chamber benthic fluxes have been measured in Puget Sound since the early 1980s and measurements exist for seven general locations ranging in depth from 3 to 200 m (table 1). The oldest measurements focused on deep water at a location off the coast of Carkeek Park, north of Seattle, that was visited on multiple occasions. Chamber fluxes were determined at mid-range depths (50–110 m) at sites in Holmes Harbor and Dabob Bay, and measured at shallow depths (4–25 m) at sites in Budd Inlet, Case Inlet, Carr Inlet, Eld Inlet, and Quartermaster Harbor. Detailed site and location information for each chamber flux measurement is provided in table A1.

Site-averaged benthic flux values are summarized in table 2. Site-average flux for nitrate was negative, indicating movement into the sediment and values ranged from -1.0 to -15.8 milligrams nitrogen per meter squared per day ([mg N/m^2]/d) with and overall average of -10.1 (mg N/m^2)/d. Measurements of nitrite flux are primarily absent from chamber studies in Puget Sound, except for the South Puget Sound flux study (Roberts and others 2008; Roberts, written comm., 2013) where nitrite flux was positive at some sites and negative at others. The range in nitrite flux was from -1.4 to 2.9 (mg N/m^2)/d with an overall average of 0.2 (mg N/m^2)/d. Ammonium benthic flux ranged from 4.5 to 115.1 (mg N/m^2)/d, with an overall average of 48.0 (mg N/m^2)/d. Ammonium fluxes were consistently positive, indicating release from the sediment to the water column across all depths. Data for each chamber flux measurement complied for this review (n=138) are provided in appendix B.

Diffusive Flux Measurements

For this study, diffusive fluxes were calculated from sediment porewater profiles using Fick's law. The literature review revealed approximately 35 sets of porewater data for one or more N species. Additionally, diffusive fluxes studies have been published for sites in Budd Inlet (Aura Nova Consultants and others, 1998), Quartermaster Harbor (Emerson and others, 1984), and a deep water site off the coast of Carkeek Park north of Seattle (Grundmanis, 1989) (fig. 2). Site information and study details of porewater data were compiled and are summarized in table 3; detailed site data for each diffusive flux measurements are provided in table A2. In all, 65 new diffusive flux measurements were calculated for various N species (NO_3^-, NO_2^-, or NH_4^+) for this study. Compilation of the diffusive flux data had added complexities because porewater samples can be collected by many different methods. Additionally, diffusive fluxes are calculated from porewater concentration gradients at the sediment-water interface and multiple methods can be used for calculating these gradients. These methods include either a simple 2-point estimate between the bottom water concentration and first subsurface sample, or regressions (linear or nonlinear) of porewater concentrations near the sediment-water interface. Where the data allowed, diffusive fluxes were calculated individually for each method of porewater collection, and were recalculated based on regressions of porewater data in cases where 2-point gradients were used originally. The purpose of these calculations was to examine how the method used to sample porewater or estimate gradients at the sediment-water interface affected flux estimates.

In addition to calculating the concentration gradient at the sediment-water interface, the bottom water temperature must be known to correct diffusion coefficients and sediment porosity at the sediment-water interface. In many cases where porewater data were available, the associated bottom temperatures and sediment porosities were difficult to find. For most datasets, this information was either in report appendixes, or not provided at all. In cases where temperatures and sediment porosities were not available, estimates were used, based on expert knowledge, from the larger population of the dataset. Where sediment porosity was missing, a value of 0.8 was assumed, which was the median value of available sediment porosity data (0.7–0.87). Missing bottom water temperatures were assigned a value of 8 °C in most cases. Of the 16 instances where no bottom temperature was available, 11 instances were from sites greater than 100 m deep. Temperatures at these depths are less variable, and were assigned the value of 8 °C based on published deep-water bottom temperatures and expert knowledge (Devol, oral comm., 2013). Remaining sites with no bottom water temperature data were in Quartermaster Harbor (assigned a value of 13 °C based on King County [2012]) and other locations that did not have enough site-specific information available to justify using a different value.

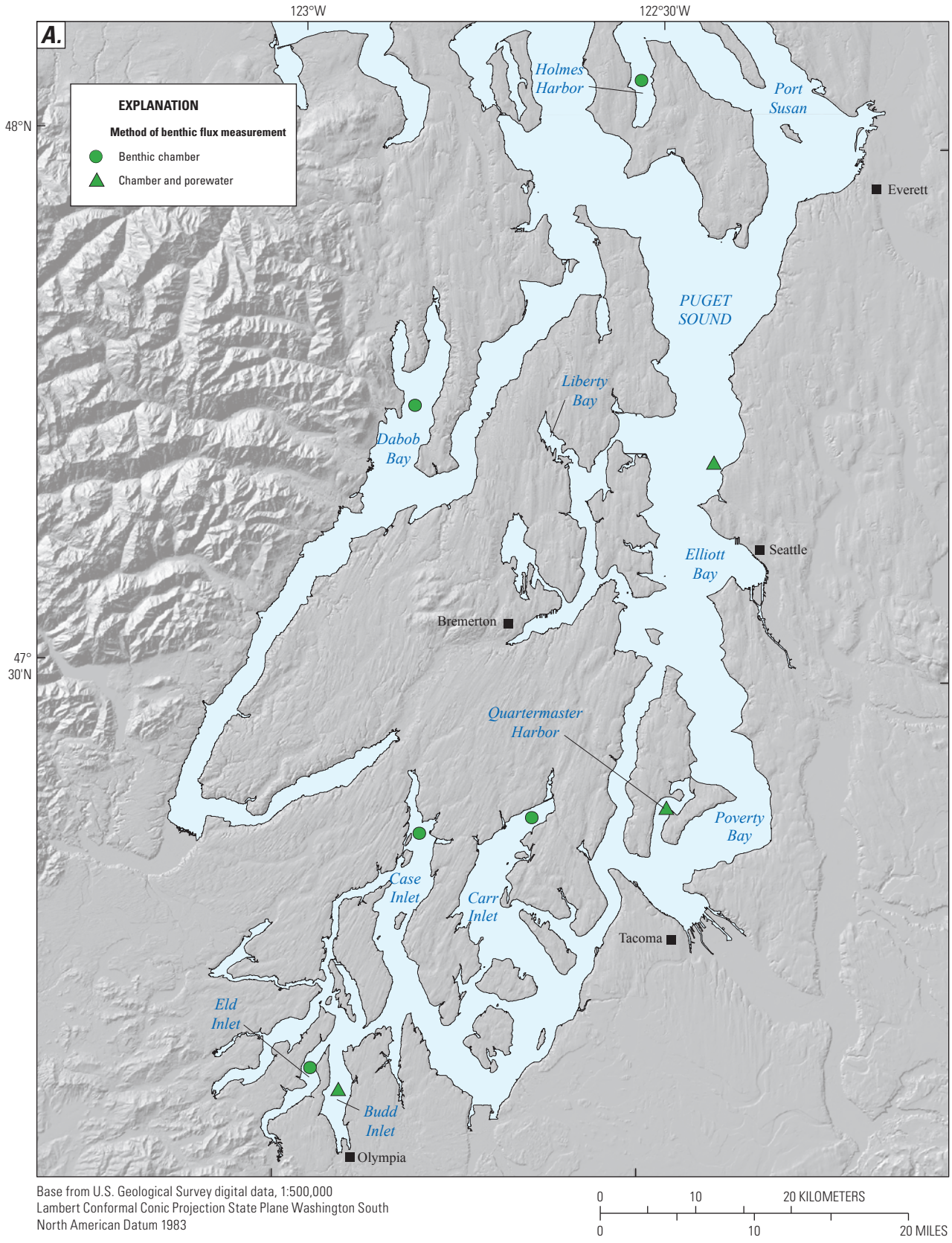

Figure 3. General locations of (*A*) existing benthic flux measurement sites and (*B*) additional sites where new benthic fluxes were calculated using existing data from Puget Sound, Washington.

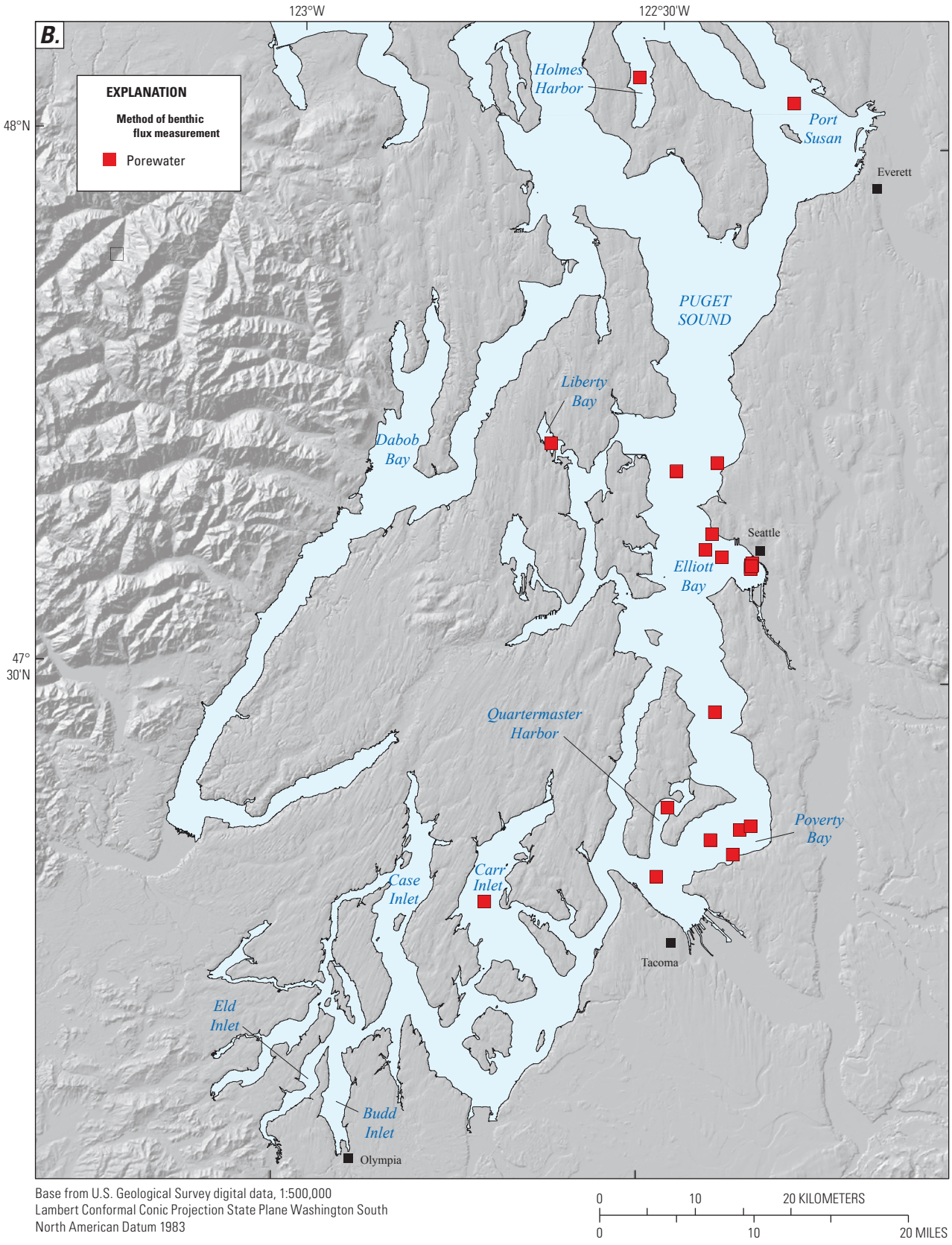

Figure 3.—Continued.

Table 1. General site information for benthic chamber sites in Puget Sound, Washington.

[For detailed site metadata, see table A1]

Station/site identifier	Date sampled	Depth (meters)	Study details	Reference
Carkeek pelagic site (PS17)	June 8–9, 1982	175	Single site, measured once	Murray (1982)
Carkeek pelagic site	Unknown	200	Single site, measured once	Grundmanis (1989)
Holmes Harbor	August 1993	50–70	Three sites, measured once	Brandes and Devol (1997)
Dabob Bay	January 1987–January 1988	110	Single site, measured 20 times during the year	Colbert and others, unpub. data (2010)
Budd Inlet	September 1996–September 1997	5–15	Four sites measured 17–19 times during the year	Aura Nova Consultants and others (1998)
Case Inlet	September–October 2007	5–25	Three depths measured 3 times	Roberts and others (2008)
Carr Inlet	September–October 2007	5–25	Three depths measured 3 times	Roberts and others (2008)
Eld Inlet	September–October 2007	5–25	Three depths measured 3 times	Roberts and others (2008)
Budd Inlet	September–October 2007	3–25	Three depths measured 3 times	Roberts and others (2008)
Quartermaster Harbor	September 1–2, 2010	4–17	Five sites measured once	King County (2012)

Table 2. Average benthic flux estimates from benthic flux chamber measurement sites, Puget Sound, Washington.

[Negative values indicate fluxes into the sediments. **Abbreviations**: (mg N/m^2)/d, milligrams of nitrogen per square meter per day; –, no data]

Station/site identifier	Number of measurements	Depth (meters)	Benthic fluxes [(mg N/m^2)/d]		
			Nitrate	Nitrite	Ammonium
Carkeek pelagic site	2	175–200	–	–	4.5
Holmes Harbor	3	50–70	-8.4	–	6.4
Dabob Bay	19	110	-12.0	–	6.3
Budd Inlet (BI-5)	19	5–15	-10.6	–	78.9
Budd Inlet (BA-1)	16	5–15	-13.7	–	42.8
Budd Inlet (LOON-1)	19	5–15	-9.2	–	57.0
Budd Inlet (BD-2)	19	5–15	-10.5	–	42.9
Case Inlet	9	5–25	-15.8	0.2	52.8
Carr Inlet	9	5–25	-8.0	2.9	47.2
Eld Inlet	9	5–25	-9.0	-0.9	68.6
Budd Inlet	9	5–25	-13.3	-1.4	115.1
Quartermaster Harbor	5	4–17	-1.0	–	53.0
Overall average			-10.1	0.2	48.0

Table 3. General site information for diffusive flux measurements in Puget Sound, Washington.

[For detailed site metadata, see table A2. **Abbreviations:** UNK, unknown; NOAA, National Oceanic and Atmospheric Administration]

Station/site identifer	Date sampled	Depth (meters)	Study details	Reference
Carkeek pelagic site	February 1976–June 1982	200	This deep water site was visited multiple times over a 6-year period	Grundmanis and Murray (1977); Murray (1982); Grundmanis (1989)
Carkeek pelagic site (PS 19)	04-19-83	174	Porewater sampled once	Miller, written commun. (2013)
Carkeek pelagic site (PS 21)	05-10-83	173	Porewater sampled once	Miller, written commun. (2013)
Liberty Bay	UNK	UNK	Porewater sampled once	Devol, oral commun. (2013)
Poverty Bay	UNK	179	Porewater sampled once	Devol, oral commun. (2013)
Port Susan (PS 98)	January 1982	104	Porewater sampled once	Peterson and Carpenter (1986)
PS51-1	September 1978	249	Porewater sampled once	Peterson and Carpenter (1986)
PS51-2	January 1982	249	Porewater sampled once	Peterson and Carpenter (1986)
East Passage (PS56)	January 1982	200	Porewater sampled once	Peterson and Carpenter (1986)
Quartermaster Harbor (PS39)	September 1978	13	Porewater sampled once	Peterson and Carpenter (1986)
Holmes Harbor	1992	45–60	Four sites porewater sampled once	Brandes and Devol (1995)
Various embayments	1980–82	55–180	NOAA study that sampled pore waters at 10 sites one time	Paulson and others (1991)
Budd Inlet	March–June 1997	5–15	Two sites sampled for porewater once	Aura Nova Consultants and others (1998)
Carr Inlet	UNK	84	One site sampled for porewater once	Tiquia and others (2006)
Quartermaster Harbor	July 1976–August 1978	15	One site sampled for porewater once	Emerson and others (1984)

Porewater concentration gradients were determined from a linear regression of the three to four data points closest to the sediment water interface, and did not include the overlying water concentration, which can lead to large errors in the flux (Klump and Martens, 1981). A simple linear regression of the porewater data was used instead of curve-fitting methods (see Klump and Martens, 1981) because in most cases not enough data points were available in the upper 10 cm of sediment to provide accurate non-linear fits of the data. Therefore, all the diffusive fluxes calculated for this study should be considered underestimates of the true flux. The statistical software Spotfire S+® (ver. 8.1 TIBCO Software Inc.) was used to test for the significance of the slope of the linear fits. Slopes with a p-value of 0.1 or less were used to calculate diffusive fluxes, indicating we are 90 percent confident that the concentration gradients from these porewater data were significantly different from zero. Porewater profiles where the slope of the concentration compared to depth was not significant ($p>0.1$) indicate that biogeochemical processes could be influencing porewater concentrations in this region of the sediment and that concentrations are not solely controlled by diffusion. Non-significant slopes also may indicate that the sampling interval was too large and did not allow the calculation of accurate concentration gradients near the sediment-water interface. This would be especially true for solutes where this gradient was steep near the sediment-water interface. Values for all calculated concentration gradients at the sediment-water interface, including values used for bottom temperature, porosity, and temperature corrected diffusion coefficients for every diffusive flux calculation, are provided in appendix C. Whole sediment diffusion coefficients used to calculate the diffusive flux were calculated using the equation $Ds=\theta^2 Do$ (Ullman and Aller, 1982). The molecular diffusion coefficient (Do) was determined using a linear interpolation between the bottom water temperature and values published in Li and Gregory (1974).

More than 60 porewater datasets across NO_3^-, NO_2^-, and NH_4^+ were analyzed and results for diffusive fluxes are provided in table 4. The methods used for sampling the porewater for calculating the concentration gradient for each instance also are provided in table 4. There were a number of cases where the porewater data near the sediment water interface yielded a non-significant slope (appendix C) and was most common for NO_2^- (15 of 19 profiles had non-significant slopes), and least common for NH_4^+ (only 2 of 24 profiles had non-significant slopes). Diffusive fluxes for NO_3^- ranged from 0.11 to -12.04 (mg N/m^2)/d with an overall average of -2.77 (mg N/m^2)/d, indicating movement of NO_3^- into the sediment. Nitrite diffusive fluxes were significant only at four sites, and were low, ranging from 0.01 to 0.04 (mg N/m^2)/d with an overall average of 0.02 (mg N/m^2)/d. Diffusive fluxes for NH_4^+ ranged from 0.34 to 6.94 (mg N/m^2)/d with an overall average value of 1.65 (mg N/m^2)/d, and NH_4^+ was released from the sediment in all cases.

Table 4. Summary of diffusive flux data for all measurements, Puget Sound, Washington.

[**Abbreviations:** (mg N/m^2)/d, milligrams of nitrogen per square meter per day; –, no data; NS, not significant]

Station/site identifier	Date sampled	Depth (meters)	Porewater method	Gradient method	Diffusive fluxes [(mg N/m^2)/d]		
					Nitrate	Nitrite	Ammonium
Carkeek pelagic site (PS 16)	May 6–7, 1982	165–185	In situ	2-point	–	–	2.25
			In situ	Linear	NS	NS	0.48
			Centrifuging	2-point	–	–	0.73
			Centrifuging	Linear	NS	NS	0.54
			Centrifuging	2-point	–	–	0.34
Carkeek pelagic site (PS 17)	June 8–9, 1982	165–185	Centrifuging	2-point	–	–	1.34
			Centrifuging	Linear	–	NS	0.96
Carkeek pelagic site (PS 19)	04-19-83	174	In situ	Linear	NS	NS	1.14
Carkeek pelagic site (PS 21)	05-10-83	173	Centrifuging	Linear	NS	NS	0.80
Liberty Bay	Unknown	Unknown	Unknown	Linear	NS	NS	3.85
Poverty Bay	Unknown	179	Unknown	Linear	NS	–	1.08
PS stat 98 (Port Susan)	January 1982	104	Centrifuging	Linear	–	–	2.10
PS 51-2 (PS7)	January 1982	249	Centrifuging	Linear	–	–	0.58
PS stat 39 (Quartermaster Harbor)	September 1978	13	Centrifuging	Linear	–	–	1.03
Carkeek pelagic site (PS 14)	02-02-76	200	In situ	Linear	-0.11	NS	1.80
Carkeek pelagic site (PS 15)	03-29-76	200	In situ	Linear	-0.09	NS	1.96
Carkeek pelagic site (PS 16)	03-29-76	200	In situ	Linear	-0.05	0.01	1.67
Carr Inlet	Unknown	84	Core squeezing	Linear	-0.02	–	2.32
EB4	02-19-80	95	Centrifuging	Linear	NS	NS	1.05
PSE4	05-22-80	100	Centrifuging	Linear	0.11	NS	2.38
PSE6	05-22-80	55	Centrifuging	Linear	NS	NS	NS
PSE11	05-22-80	180	Centrifuging	Linear	NS	NS	0.87
EB4	09-12-80	95	Centrifuging	Linear	NS	NS	1.06
EB4-4	08-25-81	110	Centrifuging	Linear	NS	NS	0.81
EB4-5	08-26-81	110	Centrifuging	Linear	NS	0.04	0.81
EB11A-4	08-25-81	180	Centrifuging	Linear	NS	0.03	2.00
PS3	08-28-81	175	Centrifuging	Linear	NS	0.02	0.98
BK1	03-02-82	170	Centrifuging	Not enough data to calculate gradient			
Carkeek pelagic site	Unknown	200	In situ	2-point	-8.98	–	1.87
Quartermaster Harbor	July 1976–August 1978	15	Various	2-point	–	–	6.94
Holmes Harbor (CB1)	1992	45	Core squeezing	Gradient provided	-0.39	–	–
Holmes Harbor (CB2)	1992	45	Core squeezing	Gradient provided	-1.56	–	–
Holmes Harbor (CB3)	1992	60	Core squeezing	Gradient provided	-1.37	–	–
Holmes Harbor (CB4)	1992	60	Core squeezing	Gradient provided	-1.17	–	–
Budd Inlet (BI-5)	March 1997	10	Centrifuging	Not reported	-7.56	–	2.80
Budd Inlet (LOON-1)	June 1997	9	Centrifuging	Not reported	-12.04	–	2.80
Overall average					-2.77	0.02	1.65

Comparison of Porewater Sampling and Gradient Calculation Methods

As stated previously, there are a number of ways to both sample porewater and determine concentration gradients near the sediment-water interface. Although many porewater sampling methods were used across the compiled data, in only one instance was diffusive flux calculated for the same location and time using data collected from different porewater sampling methods. In May 1982, porewater was collected at a deep-water site north of Seattle (Carkeek pelagic site PS16, table 4) using an in situ sampler and using a lander to collect sediment cores that were sectioned and centrifuged. Only NH_4^+ data were available from this effort, and the diffusive fluxes calculated using the linear gradient method and data from the in situ sampler [0.48 (mg N/m^2)/d] and lander cores [0.54 (mg N/m^2)/d] were comparable. Although this is a single comparison, previous research has also shown that the method of porewater sampling does not drastically affect the value of the calculated diffusive flux (Qu and others, 2005), except when sampling includes the use of porewater equilibrators or peepers (Moore and others, 1998, summarized in Environmental Consulting Technology, Inc., 2007).

Three diffusive flux estimates were published based on a 2-point concentration gradient method with the porewater profile data, allowing a direct comparison of the methods for determining concentration gradients at the sediment-water interface (table 5). These estimates are for the same deep-water area north of Seattle in May–June 1982 (Carkeek pelagic sites). In each case, the diffusive flux calculated using a 2-point gradient gave NH_4^+ fluxes 1.36–4.69 times greater than those calculated using a linear regression of the porewater data. There was better agreement between the two gradient methods when porewater data were from lander cores that were collected and centrifuged, likely because the bottom water sample would have been collected from inside the lander flux chamber. For a case where the porewater was collected from an in situ sampler, the bottom water concentration used in the 2-point gradient approach could be different from the actual concentration diffusing out of the sediment because of dilution of the bulk bottom water environment.

Several assumptions must be made when using the 2-point gradient approach, which include (1) only one dominant biogeochemical reaction occurs within the section near the sediment water interface, (2) the concentration of porewaters between the first porewater sample and the bottom water are linear, (3) the measured concentrations represent the average of the linear concentration beginning with the concentration at the sediment water interface, and (4) the concentration at the sediment water interface is represented by the measured water column concentration, no matter how high off the bottom the sample was collected. Generally, whether the 2-point gradient or linear regression gradient method is used, researchers can benefit from collecting higher resolution porewater samples from the upper sediment. This will result in better definition of the typically steep concentration gradients near the sediment-water interface.

Diffusive and Bioirrigation Flux

Research has shown that activity in the form of bioirrigation and bioturbation can influence the amount of exchange across the sediment-water interface. A non-local diffusion model can be used to estimate the total flux from the sediment resulting from the bioirrigation process. Diffusive and irrigation flux models were used in two cases in the dataset from Puget Sound, which allowed for a comparison of this approach (table 6). The first case was at a deep water site north of Seattle (Carkeek) where NO_3^- and NH_4^+ fluxes for both models were determined (Grundmanis, 1989).

Table 5. Comparison of concentration gradient calculation methods for measurements at Carkeek pelagic site, Puget Sound, Washington.

[**Abbreviation:** (mg N/m^2)/d; milligrams of nitrogen per square meter per day]

Station/site identifier	Date sampled	Porewater method	Gradient method	Ammonium flux [(mg N/m^2)/d]	Ratio of flux
Carkeek pelagic site (PS 16)	May 6–7, 1982	In situ	2-point Linear	2.25 0.48	4.69
Carkeek pelagic site (PS 16)	May 6–7, 1982	Centrifuging	2-point Linear	0.73 0.54	1.36
Carkeek pelagic site (PS 17)	June 8–9, 1982	Centrifuging	2-point Linear	1.34 0.96	1.39

Table 6. Comparison of irrigation flux models of nitrate and ammonium in Puget Sound, Washington.

[**Abbreviations**: (mg N/m^2)/d; milligrams of nitrogen per square meter per day; –, no data]

Station/site identifier	Date sampled	Depth (meters)	Flux model	Flux [(mg N/m^2)/d]	
				Nitrate	Ammonium
Carkeek site	Unknown	200	Irrigation	-5.35	26.61
			Diffusive	-8.98	1.87
Quartermaster Harbor	July 1976–August 1978	15	Irrigation	–	6.96–34.78
			Diffusive	–	6.94±1.87

The NO_3^-, diffusional flux was slightly greater than the flux from the irrigation model. Conversely, the NH_4^+ irrigation flux was about 14 times greater than the flux calculated for diffusion only (table 6). At a shallow water site in Quartermaster Harbor (Emerson and others, 1984), average fluxes from four measurements over the course of a year were comparable between the two flux models. However, the variability in the irrigation model flux was large and was dependent on the value used for the irrigation exchange coefficient (Emerson and others, 1984). At Dabob Bay, irrigation fluxes were two to four times greater than diffusional fluxes (A. Devol, University of Washington, written commun., 2013), which further illustrates that bioirrigation can be important in deep water in Puget Sound.

Factors Influencing Benthic Nitrogen Fluxes in Puget Sound

Environmental factors have been shown to influence the magnitude of benthic fluxes. The dataset compiled for this study lacked detailed site-specific metadata. In particular, information about sediment composition and sediment organic matter, which are likely important controls on nitrogen flux, were not available. The compiled dataset does, however, provide insight into how season, water depth, and bottom water temperature affect the N flux resulting from remineralization from particles reaching the sediments.

Seasonal Effects

Chamber flux measurements have been made more than once during a given year in two studies in Puget Sound. In the first study, 19 chamber fluxes were measured in Dabob Bay at a deep-water site (110 m) from January 1987 to January 1988 (table B1; Colbert and others, University of Washington, unpub. data, 2010). Nitrate fluxes were into the sediment during the whole year and varied between about -10 and -25 (mg N/m^2)/d throughout the year (fig. 4). Ammonium fluxes were generally out of the sediment except for one point in July 1987, when NH_4^+ flux was -11.2 (mg N/m^2)/d. NH_4^+ fluxes were commonly between 0 and 10 (mg N/m^2)/d most of the year. The high late October peak in NH_4^+ flux was attributed to a response to increased primary productivity during the late summer (Colbert and others, University of Washington, unpub. data, 2010). The increase in organic matter production from the summer bloom needs time to settle and become remineralized on the seafloor causing the lag time between the summer bloom and increased benthic NH_4^+ flux.

In the second study, seasonal changes in benthic N flux were examined at four sites in Budd Inlet from September 1996 to September 1997 (Aura Nova Consultants and others, 1998). Fluxes of NO_3^- and NH_4^+ were determined in approximately 19 samples from each site (fig. 5). Fluxes of NH_4^+ were positive throughout the year, indicating a release from the sediment. Fluxes of NH_4^+ generally decreased during autumn and winter (October–February), reaching a minimum

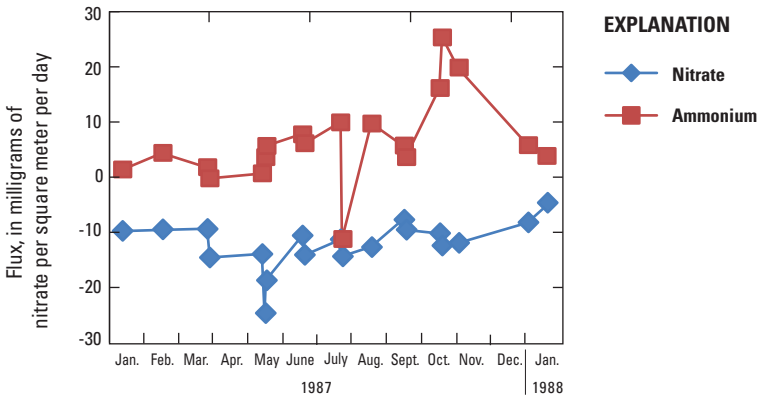

Figure 4. Time-series plot showing nitrate (NO_3^-) and ammonium (NH_4^+) benthic flux in Dabob Bay, Puget Sound, Washington. Negative values indicate flux into the sediment. Data from Colbert and others, University of Washington, unpub. data, 2010.

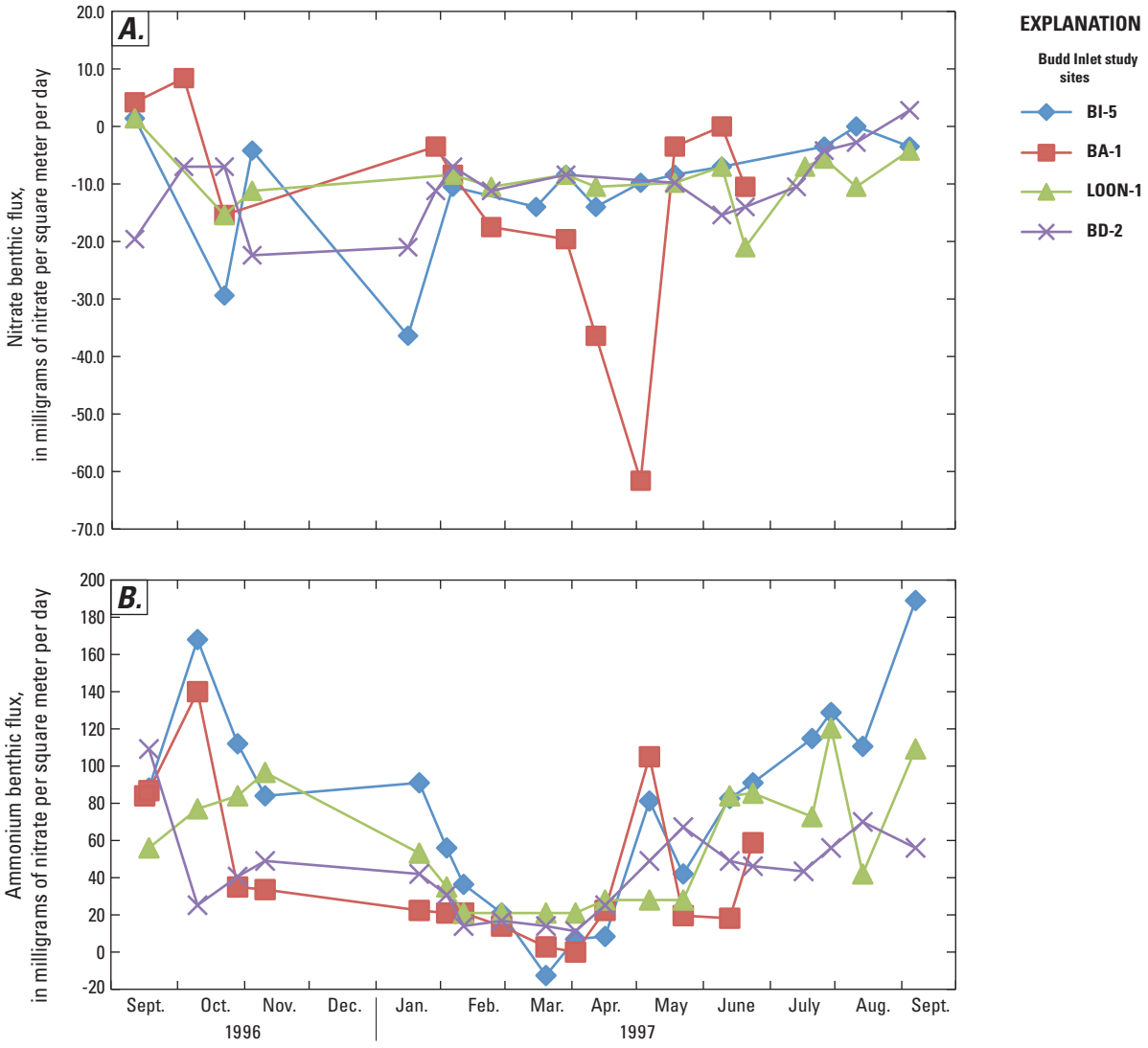

Figure 5. Time-series plot showing (*A*) nitrate and (*B*) ammonium chamber benthic flux from four sites in Budd Inlet, Puget Sound, Washington. Data from Aura Nova Consultants and others, 1998.

in March (fig. 5*A*). From March through the end of the study in September, fluxes increased at all sites. Flux of NO_3^- was almost always negative (into the sediment) and showed little seasonal response at three of the four sites (fig. 5*B*). At one site (BA-1), a substantial peak in NO_3^- flux into the sediment was easured during April–May.

Effects of Depth

Water depth controls many variables that can influence the amount of N flux in the environment. The bottom water temperature, the amount of light penetration, and the amount of organic matter delivery to the seafloor are all related to the depth of the water column. Two depth categories (shallow and deep) were used for this study to determine if depth affects the amount of N released to or taken from the water column. Water depths of 50 m or less were grouped into the shallow category, and depths greater than 50 m were considered the 'deep' sites. The deep sites were represented primarily by depths of 100 m or greater (n=48), and only a few sites (n=6) were between depths of 50–100 m. Distributions of flux data for chambers and porewaters for NO_3^-, NO_2^-, and NH_4^+, respectively are shown in figure 6. No significant differences (t-test, $p>0.2$) were noted in NO_3^- flux for shallow and deep sites for both types of flux (chamber and porewater), although the variability was greater in shallow depths (fig. 6*A*).

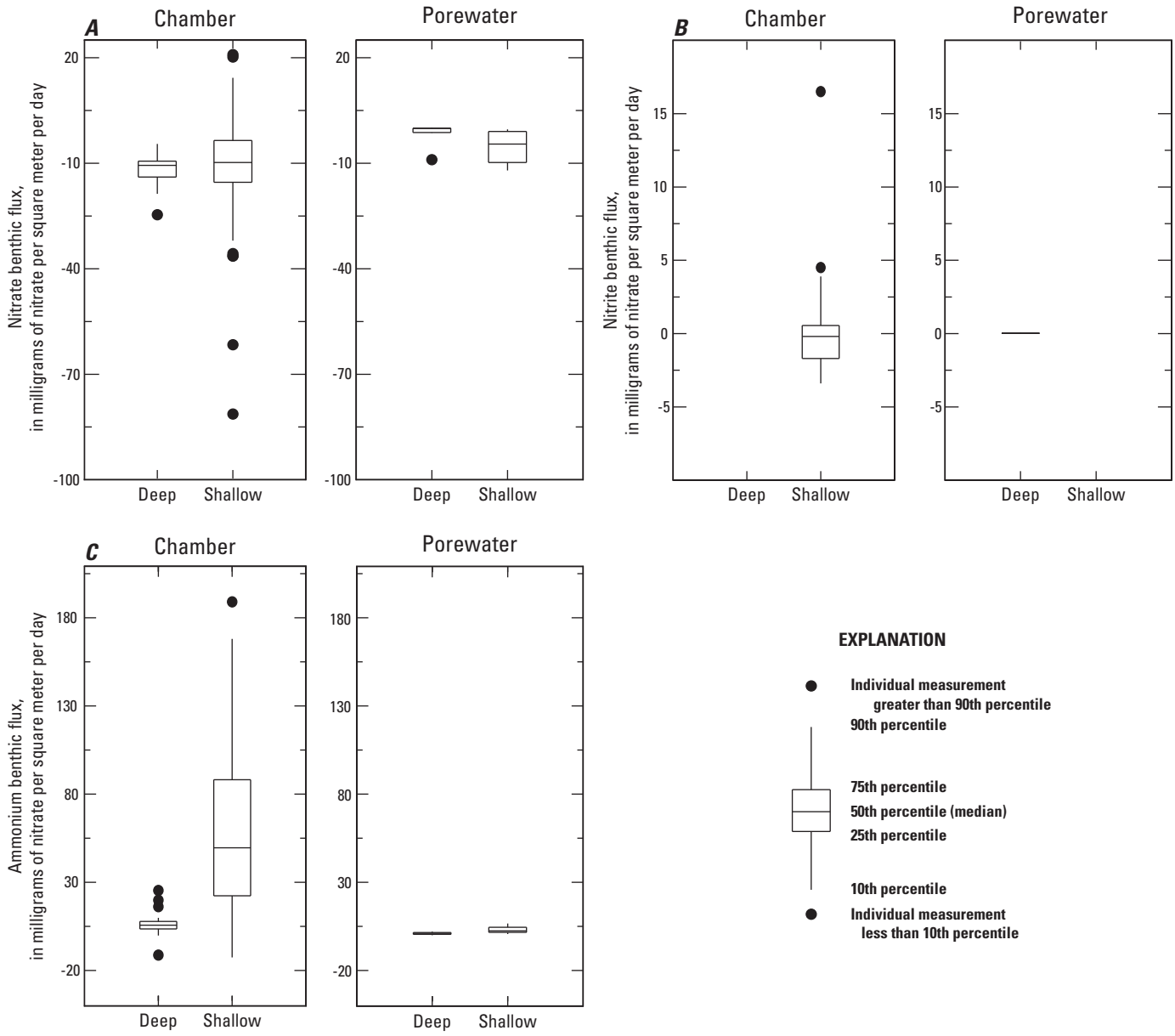

Figure 6. Depth dependence of benthic flux measurements for benthic chambers and diffusive flux using porewater for (*A*) nitrate, (*B*) nitrite, and (*C*) ammonium by method of measuring the flux. Deep sites are greater than 50 meters, shallow sites are less than 50 meters.

Few measurements of NO_2^- flux were made (fig. 6*B*), and all diffusive fluxes were focused in deep water and all chamber fluxes were focused in shallow water. Looking across methods there was no effect of depth on NO_2^- flux, but the data set is limited. However, there was an effect with depth for the NH_4^+ flux (fig. 6*C*). In both chamber and diffusive flux measurements, a significant increase in magnitude and variability of flux was noted in the shallow sites compared to the deep sites (t-test, $p<0.05$ for chamber data; $p<0.08$ for porewater data). These same depth patterns were apparent for all N species when the flux data from both chambers and porewaters were combined (data not shown). Overall, the data indicate that depth generally is not the only factor affecting N flux and that additional research into other controls such as temperature or primary productivity is warranted.

Effects of Bottom Temperature

Temperature has been shown to have an effect on the magnitude of benthic flux. The relation between benthic flux and bottom temperature for the compiled dataset (chamber and diffusive fluxes combined) is shown in figure 7. Bottom temperatures ranged from 5 to 16 °C across all flux measurements. These data include only fluxes where a temperature was reported in the respective publication, or were available from ancillary datasets. In many cases, bottom temperature was not available, or a single temperature was used for multiple flux measurements from a single study, which could have complicated the analysis. For example, the Dabob Bay study stated a bottom temperature of 10 °C (Colbert and others, University of Washington, unpub. data, 2010) but did not provide the actual temperature for each of the multiple flux deployments (n=21). In this case, the Dabob Bay flux data were assigned the same value for bottom temperature. Figure 7 shows the locally weighted linear regression of the data to discern any relation between flux and temperature. NO_3^- flux did not vary greatly with temperature, although the variability in NO_3^- flux increased at the higher range of temperatures (12–16 °C) (fig. 7*A*). A similar result is shown for NO_2^- and there was no clear relation between flux and temperature (fig. 7*B*). However, NO_2^- fluxes generally were low, had a smaller samples size, and had a narrower range in bottom temperature (11–16 °C). However, NH_4^+ flux did seem to show a relation with temperature ($p<0.001$). For NH_4^+, benthic fluxes were similar between 5–10 °C and then began to increase at greater temperatures (fig. 7*C*). As with NO_3^-, the NH_4^+ flux became more variable as temperature increased. This could be related to the large number of shallow chamber studies where temperature is more likely to affect N dynamics at the sediment-water interface.

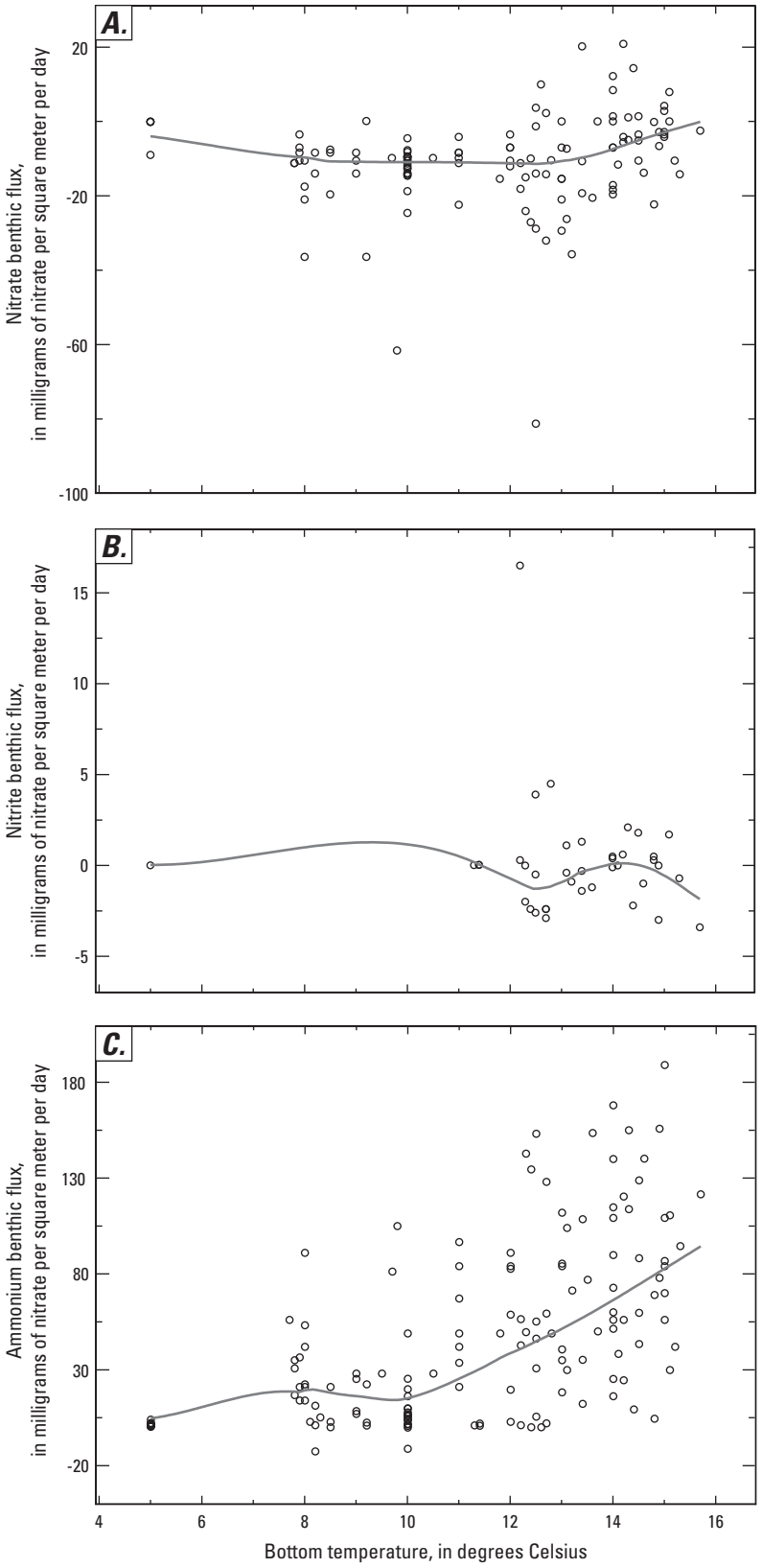

Figure 7. Bottom temperature dependence of benthic flux measurements for (*A*) nitrate, (*B*) nitrite, and (*C*) ammonium for all measurements combined (chamber and diffusive estimates), Puget Sound, Washington.

Summary of Puget Sound Benthic Fluxes

A total of 138 chamber measurements and 35 diffusive flux measurements were compiled for at least one N species for this report (table 7). The combined, chamber-only and diffusive flux (porewater)-only data are shown in figures 8*A–C*, respectively. For each N species, overall mean, median, and maximum fluxes are greater for chambers compared to those from porewater estimates. This likely is because flux measurements from chamber data incorporate not only diffusive flux, but flux from biological activity and N processing that takes place on the sediment surface. However, most of the chamber flux measurements in Puget Sound have been done in shallow depths (mean=28 m) compared to greater depths where porewater diffusive fluxes have been measured (mean=134 m). As was shown previously, shallow depths, particularly for NH_4^+ fluxes, in particular, were at shallow depths compared to deep sites. Both chamber and porewater diffusive fluxes were determined at the same site in a few cases and chamber fluxes were larger than diffusion fluxes in all cases.

One question still remains: are benthic sediments of Puget Sound a net source or sink of nitrogen to the overlying water column? To begin to address this question, the focus was placed on the chamber flux data (appendix B). A net inorganic N flux was calculated by summing the NO_3^-, NO_2^-, and NH_4^+ fluxes out of the sediment. Overall, about 78 percent of the data pairs show that the net inorganic N flux is out of the sediment and acts as an inorganic N source, and 22 percent of the data pairs indicate that sediments are a net inorganic N sink. Although this was not an exhaustive analysis and the study did not consider the organic forms of nitrogen, it is probable that sediments in Puget Sound generally release NH_4^+ to the water column. A more detailed study of the overall net effect from benthic flux is warranted. A similar analysis with the porewater diffusive fluxes could not be done because in most cases, NO_3^- flux was not statistically significant. Additionally, so little information is available on organic nitrogen fluxes in Puget Sound that total nitrogen mass balances between the water and sediment layers could not be evaluated.

Table 7. Summary statistics for benthic flux measurements, Puget Sound, Washington.

[**Abbreviations:** °C, degrees Celsius; (mg N/m^2)/d; milligrams of nitrogen per square meter per day]

Statistic	Depth (meters)	Bottom temperature (°C)	Flux [(mg N/m^2)/d]		
			Nitrate	Nitrite	Ammonium
All flux measurements					
Mean	50.9	11.1	-10.0	0.130	42.1
Standard deviation	64.2	2.88	12.6	3.16	45.4
Median	13.0	11.4	-9.50	0.00	25.2
Minimum	2.50	5.00	-81.3	-3.40	-12.6
Maximum	249	15.7	20.9	16.5	189
No. of measurements	175	159	131	40	168
Chamber measurements					
Mean	28.5	11.7	-10.8	0.140	50.8
Standard deviation	40.0	2.48	13.0	3.34	45.6
Median	11.0	12.2	-10.0	-0.200	39.5
Minimum	2.50	5.00	-81.3	-3.40	-12.6
Maximum	200	15.7	20.9	16.5	189
No. of measurements	138	135	119	36	138
Porewater measurements					
Mean	134	7.80	-2.77	0.0300	1.64
Standard deviation	69.5	2.84	4.20	0.0100	1.30
Median	174	8.20	-0.780	0.0250	1.11
Minimum	9.00	5.00	-12.0	0.0100	0.340
Maximum	249	12.2	0.110	0.0400	6.94
No. of measurements	37	24	12	4	30

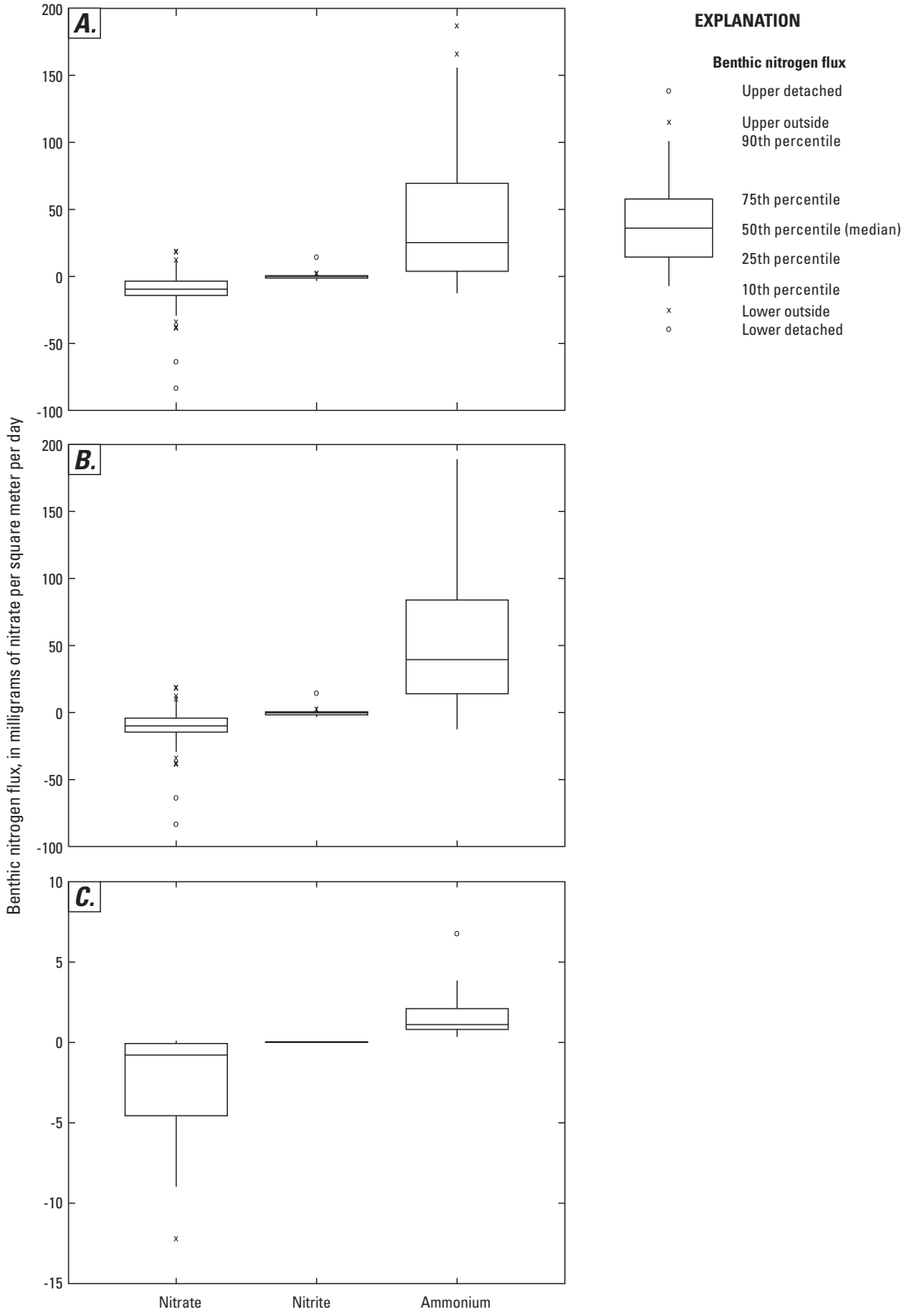

Figure 8. Summary of benthic nitrogen fluxes compiled for this report for (*A*) all measurements combined, (*B*) chamber measurements, and (*C*) diffusive fluxes from porewater measurements, Puget Sound, Washington.

Incorporating Benthic Fluxes into Marine Water Quality Models

Water-quality models simulate the interactions between the bottom sediments and the water column for parameters relevant to the modeling question. For modeling dissolved oxygen, the flux of nutrients and oxygen is fundamental to simulating system responses to current and alternative loading scenarios. Most sediment-water interactions are represented in water-quality models using one of three approaches:

- Fluxes are specified in the model using externally developed information (zero-order approach);
- Aerobic sediment layers are determined using a first-order approach; or
- Aerobic and anaerobic sediment layers are determined using sediment diagenesis.

In Puget Sound, the dominant approach to date has been to externally specify the fluxes based on patterns in observed benthic fluxes and to then adjust those specified benthic fluxes based on reductions or increases in external loads (M. Roberts, Washington State Department of Ecology, personal commun., 2013). The Washington State Department of Ecology plans to include sediment diagenesis in models under development to directly link the benthic fluxes to changes in external loads. Each approach requires different field-based or literature-based parameters and the more complicated approaches generally require the most parameters (table 8).

Zero-Order Approach

Providing externally derived benthic flux values is the simplest approach to link water-quality models and benthic fluxes. For this approach, measurements of benthic flux are used as a source and (or) sink term, typically combined with a mass-balance approach for a given water body. Using the zero-order approach, an estimate of benthic flux and the area of the water body is needed to scale these estimates to the study site of interest. These values then can be compared to other internal and external nutrient inputs to the system to assess the importance of the benthic flux pathway. Specified fluxes can be measured at one time and assumed to be constant at other times of the year, or fluxes can be estimated throughout the year to incorporate seasonality into the model. However, this zero-order approach is not well suited for examining hypothetical model scenarios with altered nutrient loading regimes. Actual sediment fluxes are likely to change for scenarios with altered nutrient loading regimes, but the same zero-order fluxes, based on calibration or a defensible method of estimating how sediment flux would change under a hypothetical model scenario, must be assumed for all scenarios.

First-Order Approach

The next level of modeling complexity takes into account not only the flux of nutrients at the sediment water interface, but also the organic matter dynamics that can fuel benthic nitrogen regeneration. In the first-order approach, spatial and

Table 8. Summary of approaches for incorporating benthic flux data into water quality models in Puget Sound, Washington.

Approach	Input data needed	Outputs
Zero-order approach	Benthic flux estimate (constant or seasonal) Surface area of study site	Areal contribution of nutrients to the study site
First-order approach	Benthic flux estimate (constant or seasonal) Surface area of study site Estimates of particulate organic matter settling	Relation between particulate organic matter and benthic flux
Sediment diagenesis	Flux to seafloor of particulate organic matter, nitrogen, phosphorus Bottom water characteristics (temperature, nutrient and dissolved oxygen concentrations, salinity, dissolved organic carbon, and depth) Benthic flux through sediment-water interface of dissolved oxygen, nitrate, ammonium, phosphorus, and other substrates (including methane and sulfide) Concentrations of nutrients and other substrates in the aerobic and anearobic regions of the sediment Estimate of the depth of the aerobic zone in the sediment	Dynamic sediment diagenesis model describing the relations between organic matter inputs to the seafloor, cycling within the sediment aerobic and aneraobic zones, and subsequent release from the sediment

(or) temporal benthic flux dynamics are explained by measuring or simulating the inputs of settling particulate matter to the sediment-water interface. For this approach, estimates of the amount of organic matter that settles to the seafloor are needed, which can be estimated or derived from the literature or measured directly in the field using sediment traps or similar methods. The result from this approach is a more realistic simulation of the internal (water column) inputs that fuel N remineralization and benthic flux.

Sediment Diagenesis

In this final approach, benthic fluxes are incorporated into models by simulating all the processes involved in sediment diagenesis. The sediment diagenesis approach simulates the relation between settling organic matter, oxidation and mineralization of this material on the seafloor, sediment dynamics in aerobic and anaerobic sediment zones, and the ultimate release of N back to the water column. Information on sediment oxygen demand should be incorporated into such models, because oxygen levels are an important driver for the type and amount of N flux at the sediment-water interface (DiToro, 2001). Estimates of sediment oxygen demand can be determined using the same methods as those for estimating N flux. This diagenesis is the most complicated approach and includes additional variables that need to be estimated or measured. To date, no known Puget Sound scale model has attempted to simulate sediment diagenesis. However, the work of Colbert and others (University of Washingotn, unpub. data, 2010) in Dabob Bay is a good example of how this approach works on the scale of a single embayment. Additionally, the Washington State Department of Ecology provides a spreadsheet model (SedFlux) that allows the user to simulate sediment nitrogen fluxes and sediment oxygen demand in the context of a sediment diagenesis model (Washington State Department of Ecology, 2013). The input data required by both these examples are similar and are summarized in table 8. The end result of this approach will be a dynamic subroutine to a larger water-quality model that fully describes the connection between pelagic and benthic processes controlling nutrient cycles at the sediment water interface.

Future Approaches and Areas of Research for Characterizing Benthic Fluxes in Critical Areas of Puget Sound

Various approaches for estimating benthic fluxes of N were reviewed for this study and the available data for Puget Sound were summarized. From that, suitable approaches for future work in the region that may be particularly beneficial for decision makers and researchers are presented here.

Collection of Ancillary Data

The collection of good metadata during the time that benthic fluxes are measured can allow researchers to better describe the spatial variability of benthic N fluxes in Puget Sound. These data include depth, bottom temperature, bottom water chemistry (NO_3^-, NH_4^+, dissolved oxygen), and sediment properties (percentage of sand, silt, clay, and organic matter). In addition, it is important to know the sediment porosity at the sediment-water interface if fluxes are derived from porewater concentrations in order to correct diffusion coefficients in a porous media. If sediment porosity at the site is unknown, then assumptions must be made, which can lead to errors in the calculated diffusive flux. Additionally, it is important that porewater samples are collected at as small a depth interval as possible. In many cases, the spatial resolution of compiled Puget Sound porewater data was not sufficient to allow for the calculation of diffusive fluxes, likely a result of a large (1 cm or more) interval between samples. Overall, the more ancillary data that is collected during benthic flux studies, the more accurate a water-quality model will be at describing the spatial and temporal factors affecting these fluxes.

Study of Temporal Variability in Flux

Although a few studies have examined the seasonal effects on benthic N flux, the results are not conclusive. In Dabob Bay (Colbert and others, University of Washington, unpub. data, 2010), seasonal changes in benthic flux were not dramatic. A peak of NH_4^+ in late summer likely corresponded to an algal bloom earlier in the season, but fluxes of NO_3^- were relatively stable. In Budd Inlet (Aura Nova Consultants and others, 1998), NH_4^+ fluxes at four sites showed a seasonal pattern. NH_4^+ fluxes decreased in autumn through winter, reached a minimum in early spring, and then began to increase through the summer. In this same study, NO_3^- fluxes were variable across all four sites and seasonal patterns were not obvious. The differences between these studies might be related to depth. Dabob Bay was a deep water site (110 m) and the Budd Inlet study took place at shallow sites (range in depth, 3–15 m). Additional seasonal studies at intermediate depths (20–100 m) and deeper (greater than 100 m) could allow researchers to better represent temporal changes in benthic flux in water-quality models.

Understanding seasonality of flux also is important relative to other factors, such as external (allochthonous) loading into Puget Sound. For example, seasonal studies in areas where a significant amount of organic matter delivery is from terrestrial sources are warranted. Unanswered questions remain: (1) Do high watershed loads of organic matter in winter settle out and become covered so they are not a concern, or can this input result in an immediate, or time-lagged pulse in benthic N flux? (2) Does high algal productivity in March–June result in a source of organic matter that takes a few months to recycle? If so, remineralization may peak during times of the year when dissolved-oxygen concentrations are the most susceptible (September).

Depth and Temperature Effects

The compiled flux data for Puget Sound suggested that high fluxes occurred in shallow waters for both NO_3^- and NH_4^+. Variability in flux from deep sites was small. This would imply that these environments are more homogeneous, and that there is a good understanding of flux patterns in these environments, although most of the deep data from chamber estimates are from a single site (Dabob Bay) (fig. 6). If resources are limited, future work could focus on shallow sites where flux was generally higher, measurements were more variable, and, fluxes likely influence water quality to a greater degree. If more resources are available, conducting a seasonal study at one to two more deep site locations in Puget Sound would prove valuable and test for consistency with the current dataset.

Flux and bottom temperature relations show that NO_3^- and NH_4^+ fluxes increased above 12 °C and were much more variable than at cooler temperatures. Fluxes compiled for this report had bottom temperatures that ranged from 5 to about 16 °C. However, one site reported a 5 °C bottom temperature, and reported temperatures from 90 of 134 chamber measurements and 14 of 20 porewater measurements were between 8 and 12 °C. This is consistent with temperature data throughout Puget Sound where large seasonal changes in temperature are not common. With such a narrow temperature range, a more thorough analysis of flux and temperature is not warranted at this time.

Methods for Determining Benthic Nitrogen Flux

Two general methods are used to estimate benthic flux; direct methods (chambers and controlled laboratory experiments), and indirect methods (flux derived from porewater data). The most appropriate approach to use depends on study questions being asked. Whenever feasible, chamber fluxes should be measured because they require fewer assumptions and present fewer potential problems with calculating the flux. Assuming that the chamber seals correctly, only concentration with time data are needed to calculate a flux. Additionally, chambers not only incorporate diffusive flux, but also any flux from biological activity (bioirrigation, bioturbation, and N processing on the sediment surface). Porewater-derived fluxes, however, require information on bottom temperature, sediment porosity, diffusion coefficients (*Do*), correction factors for *Do* resulting from transport in a porous medium (tortuosity) in addition to the porewater concentration data. Even in cases where this information is available, errors can result because realistic concentration gradients cannot be represented at the sediment water interface if sample intervals are too large to resolve steep gradients in this region of the sediment. Porewater diffusive fluxes that incorporate biological activity (irrigation flux) have shown promise in Puget Sound (Emerson and others, 1984; Grundmanis, 1989) to better reflect total flux from the sediment. However, this approach requires information on the irrigation exchange rate, which is another poorly constrained parameter that needs to be estimated or simulated. In Puget Sound, biological influence on flux has been shown to depths of about 200 m; (Grundmanis, 1989) and is likely important at most locations in the region. If calculating flux using porewater data, high-resolution depth intervals less than 1 cm data generally should be collected to accurately represent concentration gradients at the sediment-water interface. Finer scale sampling also will allow for the use of more accurate non-linear curve fitting of porewater data.

In some cases, the availability of project resources may dictate the approach used. Chamber studies (either sophisticated landers or simpler designs) are time and labor intensive, which can limit the number of locations visited. Additionally, costs can be high, with sophisticated deep-water landers ranging from $10,000–$100,000. For studies focused on shallow waters, small non-automated chambers can be inexpensive (approximately $1,000 or less). Collection of sediment cores for laboratory determination of flux from porewater data can be fast and relatively inexpensive, allowing for greater coverage of a study area. The costs for a reliable sediment coring system can be as high as a few thousand dollars, but inexpensive alternatives also exist. The difficulty (and cost) of using chambers at deep depths also might limit available study locations in Puget Sound, whereas sediment cores can be collected from almost anywhere. A potential intermediate approach would be to use controlled laboratory column incubations. To date, no known column incubation studies have taken place in Puget Sound. Previous studies have shown that fluxes from column experiments are comparable to chambers, if care is taken to reproduce bottom water conditions (temperature and dissolved oxygen concentrations) (Miller-Way and others, 1994).

When possible, the use of chambers to estimate flux will result in the most direct estimate of benthic N flux. If broader spatial coverage and resources are limited, then porewater estimated fluxes that incorporate bioirrigation flux will yield more accurate results. However, investigating the use of column incubations in Puget Sound is needed and combines valuable features of chamber and porewater studies. These include a more direct estimate of benthic flux, and the ability to cover a broader area for characterizing benthic inputs.

Other Considerations

Although not discussed in detail in this report, the stirring rates used in chambers may not represent the boundary layer thickness that exists in the bulk environment. For example, the inverted aquaria chambers used in several studies in Puget Sound (Roberts and others, 2008; King County, 2012) might not stir enough to represent the true boundary layer thickness, resulting in possible underestimates of benthic flux

(M. Roberts, Washington Department of Ecology, written comm., 2013). Although some literature states that stirring rates are not that important as long as some stirring is involved (Tengberg and others, 2004), there is not a clear consensus, and information about this for the Puget Sound does not currently exist.

Geographically, existing flux measurements represent a large area of the Puget Sound except areas north of Seattle. When selecting locations for additional work, consideration should be given to bays and inlets where external watershed loads of organic matter are large compared to internal inputs. In these locations, a larger proportion of overall nutrient inputs likely could come from remineralization of the deposited organic matter.

Conclusions

Understanding benthic fluxes is important for understanding the fate of materials that settle to the Puget Sound, Washington, seafloor as well as the impact these fluxes have on the chemical composition and biogeochemical cycles of marine waters. Factors for selecting an appropriate approach for gathering information about benthic flux include: availability of resources, objectives of projects, and determination of which processes each approach measures. Benthic fluxes compiled for Puget Sound showed that fluxes beneath deep (greater than 50 meters) water tended to be lower than those beneath shallow (less than 50 meters) water. Additionally, variability in flux at the shallow depths was greater, possibly indicating a more dynamic interaction between the benthic and pelagic environments. The overall range of bottom temperatures from studies in the Puget Sound area was small (5–16 degrees Celsius), and only NH_4^+ flux showed any pattern with temperature. For NH_4^+, flux values and variability increased at greater than about 12 degrees Celsius. Collection of additional study site metadata (bottom temperature, depth, sediment porosity, sediment type, and sediment organic matter) will help with development of a broader regional understanding benthic nitrogen flux in the Puget Sound.

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Appendix A. Detailed Site and Location Information from All Compiled Flux Measurements

Table A1. Site and location information for all flux chamber measurements, Puget Sound, Washington.

[Latitude and Longitude in decimal degrees referenced to the North American Datum of 1983. **Abbreviations:** °C, degrees Celsius; UNK, unknown]

Station/site identifier	Date	Depth (meters)	Bottom temperature (°C)	Latitude	Longitude	Reference
Carkeek pelagic site (PS 17)	June 8–9, 1982	165–185	5.0	47.703333	-122.4100000	Murray (1982)
Carkeek pelagic site	UNK	200	8.3	47.703333	-122.4100000	Grundmanis (1989)
Holmes Harbor (HH1)	August 1993	50	UNK	48.03883333	-122.5256667	Brandes and Devol (1997)
Holmes Harbor (HH2)	August 1993	70	UNK	48.09133333	-122.5573333	Brandes and Devol (1997)
Holmes Harbor (HH3)	August 1993	70	UNK	48.09133333	-122.5573333	Brandes and Devol (1997)
Dabob Bay	02-17-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	03-29-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	03-31-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	05-17-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	05-20-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	05-21-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	06-22-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	06-24-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	07-26-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	07-28-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	08-23-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	09-21-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	09-23-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	10-23-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	10-25-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	11-09-87	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	01-10-88	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Dabob Bay	01-30-88	110	10.0	UNK	UNK	Colbert and others, unpub. data (2010)
Budd Inlet (BI-5)	09-10-96	8	14.5	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	10-03-96	12	14.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	10-22-96	13	13.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	11-04-96	13	11.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	01-16-97	13	8.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	01-29-97	12	7.7	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	02-06-97	12	7.9	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	02-24-97	11	8.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	03-17-97	10	8.2	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	03-31-97	10	9.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	04-14-97	10	9.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	05-05-97	10	9.7	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	05-21-97	13	11.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	06-12-97	10	12.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	06-23-97	10	12.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	07-21-97	13	14.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	07-30-97	13	14.5	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	08-14-97	9	15.1	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BI-5)	09-08-97	11	15.0	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	09-08-96	6	15.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	09-10-96	6	15.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	10-03-96	12	14.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)

Table A1. Site and location information for all flux chamber measurements, Puget Sound, Washington.—Continued

[Latitude and Longitude in decimal degrees referenced to the North American Datum of 1983. **Abbreviations:** °C, degrees Celsius; UNK, unknown]

Station/site identifier	Date	Depth (meters)	Bottom temperature (°C)	Latitude	Longitude	Reference
Budd Inlet (BA-1)	10-22-96	12	13.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	11-04-96	10	11.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	01-16-97	7	8.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	01-29-97	5	7.9	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	02-06-97	3	11.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	02-24-97	5	8.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	03-17-97	3	8.1	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	03-31-97	3	8.5	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	04-14-97	3	9.2	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	05-05-97	5	9.8	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	05-21-97	8	12.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	06-12-97	3	13.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	06-23-97	7	12.0	47.074097	-122.912807	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	09-10-96	10	14.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	10-03-96	10	13.5	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	10-22-96	10	13.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	11-04-96	10	11.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	01-16-97	8	8.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	01-29-97	7	7.8	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	02-06-97	9	7.9	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	02-24-97	11	8.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	03-17-97	8	8.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	03-31-97	9	8.5	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	04-14-97	9	9.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	05-05-97	8	9.5	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	05-21-97	8	10.5	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	06-12-97	9	12.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	06-23-97	8	13.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	07-21-97	5	14.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	07-30-97	12	14.2	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	08-14-97	8	15.2	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BA-1)	09-08-97	9	15.0	47.091338	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	09-10-96	10	14.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	10-03-96	10	14.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	10-22-96	10	13.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	11-04-96	10	11.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	01-16-97	10	8.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	01-29-97	10	7.8	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	02-06-97	11	7.9	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	02-24-97	8	7.8	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	03-17-97	11	8.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	03-31-97	11	8.2	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	04-14-97	13	9.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	05-05-97	5	10.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	05-21-97	10	11.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	06-12-97	13	11.8	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	06-23-97	10	12.5	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	07-17-97	12	14.5	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	07-30-97	14	14.2	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	08-14-97	10	15.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Budd Inlet (BD-2)	09-08-97	13	15.0	47.113189	-122.910404	Aura Nova Consultants and others (1998)
Case Inlet (Case05)	09-10-07	7	14.9	47.06933333	-122.9160833	Roberts and others (2008)

Table A1. Site and location information for all flux chamber measurements, Puget Sound, Washington.—Continued

[Latitude and Longitude in decimal degrees referenced to the North American Datum of 1983. **Abbreviations:** °C, degrees Celsius; UNK, unknown]

Station/site identifier	Date	Depth (meters)	Bottom temperature (°C)	Latitude	Longitude	Reference
Case Inlet (Case15)	09-10-07	14	14.8	47.11468333	-122.9184	Roberts and others (2008)
Case Inlet (Case25)	09-10-07	26	14.5	47.12763333	-122.91945	Roberts and others (2008)
Carr Inlet (Carr05)	09-10-07	7	14.0	47.38016667	-122.6297	Roberts and others (2008)
Carr Inlet (Carr15)	09-10-07	16	13.2	47.37285	-122.63955	Roberts and others (2008)
Carr Inlet (Carr25)	09-10-07	26	12.8	47.36223333	-122.6619167	Roberts and others (2008)
Eld Inlet (Eld05)	09-10-07	8	15.1	47.3759	-122.8195	Roberts and others (2008)
Eld Inlet (Eld15)	09-10-07	17	14.0	47.35946667	-122.8159	Roberts and others (2008)
Eld Inlet (Eld25)	09-10-07	25	13.4	47.34141667	-122.8067833	Roberts and others (2008)
Budd Inlet (Budd05)	09-10-07	7	15.7	47.08075	-122.9962667	Roberts and others (2008)
Budd Inlet (Budd15)	09-10-07	14	15.3	47.10166667	-122.96225	Roberts and others (2008)
Budd Inlet (Budd25)	09-10-07	27	14.8	47.13868333	-122.9439833	Roberts and others (2008)
Case Inlet (Case05)	09-24-07	5	14.4	47.06913	-122.91806	Roberts and others (2008)
Case Inlet (Case15)	09-24-07	15	14.1	47.113255	-122.9168617	Roberts and others (2008)
Case Inlet (Case25)	09-24-07	25	14.0	47.12774667	-122.9208333	Roberts and others (2008)
Carr Inlet (Carr05)	09-24-07	5	13.4	47.38065333	-122.6293867	Roberts and others (2008)
Carr Inlet (Carr15)	09-24-07	15	13.1	47.37225333	-122.6390467	Roberts and others (2008)
Carr Inlet (Carr25)	09-24-07	25	13.1	47.36370667	-122.6551917	Roberts and others (2008)
Eld Inlet (Eld05)	09-24-07	5	14.2	47.383125	-122.8192783	Roberts and others (2008)
Eld Inlet (Eld15)	09-24-07	15	13.6	47.35958833	-122.816985	Roberts and others (2008)
Eld Inlet (Eld25)	09-24-07	25	13.4	47.339695	-122.8094983	Roberts and others (2008)
Budd Inlet (Budd05)	09-24-07	5	14.9	47.082095	-122.9955083	Roberts and others (2008)
Budd Inlet (Budd15)	09-24-07	15	14.6	47.10241833	-122.9589383	Roberts and others (2008)
Budd Inlet (Budd25)	09-24-07	25	14.3	47.13963333	-122.94425	Roberts and others (2008)
Case Inlet (Case05)	10-22-07	5	12.5	47.06918667	-122.9188733	Roberts and others (2008)
Case Inlet (Case15)	10-22-07	15	12.5	47.11460833	-122.9205167	Roberts and others (2008)
Case Inlet (Case25)	10-22-07	25	12.3	47.12758333	-122.9218	Roberts and others (2008)
Carr Inlet (Carr05)	10-22-07	6	12.5	47.38049167	-122.6303883	Roberts and others (2008)
Carr Inlet (Carr15)	10-22-07	15	12.2	47.37340667	-122.6389867	Roberts and others (2008)
Carr Inlet (Carr25)	10-22-07	25	12.2	47.36454333	-122.656465	Roberts and others (2008)
Eld Inlet (Eld05)	10-22-07	5	12.7	47.38322667	-122.8192767	Roberts and others (2008)
Eld Inlet (Eld15)	10-22-07	15	12.7	47.36036	-122.81674	Roberts and others (2008)
Eld Inlet (Eld25)	10-22-07	25	12.5	47.34973333	-122.81452	Roberts and others (2008)
Budd Inlet (Budd05)	10-22-07	5	12.7	47.08187333	-122.997235	Roberts and others (2008)
Budd Inlet (Budd15)	10-22-27	15	12.4	47.10338333	-122.9522267	Roberts and others (2008)
Budd Inlet (Budd25)	10-22-07	25	12.3	47.13995167	-122.9457967	Roberts and others (2008)
Quartermaster Harbor (QMH_A)	September 1–2, 2010	4	14.3	47.39786189	-122.4574936	King County (2012)
Quartermaster Harbor (QMH_B)	September 1–2, 2010	6	14.0	47.38793266	-122.437283	King County (2012)
Quartermaster Harbor (QMH_C)	September 1–2, 2010	8	13.7	47.37477973	-122.4541686	King County (2012)
Quartermaster Harbor (QMH_D)	September 1–2, 2010	14	12.6	47.38105796	-122.4734957	King County (2012)
Quartermaster Harbor (QMH_E)	September 1–2, 2010	17	12.4	47.36029465	-122.4795354	King County (2012)

Table A2. Site and location information for all flux porewater measurements, Puget Sound, Washington.

[Latitude and Longitude in decimal degrees referenced to the North American Datum of 1983. **Abbreviations:** °C, degrees celsius; UNK, unknown]

Station/site identifier	Date	Depth (meters)	Bottom temperature (°C)	Sediment porosity	Latitude	Longitude	Reference
Carkeek pelagic site (PS 16)	May 6–7, 1982	165–185	5	0.8	47.703333	-122.41	Murray (1982)
Carkeek pelagic site (PS 16)	May 6–7, 1982	165–185	5	0.8	47.703333	-122.41	Murray (1982)
Carkeek pelagic site (PS 17)	June 8–9, 1982	165–185	5	0.8	47.703333	-122.41	Murray (1982)
Carkeek pelagic site (PS 19)	04-19-83	174	UNK	UNK	47.35	-122.40667	Miller, written commun. (2013)
Carkeek pelagic site (PS 21)	05-10-83	173	UNK	UNK	47.36	-122.36667	Miller, written commun. (2013)
Liberty Bay	UNK	UNK	UNK	UNK	UNK	UNK	Devol, oral commun. (2013)
Poverty Bay	UNK	179	UNK	UNK	47.36383333	-122.3516667	Devol, oral commun. (2013)
PS Stat 98 (Port Susan)	January 1982	104	UNK	UNK	48.041824	-122.314224	Peterson and Carpenter (1986)
PS Stat 51-1 (PS7)	September 1978	249	UNK	UNK	47.694512	-122.465973	Peterson and Carpenter (1986)
PS 51-2 (PS7)	January 1982	249	UNK	UNK	47.694512	-122.465973	Peterson and Carpenter (1986)
PS Stat 56 (East Passage)	January 1982	200	UNK	UNK	47.469878	-122.404861	Peterson and Carpenter (1986)
PS Stat 39 (Quartermaster Harbor)	September 1978	13	UNK	UNK	47.379289	-122.46666	Peterson and Carpenter (1986)
Carkeek pelagic site (PS 14)	02-02-76	200	5	0.8	47.703333	-122.41	Grundmanis and Murray (1977)
Carkeek pelagic site (PS 15)	03-29-76	200	5	0.8	47.703333	-122.41	Grundmanis and Murray (1977)
Carkeek pelagic site (PS 16)	03-29-76	200	5	0.8	47.703333	-122.41	Grundmanis and Murray (1977)
Carr Inlet	UNK	84	UNK	UNK	47.28683	-122.71583	Tiquia and others (2006)
EB4	02-19-80	95	8.2	0.8	47.60633	-122.36033	Paulson and others (1991)
PSE4	05-22-80	100	9.2	0.8	47.60833	-122.35833	Paulson and others (1991)
PSE6	05-22-80	55	9.2	0.8	47.59167	-122.63333	Paulson and others (1991)
PSE11	05-22-80	180	9.2	0.7	47.615	-122.4	Paulson and others (1991)
EB4	09-12-80	95	12.2	0.75	47.60467	-122.36033	Paulson and others (1991)
EB4-4	08-25-81	110	11.4	0.8	47.60833	-122.36	Paulson and others (1991)
EB4-5	08-26-81	110	11.4	0.87	47.61	-122.35833	Paulson and others (1991)
EB11A-4	08-25-81	180	11.4	0.75	47.62167	-122.42333	Paulson and others (1991)
PS3	08-28-81	175	11.3	0.8	47.33	-122.35917	Paulson and others (1991)
BK1	03-02-82	170	8.2	0.73	47.31417	-122.48	Paulson and others (1991)
Holmes Harbor (CB1)	1992	45	UNK	UNK	48.03883333	-122.5256667	Brandes and Devol (1995)
Holmes Harbor (CB2)	1992	45	UNK	UNK	48.03883333	-122.5256667	Brandes and Devol (1995)
Holmes Harbor (CB3)	1992	60	UNK	UNK	48.09133333	-122.5573333	Brandes and Devol (1995)
Holmes Harbor (CB4)	1992	60	UNK	UNK	48.09133333	-122.5573333	Brandes and Devol (1995)
Quartermaster Harbor	July 1976–August 1978	15	10	0.9	UNK	UNK	Emerson and others (1984)
Carkeek pelagic site	UNK	200	8.3	0.8	47.703333	-122.41	Grundmanis (1989)
Budd Inlet (BI-5)	March 1997	10	8.5	UNK	47.051704	-122.908516	Aura Nova Consultants and others (1998)
Budd Inlet (LOON-1)	May 6–7, 1982	9	12	UNK	47.091338	-122.910404	Aura Nova Consultants and others (1998)

Appendix B. Summary of Compiled Benthic Flux Data for Nitrogen for All Individual Chamber Measurements

Table B1. Summary of benthic flux data for all individual chamber measurements, Puget Sound, Washington.

[**Abbreviations:** °C, degrees Celsius; (mg N/m^2)/d, milligrams of nitrogen per square meter per day; –, no data; UNK, unknown; DIN, dissolved inorganic nitrogen]

Station/site identifier	Date	Depth (meters)	Bottom temperture (°C)	Benthic fluxes [(mg N/m^2)/d]			
				Nitrate	Nitrite	Ammonium	Net DIN
Carkeek pelagic site (PS17)	June 8–9, 1982	175	5	–	–	3.9	–
Carkeek pelagic site	UNK	200	8.3	–	–	5.1	–
Holmes Harbor (HH1)	August 1993	50	UNK	-10.8	–	7.0	-3.8
Holmes Harbor (HH2)	August 1993	70	UNK	-6.2	–	6.4	0.2
Holmes Harbor (HH3)	August 1993	70	UNK	-7.9	–	5.7	-2.2
Dabob Bay	01-12-87	110	10	-9.7	–	1.4	-8.3
Dabob Bay	02-17-87	110	10	-9.5	–	4.4	-5.0
Dabob Bay	03-29-87	110	10	-9.4	–	1.8	-7.6
Dabob Bay	03-31-87	110	10	-14.6	–	-0.2	-14.8
Dabob Bay	05-17-87	110	10	-13.9	–	0.7	-13.2
Dabob Bay	05-20-87	110	10	-24.6	–	3.6	-21.0
Dabob Bay	05-21-87	110	10	-18.7	–	5.7	-13.0
Dabob Bay	06-22-87	110	10	-10.6	–	7.8	-2.8
Dabob Bay	06-24-87	110	10	-14.1	–	6.2	-7.9
Dabob Bay	07-26-87	110	10	-11.3	–	9.9	-1.3
Dabob Bay	07-28-87	110	10	-14.4	–	-11.2	-25.6
Dabob Bay	08-23-87	110	10	-12.7	–	9.7	-2.9
Dabob Bay	09-21-87	110	10	-7.7	–	5.7	-2.0
Dabob Bay	09-23-87	110	10	-9.5	–	3.6	-5.9
Dabob Bay	10-23-87	110	10	-10.2	–	16.2	6.0
Dabob Bay	10-25-87	110	10	-12.4	–	25.3	13.0
Dabob Bay	11-09-87	110	10	-11.9	–	19.9	8.0
Dabob Bay	01-10-88	110	10	-8.2	–	5.8	-2.4
Dabob Bay	01-30-88	110	10	-4.5	–	3.9	-0.6
Budd Inlet (BI-5)	09-10-96	8	14.5	1.4	–	88.2	89.6
Budd Inlet (BI-5)	10-03-96	12	14	–	–	168.0	–
Budd Inlet (BI-5)	10-22-96	13	13	-29.4	–	112.0	82.6
Budd Inlet (BI-5)	11-04-96	13	11	-4.2	–	84.0	79.8
Budd Inlet (BI-5)	01-16-97	13	8	-36.4	–	91.0	54.6
Budd Inlet (BI-5)	01-29-97	12	7.7	–	–	56.0	–
Budd Inlet (BI-5)	02-06-97	12	7.9	-10.5	–	36.4	25.9
Budd Inlet (BI-5)	02-24-97	11	8	–	–	21.0	–
Budd Inlet (BI-5)	03-17-97	10	8.2	-14.0	–	-12.6	-26.6
Budd Inlet (BI-5)	03-31-97	10	9	-8.4	–	7.0	-1.4
Budd Inlet (BI-5)	04-14-97	10	9	-14.0	–	8.4	-5.6
Budd Inlet (BI-5)	05-05-97	10	9.7	-9.8	–	81.2	71.4
Budd Inlet (BI-5)	05-21-97	13	11	-8.4	–	42.0	33.6
Budd Inlet (BI-5)	06-12-97	10	12	-7.0	–	82.6	75.6
Budd Inlet (BI-5)	06-23-97	10	12	–	–	91.0	–
Budd Inlet (BI-5)	07-21-97	13	14	–	–	114.8	–
Budd Inlet (BI-5)	07-30-97	13	14.5	-3.5	–	128.8	125.3
Budd Inlet (BI-5)	08-14-97	9	15.1	0.0	–	110.6	110.6
Budd Inlet (BI-5)	09-08-97	11	15	-3.5	–	189.0	185.5
Budd Inlet (BA-1)	09-08-96	6	15	–	–	84.0	–
Budd Inlet (BA-1)	09-10-96	6	15	4.2	–	86.8	91.0
Budd Inlet (BA-1)	10-03-96	12	14	8.4	–	140.0	148.4

Table B1. Summary of benthic flux data for all individual chamber measurements, Puget Sound, Washington.—Continued

[**Abbreviations:** °C, degrees Celsius; (mg N/m^2)/d, milligrams of nitrogen per square meter per day; –, no data; UNK, unknown; DIN, dissolved inorganic nitrogen]

Station/site identifier	Date	Depth (meters)	Bottom temperture (°C)	Benthic fluxes [(mg N/m^2)/d]			
				Nitrate	Nitrite	Ammonium	Net DIN
Budd Inlet (BA-1)	10-22-96	12	13	-15.4	–	35.0	19.6
Budd Inlet (BA-1)	11-04-96	10	11	–	–	33.6	–
Budd Inlet (BA-1)	01-16-97	7	8	–	–	22.4	–
Budd Inlet (BA-1)	01-29-97	5	7.9	-3.5	–	21.0	17.5
Budd Inlet (BA-1)	02-06-97	2.5	11	-8.4	–	21.0	12.6
Budd Inlet (BA-1)	02-24-97	5	8	-17.5	–	14.0	-3.5
Budd Inlet (BA-1)	03-17-97	3	8.1	–	–	2.8	–
Budd Inlet (BA-1)	03-31-97	3	8.5	-19.6	–	0.0	-19.6
Budd Inlet (BA-1)	04-14-97	3	9.2	-36.4	–	22.4	-14.0
Budd Inlet (BA-1)	05-05-97	5	9.8	-61.6	–	105.0	43.4
Budd Inlet (BA-1)	05-21-97	8	12	-3.5	–	19.6	16.1
Budd Inlet (BA-1)	06-12-97	3	13	0.0	–	18.2	18.2
Budd Inlet (BA-1)	06-23-97	7	12	-10.5	–	58.8	48.3
Budd Inlet (LOON-1)	09-10-96	10	14	1.4	–	56.0	57.4
Budd Inlet (LOON-1)	10-03-96	10	13.5	–	–	77.0	–
Budd Inlet (LOON-1)	10-22-96	10	13	-15.4	–	84.0	68.6
Budd Inlet (LOON-1)	11-04-96	10	11	-11.2	–	96.6	85.4
Budd Inlet (LOON-1)	01-16-97	8	8	–	–	53.2	–
Budd Inlet (LOON-1)	01-29-97	7	7.8	–	–	35.0	–
Budd Inlet (LOON-1)	02-06-97	9	7.9	-8.4	–	21.0	12.6
Budd Inlet (LOON-1)	02-24-97	11	8	-10.5	–	21.0	10.5
Budd Inlet (LOON-1)	03-17-97	8	8	–	–	21.0	
Budd Inlet (LOON-1)	03-31-97	9	8.5	-8.4	–	21.0	12.6
Budd Inlet (LOON-1)	04-14-97	9	9	-10.5	–	28.0	17.5
Budd Inlet (LOON-1)	05-05-97	8	9.5	–	–	28.0	–
Budd Inlet (LOON-1)	05-21-97	8	10.5	-9.8	–	28.0	18.2
Budd Inlet (LOON-1)	06-12-97	9	12	-7.0	–	84.0	77.0
Budd Inlet (LOON-1)	06-23-97	8	13	-21.0	–	85.4	64.4
Budd Inlet (LOON-1)	07-21-97	5	14	-7.0	–	72.8	65.8
Budd Inlet (LOON-1)	07-30-97	12	14.2	-5.6	–	120.4	114.8
Budd Inlet (LOON-1)	08-14-97	8	15.2	-10.5	–	42.0	31.5
Budd Inlet (LOON-1)	09-08-97	9	15	-4.2	–	109.2	105.0
Budd Inlet (BD-2)	09-10-96	10	14	-19.6	–	109.2	89.6
Budd Inlet (BD-2)	10-03-96	10	14	-7.0	–	25.2	18.2
Budd Inlet (BD-2)	10-22-96	10	13	-7.0	–	40.6	33.6
Budd Inlet (BD-2)	11-04-96	10	11	-22.4	–	49.0	26.6
Budd Inlet (BD-2)	01-16-97	10	8	-21.0	–	42.0	21.0
Budd Inlet (BD-2)	01-29-97	10	7.8	-11.2	–	30.8	19.6
Budd Inlet (BD-2)	02-06-97	11	7.9	-7.0	–	14.0	7.0
Budd Inlet (BD-2)	02-24-97	8	7.8	-11.2	–	16.8	5.6
Budd Inlet (BD-2)	03-17-97	11	8	–	–	14.0	–
Budd Inlet (BD-2)	03-31-97	11	8.2	-8.4	–	11.2	2.8
Budd Inlet (BD-2)	04-14-97	13	9	–	–	25.2	–
Budd Inlet (BD-2)	05-05-97	5	10	–	–	49.0	–
Budd Inlet (BD-2)	05-21-97	10	11	-9.8	–	67.2	57.4
Budd Inlet (BD-2)	06-12-97	13	11.8	-15.4	–	49.0	33.6
Budd Inlet (BD-2)	06-23-97	10	12.5	-14.0	–	46.2	32.2
Budd Inlet (BD-2)	07-17-97	12	14.5	-10.5	–	43.4	32.9
Budd Inlet (BD-2)	07-30-97	14	14.2	-4.2	–	56.0	51.8
Budd Inlet (BD-2)	08-14-97	10	15	-2.8	–	70.0	67.2
Budd Inlet (BD-2)	09-08-97	13	15	2.8	–	56.0	58.8

Table B1. Summary of benthic flux data for all individual chamber measurements, Puget Sound, Washington.—Continued

[**Abbreviations:** °C, degrees Celsius; (mg N/m^2)/d, milligrams of nitrogen per square meter per day; –, no data; UNK, unknown; DIN, dissolved inorganic nitrogen]

Station/site identifier	Date	Depth (meters)	Bottom temperture (°C)	Benthic fluxes [(mg N/m^2)/d]			
				Nitrate	Nitrite	Ammonium	Net DIN
Case Inlet (Case05)	09-10-07	7	14.9	-2.8	0.0	78.0	75.3
Case Inlet (Case15)	09-10-07	14	14.8	-22.3	0.3	69.0	47.0
Case Inlet (Case25)	09-10-07	26	14.5	-5.1	1.8	59.7	56.4
Carr Inlet (Carr05)	09-10-07	7	14	12.2	0.4	16.2	28.8
Carr Inlet (Carr15)	09-10-07	16	13.2	-35.7	-0.9	71.3	34.7
Carr Inlet (Carr25)	09-10-07	26	12.8	-10.4	4.5	49.0	43.1
Eld Inlet (Eld05)	09-10-07	8	15.1	7.9	1.7	29.9	39.4
Eld Inlet (Eld15)	09-10-07	17	14	-18.4	-0.1	51.4	32.9
Eld Inlet (Eld25)	09-10-07	25	13.4	-10.7	-0.3	35.2	24.2
Budd Inlet (Budd05)	09-10-07	7	15.7	-2.5	-3.4	121.6	115.7
Budd Inlet (Budd15)	09-10-07	14	15.3	-14.2	-0.7	94.5	79.7
Budd Inlet (Budd25)	09-10-07	27	14.8	-0.1	0.5	4.5	4.8
Case Inlet (Case05)	09-24-07	5	14.4	14.3	-2.2	9.3	21.3
Case Inlet (Case15)	09-24-07	15	14.1	-11.6	0.0	38.3	26.7
Case Inlet (Case25)	09-24-07	25	14	-17.1	0.5	89.8	73.1
Carr Inlet (Carr05)	09-24-07	5	13.4	20.2	1.3	12.2	33.7
Carr Inlet (Carr15)	09-24-07	15	13.1	-26.2	1.1	104.0	79.0
Carr Inlet (Carr25)	09-24-07	25	13.1	-7.3	-0.4	29.9	22.2
Eld Inlet (Eld05)	09-24-07	5	14.2	20.9	0.6	24.5	46.0
Eld Inlet (Eld15)	09-24-07	15	13.6	-20.5	-1.2	153.5	131.8
Eld Inlet (Eld25)	09-24-07	25	13.4	-19.3	-1.4	108.6	87.9
Budd Inlet (Budd05)	09-24-07	5	14.9	-6.6	-3.0	155.8	146.2
Budd Inlet (Budd15)	09-24-07	15	14.6	-13.8	-1.0	140.2	125.4
Budd Inlet (Budd25)	09-24-07	25	14.3	1.1	2.1	113.8	117.0
Case Inlet (Case05)	10-22-07	5	12.5	-1.3	-0.5	5.6	3.8
Case Inlet (Case15)	10-22-07	15	12.5	-81.3	-0.5	55.2	-26.6
Case Inlet (Case25)	10-22-07	25	12.3	-15.0	0.0	49.6	34.6
Carr Inlet (Carr05)	10-22-07	6	12.5	3.7	3.9	30.7	38.2
Carr Inlet (Carr15)	10-22-07	15	12.2	-18.1	16.5	56.4	54.8
Carr Inlet (Carr25)	10-22-07	25	12.2	-11.2	0.3	42.7	31.8
Eld Inlet (Eld05)	10-22-07	5	12.7	2.3	-2.9	2.1	1.5
Eld Inlet (Eld15)	10-22-07	15	12.7	-14.2	-2.4	59.3	42.7
Eld Inlet (Eld25)	10-22-07	25	12.5	-28.8	-2.6	153.2	121.8
Budd Inlet (Budd05)	10-22-07	5	12.7	-32.0	-2.4	128.0	93.5
Budd Inlet (Budd15)	10-22-07	15	12.4	-27.1	-2.4	134.5	105.0
Budd Inlet (Budd25)	10-22-07	25	12.3	-24.1	-2.0	142.8	116.7
Quartermaster Harbor (QMH_A)	September 1–2, 2010	4	14.3	-5.0	–	155.0	150.0
Quartermaster Harbor (QMH_B)	September 1–2, 2010	6	14	0.0	–	60.0	60.0
Quartermaster Harbor (QMH_C)	September 1–2, 2010	8	13.7	0.0	–	50.0	50.0
Quartermaster Harbor (QMH_D)	September 1–2, 2010	14	12.6	10.0	–	0.0	10.0
Quartermaster Harbor (QMH_E)	September 1–2, 2010	17	12.4	-10.0	–	0.0	-10.0

Appendix C. Summary of All Compiled Porewater Concentration Gradients

Table C1. Porewater concentration gradient data used to calculate diffusive fluxes for nitrate, Puget Sound, Washington.

[Values in **bold** were not provided by the individual study and estimated in order to calculate a diffusive flux, see text for more details. **Abbreviations:** (µg N/L)/cm^2, micrograms of nitrogen per liter per square centimeter; °C, degrees Celsius; Ds, whole sediment diffusion coefficient; cm^2/s, square centimeters per second; NS, not significant; UNK, unknown; NA, not applicable]

Station/site identifier	Date	Gradient [(µg N/L)/cm^2]	p-value	Bottom temperature (°C)	Ds (10^{-6} cm^2/s)	Sediment porosity
Carkeek pelagic site (PS 16)	May 6–7 1982	NS	0.840	5	2.4	0.8
Carkeek pelagic site (PS 16)	May 6–7 1982	NS	0.200	5	2.4	0.8
Carkeek pelagic site (PS 19)	04-19-83	NS	0.200	**8**	12.9	**0.8**
Carkeek pelagic site (PS 21)	05-10-83	NS	0.200	**8**	12.9	**0.8**
Liberty Bay	UNK	NS	1.000	**8**	12.9	**0.8**
Poverty Bay	UNK	NS	0.340	**8**	12.9	**0.8**
Carkeek pelagic site (PS 14)	02-02-1976	-20.0	0.002	**8**	12.9	**0.8**
Carkeek pelagic site (PS 15)	03-29-1976	-16.5	0.001	**8**	12.9	**0.8**
Carkeek pelagic site (PS 16)	03-29-1976	-9.4	0.004	**8**	12.9	**0.8**
Carr Inlet	UNK	-3.7	0.002	8	12.9	0.8
EB4	02-19-80	NS	0.640	8.2	13.0	0.8
PSE4	05-22-80	19.5	0.000	9.2	13.4	0.8
PSE6	05-22-80	NS	1.000	9.2	13.4	0.8
PSE11	05-22-80	NS	0.865	9.2	13.4	0.7
EB4	09-12-80	NS	0.540	12.2	14.5	0.75
EB4-4	08-25-81	NS	0.420	11.4	14.2	0.8
EB4-5	08-26-81	NS	1.000	11.4	14.2	0.87
EB11A-4	08-25-81	NS	1.000	11.4	14.2	0.75
PS3	08-28-81	NS	1.000	11.3	14.2	0.8
BK1	03-02-82	Not enough porewater data to calculate gradient				
Holmes Harbor (CB1)	1992	-70	NA	**8**	12.6	**0.8**
Holmes Harbor (CB2)	1992	-280	NA	**8**	12.6	**0.8**
Holmes Harbor (CB3)	1992	-245	NA	**8**	12.6	**0.8**
Holmes Harbor (CB4)	1992	-210	NA	**8**	12.6	**0.8**

Table C2. Porewater concentration gradient data used to calculate diffusive fluxes for nitrite, Puget Sound, Washington.

[Values in **bold** were not provided by the individual study and estimated in order to calculate a diffusive flux, see text for more details. **Abbreviations:** (µg N/L)/cm^2, micrograms of nitrogen per liter per square centimeter; °C, degrees Celsius; Ds, whole sediment diffusion coefficient; cm^2/s, square centimeters per second; >, greater than; NS, not significant; UNK, unknown]

Station/site identifier	Date	Gradient [(µg N/L)cm^2]	p-value	Bottom temperature (°C)	Ds (10^{-6} cm^2/s)	Sediment porosity
Carkeek pelagic site (PS 16)	May 6–7, 1982	NS	0.179	5	12.5	0.8
Carkeek pelagic site (PS 16)	May 6–7, 1982	NS	0.333	5	12.5	0.8
Carkeek pelagic site (PS 17)	June 8–9, 1982	NS	>0.20	5	12.5	0.8
Carkeek pelagic site (PS 19)	04-19-83	NS	>0.20	**8**	13.3	**0.8**
Carkeek pelagic site (PS 21)	05-10-83	NS	>0.20	**8**	13.3	**0.8**
Liberty Bay	UNK	NS	>0.20	**8**	13.3	**0.8**
Carkeek pelagic site (PS 14)	02-02-76	NS	0.450	**8**	13.3	**0.8**
Carkeek pelagic site (PS 15)	03-29-76	NS	0.230	**8**	13.3	**0.8**
Carkeek pelagic site (PS 16)	03-29-76	1.0	0.037	**8**	13.3	**0.8**
EB4	02-19-80	NS	0.780	8.2	13.3	0.8
PSE4	05-22-80	NS	0.757	9.2	13.6	0.8
PSE6	05-22-80	NS	0.490	9.2	13.6	0.8
PSE11	05-22-80	NS	0.740	9.2	13.6	0.7
EB4	09-12-80	NS	>0.20	12.2	14.3	0.75
EB4-4	08-25-81	NS	0.450	11.4	14.1	0.8
EB4-5	08-26-81	4.5	0.000	11.4	14.1	0.87
EB11A-4	08-25-81	6.4	0.073	11.4	14.1	0.75
PS3	08-28-81	2.7	0.051	11.3	14.1	0.8
BK1	03-02-82	Not enough porewater data to calculate gradient				

Table C3. Porewater concentration gradient data used to calculate diffusive fluxes for ammonium, Puget Sound, Washington.

[Values in **bold** were not provided by the individual study and estimated in order to calculate a diffusive flux, see text for more details. **Abbreviations:** (µg N/L)/cm^2, micrograms of nitrogen per liter per square centimeter; °C, degrees Celsius; cm^2/s, square centimeters per second; NS, not significant; UNK, unknown]

Station/site identifier	Date	Gradient [(µg N/L)/cm^2]	p-value	Bottom temperature (°C)	Do (10^{-6} cm^2/s)	Sediment porosity
Carkeek pelagic site (PS 16)	May 6–7 1982	289.9	0.003	5	2.4	0.8
Carkeek pelagic site (PS 16)	May 6–7 1982	323.7	0.100	5	2.4	0.8
Carkeek pelagic site (PS 17)	June 8–9 1982	581.5	0.089	5	2.4	0.8
Carkeek pelagic site (PS 19)	04-19-83	199.6	0.003	**8**	12.9	**0.8**
Carkeek pelagic site (PS 21)	05-10 83	140.8	0.004	**8**	12.9	**0.8**
Liberty Bay	UNK	674.1	0.044	**8**	12.9	**0.8**
Poverty Bay	UNK	189.7	0.052	**8**	12.9	**0.8**
PS Stat 98 (Port Susan)	January 1982	367.6	0.000	**8**	12.9	**0.8**
PS 51-2 (PS7)	January 1982	101.6	0.070	**8**	12.9	**0.8**
PS Stat 39 (Quartermaster harbor)	September 1978	157.5	0.077	**13**	12.9	**0.8**
Carkeek pelagic site (PS 14)	02-02-76	314.4	0.001	**8**	12.9	**0.8**
Carkeek pelagic site (PS 15)	03-29-76	343.0	0.001	**8**	12.9	**0.8**
Carkeek pelagic site (PS 16)	03-29-76	292.0	0.001	**8**	12.9	**0.8**
Carr Inlet	UNK	406.7	0.080	8	12.9	0.8
EB4	02-19-80	182.3	0.046	8.2	13.0	0.8
PSE4	05-22-80	402.3	0.064	9.2	13.4	0.8
PSE6	05-22-80	NS	0.890	9.2	13.4	0.8
PSE11	05-22-80	218.8	0.007	9.2	13.4	0.7
EB4	09-12-80	199.2	0.003	12.2	14.5	0.75
EB4-4	08-25-81	129.4	0.015	11.4	14.2	0.8
EB4-5	08-26-81	100.1	0.028	11.4	14.2	0.87
EB11A-4	08-25-81	386.4	0.053	11.4	14.2	0.75
PS3	08-28-81	156.8	0.049	11.3	14.2	0.8
BK1	03-02-82	Not enough porewater data to calculate gradient				

Appendix D. Compilation of All Orthophosphate Benthic Flux Data

Table D1. Compiled benthic flux data for phosphate from all individual chamber measurements, Puget Sound, Washington.

[**Abbreviations:** °C, degrees Celsius; (mg P/m^2)/d; milligrams of phosphorus per square meter per day; UNK, unknown; –, no data]

Station/site identifier	Date	Depth (meters)	Bottom temperature (°C)	Phosphate flux [(mg P/m^2)/d]
Carkeek pelagic site (PS 17)	June 8–9, 1982	175	5	4.3
Carkeek pelagic site	UNK	200	8.3	4.3
Dabob Bay	01-12-87	110	10	1.3
Dabob Bay	02-17-87	110	10	2.3
Dabob Bay	03-29-87	110	10	0.7
Dabob Bay	03-31-87	110	10	0.0
Dabob Bay	05-17-87	110	10	5.3
Dabob Bay	05-20-87	110	10	2.5
Dabob Bay	05-21-87	110	10	3.3
Dabob Bay	06-22-87	110	10	2.6
Dabob Bay	06-24-87	110	10	2.3
Dabob Bay	07-26-87	110	10	0.9
Dabob Bay	07-28-87	110	10	7.6
Dabob Bay	08-23-87	110	10	5.4
Dabob Bay	09-21-87	110	10	3.9
Dabob Bay	09-23-87	110	10	2.6
Dabob Bay	10-23-87	110	10	3.1
Dabob Bay	10-25-87	110	10	10.5
Dabob Bay	11-09-87	110	10	5.3
Dabob Bay	01-10-88	110	10	2.8
Dabob Bay	01-30-88	110	10	2.5
Quartermaster Harbor (QMH_A)	September 1–2, 2010	4	14.3	40
Quartermaster Harbor (QMH_B)	September 1–2, 2010	6	14	10
Quartermaster Harbor (QMH_C)	September 1–2, 2010	8	13.7	0
Quartermaster Harbor (QMH_D)	September 1–2, 2010	14	12.6	0
Quartermaster Harbor (QMH_E)	September 1–2, 2010	17	12.4	0
QMH average	September 1–2, 2010	10	13.4	10
Case Inlet (Case05)	09-10-07	7	14.9	–
Case Inlet (Case15)	09-10-07	14	14.8	–
Case Inlet (Case25)	09-10-07	26	14.5	–
Carr Inlet (Carr05)	09-10-07	7	14	–
Carr Inlet (Carr15)	09-10-07	16	13.2	–
Carr Inlet (Carr25)	09-10-07	26	12.8	–
Eld Inlet (Eld05)	09-10-07	8	15.1	–
Eld Inlet (Eld15)	09-10-07	17	14	–
Eld Inlet (Eld25)	09-10-07	25	13.4	–
Budd Inlet (Budd05)	09-10-07	7	15.7	–
Budd Inlet (Budd15)	09-10-07	14	15.3	–
Budd Inlet (Budd25)	09-10-07	27	14.8	–
Case Inlet (Case05)	09-24-07	5	14.4	–
Case Inlet (Case15)	09-24-07	15	14.1	–

Table D1. Compiled benthic flux data for phosphate from all individual chamber measurements, Puget Sound, Washington.—Continued

[**Abbreviations:** °C, degrees Celsius; (mg P/m^2)/d; milligrams of phosphorus per square meter per day; UNK, unknown; –, no data]

Station/site identifier	Date	Depth (meters)	Bottom temperature (°C)	Phosphate flux [(mg P/m^2)/d]
Case Inlet (Case25)	09-24-07	25	14	–
Carr Inlet (Carr05)	09-24-07	5	13.4	–
Carr Inlet (Carr15)	09-24-07	15	13.1	–
Carr Inlet (Carr25)	09-24-07	25	13.1	–
Eld Inlet (Eld05)	09-24-07	5	14.2	–
Eld Inlet (Eld15)	09-24-07	15	13.6	–
Eld Inlet (Eld25)	09-24-07	25	13.4	–
Budd Inlet (Budd05)	09-24-07	5	14.9	–
Budd Inlet (Budd15)	09-24-07	15	14.6	–
Budd Inlet (Budd25)	09-24-07	25	14.3	–
Case Inlet (Case05)	10-22-07	5	12.5	–
Case Inlet (Case15)	10-22-07	15	12.5	–
Case Inlet (Case25)	10-22-07	25	12.3	–
Carr Inlet (Carr05)	10-22-07	6	12.5	–
Carr Inlet (Carr15)	10-22-07	15	12.2	–
Carr Inlet (Carr25)	10-22-07	25	12.2	–
Eld Inlet (Eld05)	10-22-07	5	12.7	–
Eld Inlet (Eld15)	10-22-07	15	12.7	–
Eld Inlet (Eld25)	10-22-07	25	12.5	–
Budd Inlet (Budd05)	10-22-07	5	12.7	–
Budd Inlet (Budd15)	10-22-07	15	12.4	–
Budd Inlet (Budd25)	10-22-07	25	12.3	–
Budd Inlet (BI-5)	09-10-96	8	14.5	27.9
Budd Inlet (BI-5)	10-03-96	12	14	31.0
Budd Inlet (BI-5)	10-22-96	13	13	27.9
Budd Inlet (BI-5)	11-04-96	13	11	12.4
Budd Inlet (BI-5)	01-16-97	13	8	9.3
Budd Inlet (BI-5)	01-29-97	12	7.7	–
Budd Inlet (BI-5)	02-06-97	12	7.9	7.7
Budd Inlet (BI-5)	02-24-97	11	8	–
Budd Inlet (BI-5)	03-17-97	10	8.2	3.1
Budd Inlet (BI-5)	03-31-97	10	9	-3.1
Budd Inlet (BI-5)	04-14-97	10	9	12.4
Budd Inlet (BI-5)	05-05-97	10	9.7	7.7
Budd Inlet (BI-5)	05-21-97	13	11	52.6
Budd Inlet (BI-5)	06-12-97	10	12	31.0
Budd Inlet (BI-5)	06-23-97	10	12	–
Budd Inlet (BI-5)	07-21-97	13	14	–
Budd Inlet (BI-5)	07-30-97	13	14.5	77.4
Budd Inlet (BI-5)	08-14-97	9	15.1	43.4
Budd Inlet (BI-5)	09-08-97	11	15	102.2
Budd Inlet (BA-1)	09-08-96	6	15	38.7
Budd Inlet (BA-1)	09-10-96	6	15	49.6
Budd Inlet (BA-1)	10-03-96	12	14	–
Budd Inlet (BA-1)	10-22-96	12	13	15.5
Budd Inlet (BA-1)	11-04-96	10	11	–
Budd Inlet (BA-1)	01-16-97	7	8	–
Budd Inlet (BA-1)	01-29-97	5	7.9	7.7

Table D1. Compiled benthic flux data for phosphate from all individual chamber measurements, Puget Sound, Washington.—Continued

[**Abbreviations:** °C, degrees Celsius; (mg P/m^2)/d; milligrams of phosphorus per square meter per day; UNK, unknown; –, no data]

Station/site identifier	Date	Depth (meters)	Bottom temperature (°C)	Phosphate flux [(mg P/m^2)/d]
Budd Inlet (BA-1)	02-06-97	3	11	3.1
Budd Inlet (BA-1)	02-24-97	5	8	–
Budd Inlet (BA-1)	03-17-97	3	8.1	–
Budd Inlet (BA-1)	03-31-97	3	8.5	–
Budd Inlet (BA-1)	04-14-97	3	9.2	7.7
Budd Inlet (BA-1)	05-05-97	5	9.8	7.7
Budd Inlet (BA-1)	05-21-97	8	12	7.7
Budd Inlet (BA-1)	06-12-97	3	13	55.7
Budd Inlet (BA-1)	06-23-97	7	12	-7.7
Budd Inlet (LOON-1)	09-10-96	10	14	3.1
Budd Inlet (LOON-1)	10-03-96	10	13.5	–
Budd Inlet (LOON-1)	10-22-96	10	13	7.7
Budd Inlet (LOON-1)	11-04-96	10	11	6.2
Budd Inlet (LOON-1)	01-16-97	8	8	–
Budd Inlet (LOON-1)	01-29-97	7	7.8	–
Budd Inlet (LOON-1)	02-06-97	9	7.9	0.0
Budd Inlet (LOON-1)	02-24-97	11	8	–
Budd Inlet (LOON-1)	03-17-97	8	8	–
Budd Inlet (LOON-1)	03-31-97	9	8.5	3.1
Budd Inlet (LOON-1)	04-14-97	9	9	0.0
Budd Inlet (LOON-1)	05-05-97	8	9.5	–
Budd Inlet (LOON-1)	05-21-97	8	10.5	46.5
Budd Inlet (LOON-1)	06-12-97	9	12	31.0
Budd Inlet (LOON-1)	06-23-97	8	13	77.4
Budd Inlet (LOON-1)	07-21-97	5	14	-9.3
Budd Inlet (LOON-1)	07-30-97	12	14.2	86.7
Budd Inlet (LOON-1)	08-14-97	8	15.2	-3.1
Budd Inlet (LOON-1)	09-08-97	9	15	-3.1
Budd Inlet (BD-2)	09-10-96	10	14	7.7
Budd Inlet (BD-2)	10-03-96	10	14	9.3
Budd Inlet (BD-2)	10-22-96	10	13	7.7
Budd Inlet (BD-2)	11-04-96	10	11	21.7
Budd Inlet (BD-2)	01-16-97	10	8	24.8
Budd Inlet (BD-2)	01-29-97	10	7.8	27.9
Budd Inlet (BD-2)	02-06-97	11	7.9	7.7
Budd Inlet (BD-2)	02-24-97	8	7.8	0.0
Budd Inlet (BD-2)	03-17-97	11	8	–
Budd Inlet (BD-2)	03-31-97	11	8.2	3.1
Budd Inlet (BD-2)	04-14-97	13	9	–
Budd Inlet (BD-2)	05-05-97	5	10	–
Budd Inlet (BD-2)	05-21-97	10	11	15.5
Budd Inlet (BD-2)	06-12-97	13	11.8	24.8
Budd Inlet (BD-2)	06-23-97	10	12.5	7.7
Budd Inlet (BD-2)	07-17-97	12	14.5	9.3
Budd Inlet (BD-2)	07-30-97	14	14.2	117.7
Budd Inlet (BD-2)	08-14-97	10	15	74.3
Budd Inlet (BD-2)	09-08-97	13	15	9.3

Table D2. Porewater concentration gradient data used to calculate diffusive fluxes for phosphate, Puget Sound, Washington.

[Values in **bold** were not provided by the individual study and estimated in order to calculate a diffusive flux, see text for more details. **Abbreviations: (**µg P/L)/cm, micrograms of phosphorus per liter per centmeter; °C, degrees celcius; cm^2/s, square centimeters per second; NS, not significant; <, less than; >, greater than; UNK, unknown]

Station/site identifier	Date	Gradient [(µg P/L)/cm]	p-value	Bottom temperature (°C)	Do (10^{-6} cm^2/s)	Sediment porosity
Carkeek pelagic site (PS 16)	May 6–7, 1982	NS	>0.10	5	2.2	0.8
Carkeek pelagic site (PS 16)	May 6–7, 1982	148.9	<0.10	5	2.2	0.8
Carkeek pelagic site (PS 17)	June 8–9, 1982	849.8	<0.10	5	2.2	0.8
Carkeek pelagic site (PS 19)	04-19-83	233.6	<0.10	**8**	5.2	**0.8**
Carkeek pelagic site (PS 21)	05-10-83	95.3	<0.10	**8**	5.2	**0.8**
Liberty Bay	UNK	260.8	<0.10	**8**	5.2	**0.8**
Poverty Bay	UNK	NS	>0.10	**8**	5.2	**0.8**
PS Stat 98 (Port Susan)	January 1982	553.9	<0.10	**8**	5.2	**0.8**
PS Stat 51-1 (PS7)	September 1978	381.4	<0.10	**8**	5.2	**0.8**
PS 51-2 (PS7)	January 1982	NS	>0.10	**8**	5.2	**0.8**
PS Stat 56 (East Passage)	January 1982	NS	>0.10	**8**	5.2	**0.8**
PS Stat 39 (Quartermaster Harbor)	September 1978	NS	>0.10	**13**	5.6	**0.8**
EB4	02-19-80	NS	>0.10	8.2	5.2	0.8
PSE4	05-22-80	NS	>0.10	9.2	5.3	0.8
PSE6	05-22-80	NS	>0.10	9.2	5.3	0.8
PSE11	05-22-80	NS	>0.10	9.2	5.3	0.7
EB4	09-12-80	NS	>0.10	12.2	5.6	0.75
EB4-4	08-25-81	245.7	<0.10	11.4	5.5	0.8
EB4-5	08-26-81	371.0	<0.10	11.4	5.5	0.87
EB11A-4	08-25-81	684.4	<0.10	11.4	5.5	0.75
PS3	08-28-81	156.6	<0.10	11.3	5.5	0.8
BK1	03-02-82	Not enough porewater data to calculate gradient				

Table D3. Compiled diffusive flux data for phosphate for all individual measurements, Puget Sound, Washington.

[Abbreviations: (mg P/m^2)/d, milligrams of phosphorus per square meter per day; NS, not significant; UNK, unknown]

Station/site identifier	Date	Depth (meters)	Porewater method	Gradient method	Phosphate flux [(mg P/m^2)/d]
Carkeek pelagic site (PS 16)	May 6–7, 1982	165–185	In situ	Linear	NS
Carkeek pelagic site (PS 16)	May 6–7, 1982	165–185	Centrifuging	2-point	0.28
Carkeek pelagic site (PS 16)	May 6–7, 1982	165–185	Centrifuging	Linear	0.14
Carkeek pelagic site (PS 16)	May 6–7, 1982	165–185	Centrifuging	2-point	0.09
Carkeek pelagic site (PS 17)	June 8–9, 1982	165–185	Centrifuging	2-point	1.73
Carkeek pelagic site (PS 17)	June 8–9, 1982	165–185	Centrifuging	Linear	0.83
Carkeek pelagic site (PS 19)	04-19-83	174		Linear	0.54
Carkeek pelagic site (PS 21)	05-10-83	173	Centrifuging	Linear	0.22
Liberty Bay	UNK	UNK	UNK	Linear	0.60
Poverty Bay	UNK	179	UNK	Linear	NS
PS Stat 98 (Port Susan)	January 1982	104	Centrifuging	Linear	1.27
PS Stat 51-1 (PS7)	September 1978	249	Centrifuging	Linear	0.87
PS 51-2 (PS7)	January 1982	249	Centrifuging	Linear	NS
PS Stat 56 (east passage)	January 1982	200	Centrifuging	Linear	NS
PS Stat 39 (Quartermaster harbor)	September 1978	13	Centrifuging	Linear	NS
EB4	02-19-80	95	Centrifuging	Linear	NS
PSE4	05-22-80	100	Centrifuging	Linear	NS
PSE6	05-22-80	55	Centrifuging	Linear	NS
PSE11	05-22-80	180	Centrifuging	Linear	NS
EB4	09-12-80	95	Centrifuging	Linear	NS
EB4-4	08-25-81	110	Centrifuging	Linear	0.60
EB4-5	08-26-81	110	Centrifuging	Linear	1.16
EB11A-4	08-25-81	180	Centrifuging	Linear	1.37
PS3	08-28-81	175	Centrifuging	Linear	0.38
Carkeek site	UNK	200	In situ	2-point	46.83
Carkeek site	UNK	200	In situ	2-point	2.07

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