Initial Assessment of Nutrient Loading to Quartermaster Harbor

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King County

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Prepared for:

U.S. EPA West Coast Estuaries Initiative Grant
Quartermaster Harbor Nitrogen Management Study

Submitted by:

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EXECUTIVE SUMMARY

This report is part of the Quartermaster Harbor Nitrogen Management Study funded in part by a West Coast Estuaries Initiative grant from Region 10 of the U.S. Environmental Protection Agency. The report documents available data sources and methods that were used to develop initial estimates of nutrient loading to Quartermaster Harbor from the atmosphere, tributary streams, nearshore septic systems, groundwater, and harbor sediments. The nutrients considered were forms of nitrogen (N), phosphorus (P), and silica (Si), which are the common essential nutrients for phytoplankton growth in estuaries and freshwater systems. Quartermaster Harbor is a shallow estuarine embayment on Vashon-Maury Island in Puget Sound that experiences low dissolved oxygen concentrations during late summer/fall that fall below the applicable state water quality standard. The likely cause of these low oxygen levels is the growth and subsequent die-off of phytoplankton that consume dissolved oxygen in the water column and sediments as they decompose and settle to the bottom.

Of the external sources of nutrients evaluated in this report, tributary streams are the most significant source of the forms of nitrogen and silica most readily available to estuarine phytoplankton. The current estimate indicates that nearshore septic systems may be the largest external source of available phosphorus. Estimates of internal benthic nutrient flux from harbor sediments indicate that this may be a far more significant source of nutrients during the late summer/fall period when dissolved oxygen concentrations are lowest. Recent investigations of Hood Canal have indicated that flow of relatively nutrient rich Puget Sound waters landward are a significant supply of nutrients for phytoplankton growth. Similar estimates for Quartermaster Harbor have not yet been developed, although a recently completed current profiling study conducted at the harbor entrance and a hydrodynamic model of the harbor currently under development will provide data and tools to support such a calculation.

Recommendations made as a result of this initial work to develop nutrient loading estimates to Quartermaster Harbor include:

- Estimate the nutrient contribution from Puget Sound to Quartermaster harbor as a result of estuarine circulation using available data and the hydrodynamic model under development for this project
- Develop plan and budget for conducting benthic nutrient flux measurements in Quartermaster Harbor during late summer/fall of 2010
- Evaluate the possibility of sampling currently unmonitored freshwater inflow sources to Quartermaster Harbor during late summer/fall of 2010
- Develop plan and budget to track source of high winter nitrate levels in Mileta Creek
- Attempt to balance groundwater and stream nutrient inputs with specific upland sources (e.g., atmosphere, nitrogen fixing alder, upland septic systems, livestock, and fertilizers applied to lawns and agricultural fields).

1.0. INTRODUCTION

King County was awarded a West Coast Estuaries Initiative (WEI) grant by Region 10 of the U.S. Environmental Protection Agency (EPA) to conduct the Quartermaster Harbor Nitrogen Management Study. The goal of this study is to support the protection and restoration of Quartermaster Harbor–a high value, coastal aquatic resource on Vashon-Maury Island (VMI) in Puget Sound. Partners working with King County on this grant-funded study include the University of Washington-Tacoma (UWT) and the Washington Department of Ecology (Ecology). The WEI grant will also support the enhancement of aquatic resource protection programs in an area threatened by growth pressures. This initial assessment of nutrient loading to Quartermaster Harbor provides the foundation for more focused investigations of nutrient sources to the harbor, particularly nitrogen, and initial loading estimates for the development of a water quality model of the harbor.

1.1 Project Overview

Dissolved oxygen levels below Washington State marine water quality standards have been observed in Quartermaster Harbor over the last four years of monthly monitoring by King County (Figure 1). Dissolved oxygen is essential for fish and other marine life - when levels fall below critical thresholds marine life can become stressed or killed or forced to escape to more oxygenated waters if possible. Low dissolved oxygen levels, combined with the high habitat value of Quartermaster Harbor and increased frequency of detection of nitrate nitrogen in VMI groundwater, in combination with ongoing population growth, make this project a high priority for King County. Quartermaster Harbor has many similarities with South Puget Sound embayments which do not meet state dissolved oxygen standards established for the protection of aquatic life.

Quartermaster Harbor was one of 19 areas of Puget Sound judged to be relatively sensitive to anthropogenic nutrient inputs (Rensel Associates and PTI 1991). Excess nutrients, nitrogen compounds in particular, can lead to excessive phytoplankton and algae growth which can deplete oxygen concentrations when the algae die (Figure 2). Nitrogen and phosphorus are essential nutrients for marine plants and phytoplankton. Although phosphorus compounds are important for phytoplankton growth, nitrogen is generally considered to be the limiting nutrient in marine waters of Puget Sound (Rensel Associates and PTI 1991).

1.2 Study Area

Vashon-Maury Island is an approximately 94 km^2 (36 mi^2) island located in King County in central Puget Sound (Figure 3). In 2008, the Puget Sound Regional Council estimated that 1,125 people lived on VMI and projected that the population would increase to 12,469 by 2040[1].

[1] Based on Puget Sound Regional Council's 2006 population forecast (http://www.psrc.org/data/forecasts/saf/).

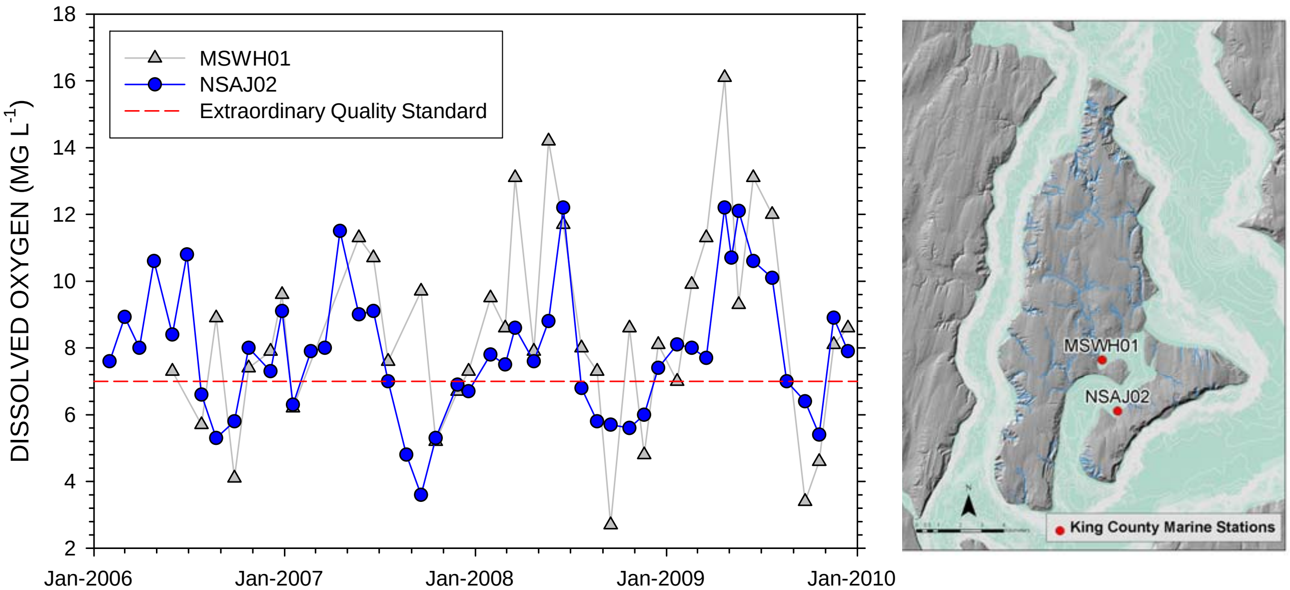

Figure 1. Monthly dissolved oxygen concentrations measured in bottom waters of Quartermaster Harbor by King County.

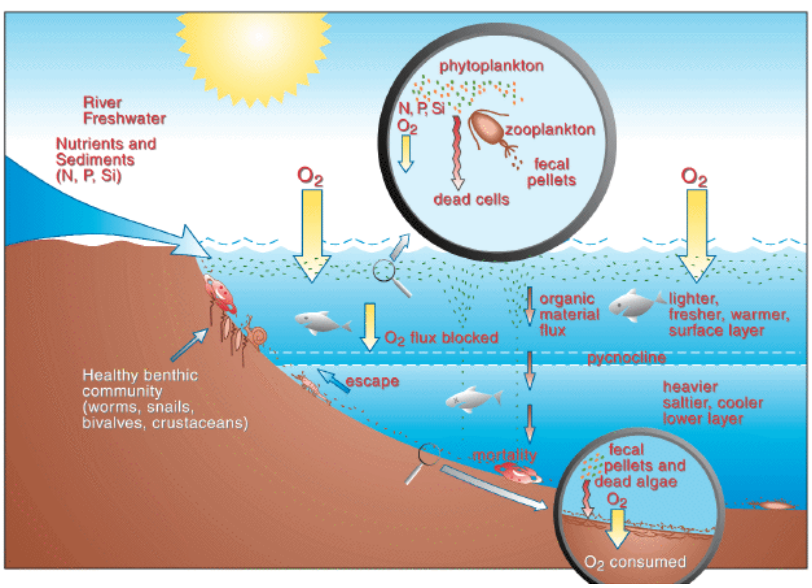

Figure 2. Conceptual diagram of marine nutrient-oxygen dynamics (Source: Downing JA, et al. Gulf of Mexico hypoxia: land and sea interactions.

Note: Task force report no. 134. Ames, IA: Council for Agricultural Science and Technology, 1999 (http://www.ehponline.org/docs/2000/108-3/focusfig2B.GIF)

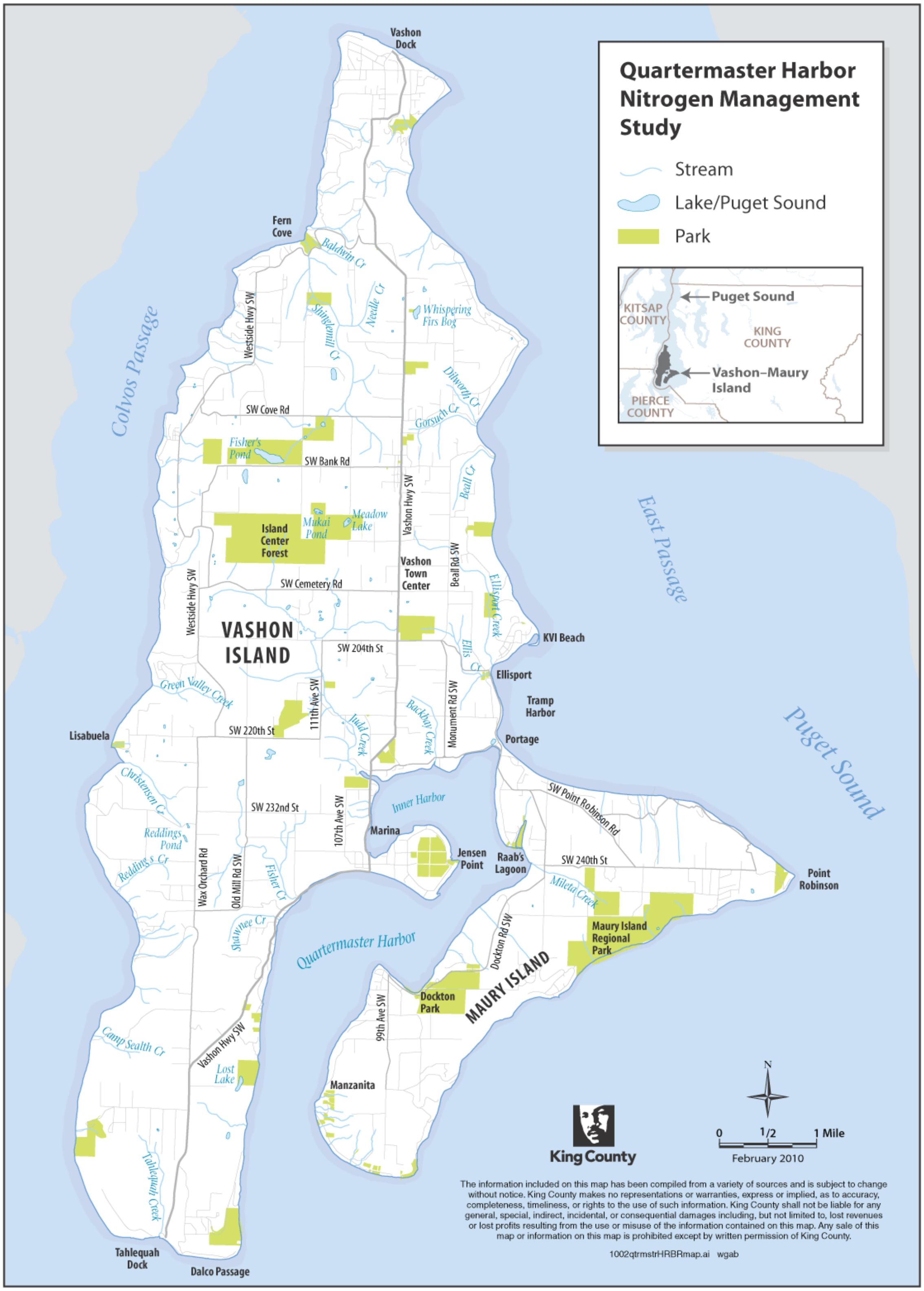

Figure 3. Map of Vashon-Maury Island showing the location of Quartermaster Harbor.

Quartermaster Harbor, located between Vashon and Maury Islands, is sheltered from the wind and waves and receives runoff from about 40 percent of VMI (see Figure 3). It is a shallow, protected embayment that comprises approximately 12.1 km^2 (3,000 acres) of water surface area in an inner and outer harbor. Inner QMH is especially sheltered and Judd Creek, located in the northwestern portion of the inner harbor, is the largest freshwater input. Transition zones between freshwater surface flows and the marine water within the bay include the estuaries at the mouth of Judd Creek, Fisher Creek, and Raab's Lagoon along with numerous smaller streams. Inner QMH is shallow, with a greatest depth of about 5 meters and very little tidal flushing. Outer QMH water depths range from about 11 to 46 meters with rapid tidal flushing. The shoreline around the inner harbor is developed with houses, a marina, a private yacht club, and roads. There are also two public parks located within the harbor area.

The harbor is a regionally significant natural resource area and provides rearing and spawning habitat for herring, surf smelt, sand lance, and salmon (i.e., Chinook, coho, chum, and cutthroat). It is an important wintering ground for migratory marine birds including western grebes, common loons, surf scoters, black scoters, goldeneyes, mergansers, and ruddy ducks. In all, approximately 60 species of fish, 78 species of birds, several species of marine mammals, and a variety of marine invertebrates inhabit or use Quartermaster Harbor[2]. Quartermaster Harbor currently contains the largest Pacific herring spawning population in this region of Puget Sound and the third largest in all of Puget Sound. The harbor was designated as an Important Bird Area by the National Audubon Society in 2001. Quartermaster Harbor also supports shellfish resources, including geoduck clams. As part of the Washington Department of Natural Resources' efforts to protect areas with import ecological features and habitats, a major portion of Quartermaster Harbor and the east side of Maury Island (subtidal and intertidal areas owned by the state) was designated as part of the Maury Island Aquatic Reserve in 2004.[3]

All of VMI is designated as rural zoned land and is outside King County's Growth Management Act (GMA)-designated urban growth boundary. Low-density residential development covers much of the island—typically zoning of one house per five to ten acres. Higher density residential areas are concentrated in Vashon Town Center, Vashon Heights, Burton, Dockton, and along parts of the shoreline (Figure 4). Land cover is predominately forest with other cover being non-forest vegetation and developed land. The residents of VMI are proactive in their interactions with public agencies regarding land-use/cover management, water resources and On-site Septic System (OSS) issues.

Vashon-Maury Island has no external source of drinking water and the underlying groundwater system was designated a Sole Source Aquifer by the EPA in June 1994. The island is one of five Groundwater Management Areas (GWMAs) in King County designated in 1986-87 under the provisions of Washington Administrative Code (WAC) 173-100. The King County groundwater protection code established a Groundwater Protection Committee for each GWMA with a certified groundwater protection plan. The plan for VMI was certified by Ecology and the VMI Groundwater Protection Committee (GWPC) was formed in 2001 along with a county-wide

[2] Final Supplemental Environmental Impact Statement: Maury Island Aquatic Reserve. Washington Dept. of Nat. Resources, Aquatic Resources Division, October 29, 2004

[3] See Washington State Department of Natural Resources Maury Island Aquatic Reserve page (http://www.roitechnicalcommunication.com/Aquatic%20Reserves%20web%20pages/maury_island_reserve.htm)

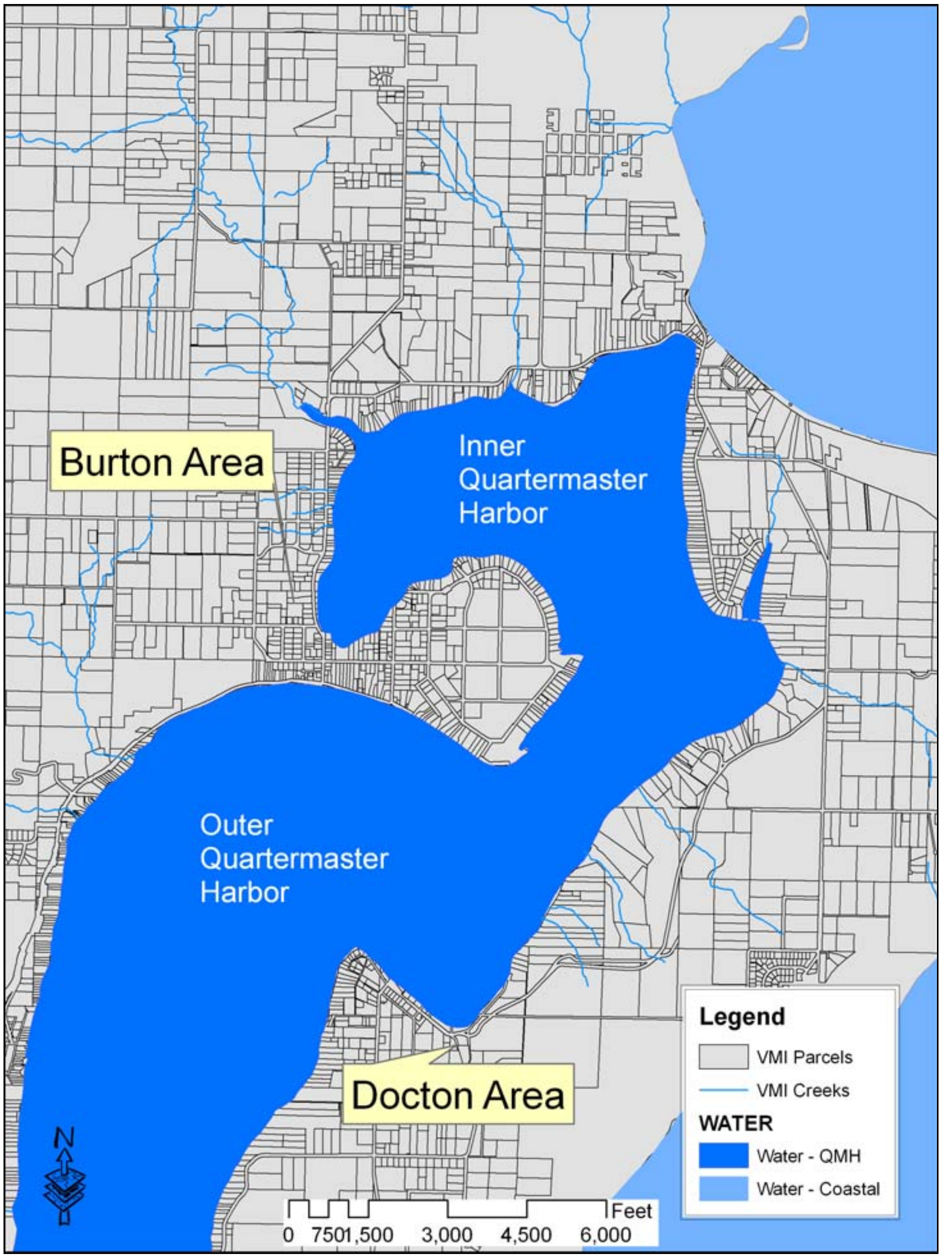

Figure 4. Map of Quartermaster Harbor showing the Burton and Dockton area.

groundwater protection program. To support the GWPC, the King County groundwater protection program designed several projects, including the Water Resources Evaluation (WRE) to describe and assess the water resources of the island (King County 2003). In 2004, King County designated three categories of Critical Aquifer Recharge Areas (CARAs) for rural areas of the county including VMI[4].

[4] For a description of the three CARA categories see http://your.kingcounty.gov/ddes/cao/Manual/II-CARA.pdf.

Like much of rural Puget Sound, nearly all the residents in the study area treat domestic wastewater with OSSs. A watershed plan for VMI was created by King County (2005a), which identified OSS as a potential threat and listed priority action areas including regular monitoring for nitrates and other potential system contaminants, development of policies for their control, education, and Best Management Practices (BMPs) for OSS operations. In 2008, Seattle and King County Public Health designated areas on VMI, including the western shoreline along outer Quartermaster Harbor as Marine Recovery Areas based on information indicating that shellfish harvesting in those areas was threatened or restricted because of contamination originating from septic systems.[5]

1.3 Background

The history of VMI and Quartermaster Harbor in particular has been documented previously–the best examples being publications by Van Olinda (1935), Lynn (1975), and University of Washington (1976), the latter heavily dependent on the first two sources and the references therein.

The University of Washington (1976) study focused on Quartermaster Harbor and was conducted in the early 1970s for the King County Division of Parks and Recreation. The study was conducted in response to public concerns over the expansion of overnight recreational boat moorage facilities at Dockton Park in Quartermaster Harbor. The study included investigation of historical recreation patterns, land use, and environmental impacts; surficial soils and geology, landslide hazards, drain field performance, and beach forming processes; marine circulation, flushing rates, and water temperatures; marine biological conditions; magnitude and spatial extent of marine fecal contamination; and terrestrial vegetation and wildlife primarily in relation to recreational activities and values.

The historical background on Quartermaster Harbor provided below is drawn from the three sources of historical information identified above.

1.3.1 Initial European Discovery and Settlement

The original inhabitants of the island were the Shomamish, a branch of the Suquamish Tribe, who hunted, fished, harvested clams, and gathered roots and berries on the island. The first European to identify Vashon Island was Captain George Vancouver in 1792, who was followed by the U.S. Exploration Expedition led by Captain Charles Wilkes who in 1841 gave separate names for Vashon and Maury Island. It is not completely clear from the historic record why Wilkes gave separate names to the island and Vancouver did not, although this was most likely due to the more specific surveying and mapping objectives of the Wilkes expedition, rather than general documentation and mapping of new discoveries. One explanation that has been given is that Vancouver charted the island at low tide, while Wilkes visited at high tide–although Lynn (1975) argues that Vancouver also passed at high tide. Wilkes charted a narrow connection between the two main land masses and the existence of a sand bar connecting the two islands during extreme low tide (Blumenthal 2009). Although the journal entry of one participant

[5] See Public Health – Seattle and King County Vashon-Maury Island Marine Recovery Area (http://www.kingcounty.gov/healthservices/health/ehs/wastewater/mra.aspx)

(Joseph Perry Sanford) in the Exploration Expedition survey of Vashon in 1841 described the Portage connection as “a very narrow isthmus of white sand,” the more correct term would have been “tombolo”–a deposition landform in which two land masses are attached by a spit or bar. Historically, this area was overtopped and perhaps eroded with unknown frequency during high tides and/or storm surges. Lynn (1975) does mention an early settler’s written account (W.T. Rendell, undated manuscript) of seeing a couple of feet of water between Vashon and Maury at high tide. The possibility of opening a permanent channel at Portage–initially for vessel traffic–was proposed as early as 1911. The suggestion has come up off and on since then–most recently as part of the University of Washington (1976) studies which explored the additional possibility of improving water quality by increasing flushing–particularly of the relatively poorly flushed inner harbor.

The Vancouver and Wilkes expeditions were followed in the mid-1800s by transient logging settlements, some of which were located in Quartermaster Harbor. A village of Chinese immigrants dedicated to catching, drying, and exporting fish was rumored to have been the first non-native settlement (at Manzanita in Quartermaster Harbor) that existed until about 1885 when anti-Chinese sentiment in the region may have been driven them from the area. The first permanent settlers established themselves on the northern shore of Quartermaster Harbor in 1877.

1.3.2 Industrial and Agricultural Development

More people came to the island and by the 1890s, industries such as shipbuilding, clay mining and brick making, lumber and shingle production, fish canning and drying, farm crop processing, and shipping had developed in Quartermaster Harbor and upland areas were being logged and converted to farms and areas for sheep grazing. With the depletion of the native timber on the island, most of the lumber mills closed by 1916 or 1917.

Dockton in particular was the site of a substantial fish processing facility that shipped canned and dried cod to locations throughout the world. As much as 15 tons of dried fish were shipped in one week and 200 tons were shipped in 1920.

Berry farming (particularly strawberries and currants) on VMI was a significant contribution to the local economy from about 1890 to 1934–strawberry shipments in 1908 were estimated at 75,000 crates. However, this boom came to an end in the 1920s due to drought, pests, disease, and competition from mainland farms. Egg production followed the berry boom–in 1923 it was estimated that there were 150,000 laying hens on the island with an annual output of 35,000 cases of eggs. Strawberry farming was still noted by Van Olinda (1935) in 1934, but the production of about 31,000 crates of eggs was also reported that year.

1.3.3 Transportation Development

Initially, wagon roads followed existing deer trails. By 1890 there were seven miles of wagon roads–one of the first roads on the island, Dougway Road, had been a deer trail. Available topographic maps developed from surveys conducted in the 1890s indicate that a permanent road of some kind had been built across Portage around that time. However, this road primarily connected Portage to the central business area on the northern portion of Vashon via upland routes. The first waterfront road was built between Portage and Ellisport in 1916 and the road from Portage was extended to Dockton via an upland route in 1925. Lynn (1975) suggests that the depression at Portage was filled at this time as part of construction of the road to Dockton.

Although a variety of vessels provided transportation around the island and to the mainland in the early years of settlement (i.e., the Mosquito Fleet[6]), the first dedicated daily passenger ferry service began in 1916 between Portage and Des Moines. At one point the island was served by ferries at three locations (Vashon Heights, Tahlequah, and Portage). With the advent of reliable transportation to the mainland and the availability of jobs there, during the 1920s people began to commute from VMI to work in Seattle and Tacoma.

1.3.4 Residential Development

The forest prior to European-American settlement was dominated by Douglas fir, western hemlock, and western redcedar, with alder limited to small areas along stream corridors, landslide zones, beach areas, and open areas generated by windfall and wildfires. Many areas that were originally cleared for homes, agriculture, and grazing have been abandoned, resulting in regeneration of forest cover–primarily Douglas fir on abandoned grazing fields and primarily deciduous forest (red alder and big leaf maple) on tilled land. Along with a return of forest cover to the island, forest clearing associated with residential development is occurring along with resurgence in farming activities. The increase in population of the island based on U.S. Census Bureau data from 1920-2000 indicates the steady progression in the number of people settling on the island. Since 1920, the population has increased about four fold (Figure 5).

The Vashon Sewer District operated a wastewater collection and treatment facility with discharge to East Passage in Puget Sound beginning in 1955. Prior to that time, most island residents relied on onsite sewage treatment and disposal. The current wastewater collection and treatment system, including a new treatment facility and extended outfall to East Passage built and operated by King County, serves about 425 residential and commercial customers, primarily in and around the island's main business area (Figure 6). Most residents within the Quartermaster Harbor watershed rely on onsite septic systems as the wastewater collection and treatment system only serves a small portion of the northern part of the drainage basin.

1.3.5 Recreational Development

The first yacht club in Quartermaster Harbor was established at Manzanita in 1890, but went bankrupt in 1894. However, boating for pleasure did not become popular until the 1920s and was not prevalent until after World War II. The Quartermaster Harbor Yacht Club was organized in 1948 and in the mid-1970s had 100 members and 48 boat slips.

Expansion of overnight recreational boat moorage facilities at the King County park at Dockton in the 1970s was the driver behind the extensive studies conducted by the University of Washington (1976). One of the concerns about increased recreational boating activity that boater-oriented park improvements would cause was the potential for increased waste inputs from onboard toilets. A survey conducted by the University of Washington in 1974 of boaters in Quartermaster Harbor indicated that about 75 percent of the boats surveyed had marine toilets and only about 10 percent had holding tanks.

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[6] See HistoryLink.org essay number 869: *Puget Sound's Mosquito Fleet* (www.historylink.org)

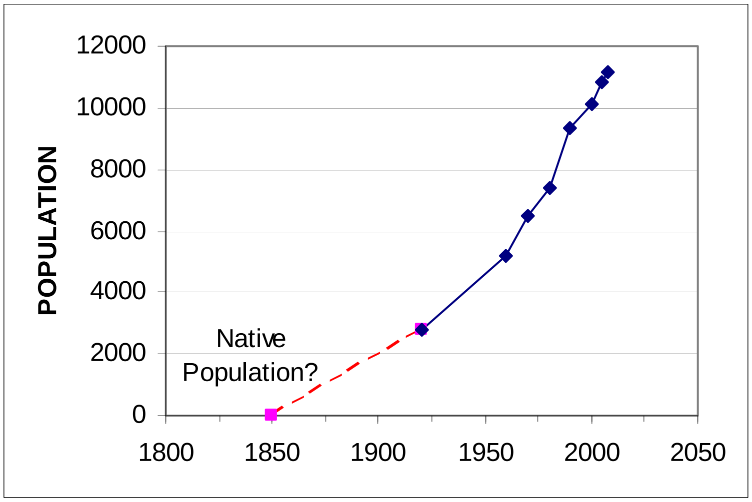

Figure 5. Graph showing the population change on Vashon-Maury Island, 1920-2000.

1.3.6 Implications

With the exception of the University of Washington (1976) study, no other previous studies have evaluated the potential effect of all of these changes on the water quality of the harbor. Along the shore (see Figure 7), the harbor has received unknown amounts of waste from log rafts and sawmills, fish and other food processing plants, shipyards, clay mining and brick making, and upland areas have delivered soil and waste from logging operations, residential home construction, and farming. Farm impacts would include inputs from sheep, horse, cattle, and chickens. Nearshore and upland areas initially delivered untreated domestic wastewater to the harbor and its receiving streams until onsite septic systems came into use. Bulkheading for waterfront industries and shoreline residential development also has also likely affected inorganic sediment delivery to the harbor shoreline and subsequent transport to depositional areas.

The background history of Quartermaster Harbor provided above is meant to remind us that past land use activity may still play an important role in the current quality of Quartermaster Harbor. This concept was emphasized by Harding et al. (1998) in their widely cited paper on "The Ghost of Land Use Past." This concept is implicit in the relatively frequent call for investigation of the potential benefit of restoring some hydrologic connection across Portage (King County 1998). To the extent possible, the Quartermaster Harbor Nitrogen Management Study will incorporate knowledge about the past into this study.

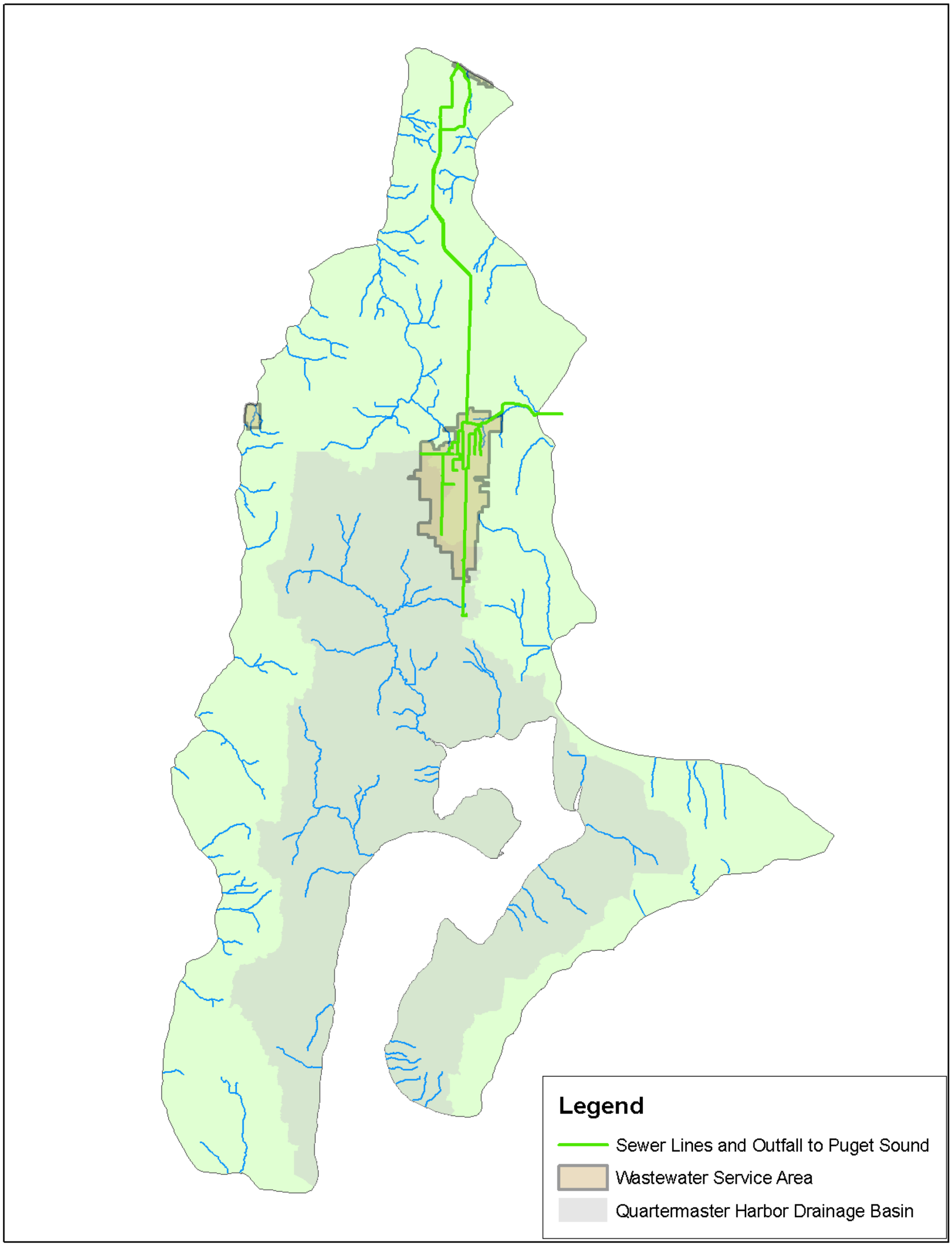

Figure 6. Map showing current service area for the Vashon Island Wastewater Treatment System.

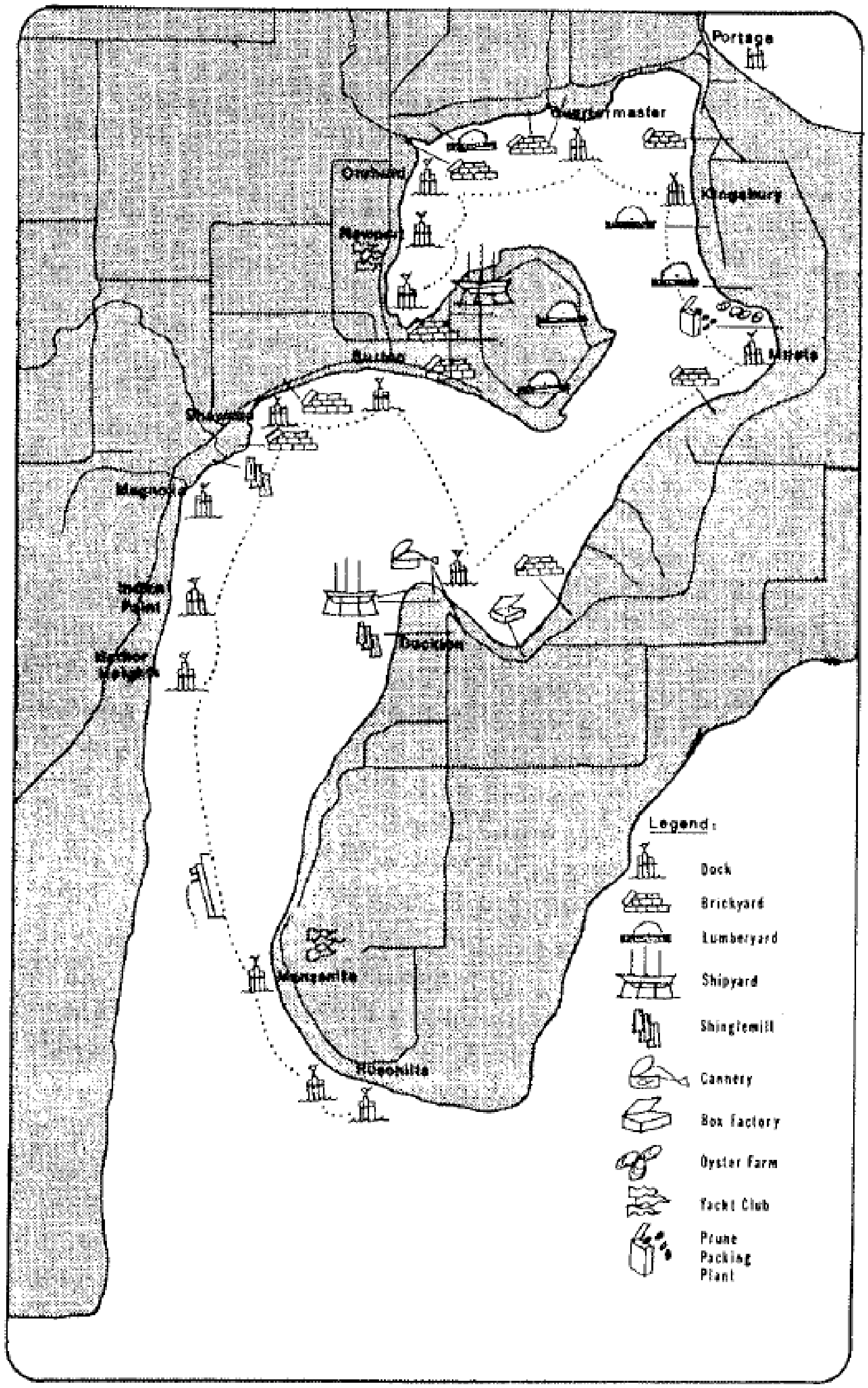

Figure 7. Map showing early distribution pattern of development activities around Quartermaster Harbor.

Source: University of Washington (1976)

1.4 Goals and Objectives

The overall goal of this project is to determine how nitrogen from a variety of sources affects dissolved oxygen levels in Quartermaster Harbor. The goal of this particular report is to document the development of preliminary estimates of nutrient loading to Quartermaster Harbor from a variety of sources. The objective of the report is to document assumptions used in developing load estimates and identify data gaps. These loading estimates will provide initial inputs for the development and testing of a marine receiving water quality model (King County 2009a).

1.5 Organization of Report

The report is organized into an introduction (this section), sections describing the methods to calculate nutrient loading to the harbor (Methods), and a section summarizing the results of those calculations (Results). Within the Methods and Results, sections are further subdivided into sub-headings for five types of sources analyzed in this report:

- Atmospheric deposition
- Stream inputs
- Regional groundwater
- Shoreline septic systems
- Benthic nutrient flux

Within each of these subheadings, methods and results for loading estimates are further separated into the major nutrient categories: nitrogen, phosphorus, and silica. A summary of the results and some conclusions drawn from the results are provided in the Summary and Conclusions section and a Recommendations section provides some suggestions for additional studies that might help reduce the uncertainty and improve the accuracy of the initial nutrient loading estimates presented in this report.

2.0. METHODS

Methods used to develop loading estimates for the five sources evaluated in this report follow below.

2.1 Atmospheric deposition

The atmospheric loading of nutrients (primarily nitrogen and phosphorus) to lakes and estuaries has been the focus of a number of studies in the United States (e.g., Eisenreich et al. 1980, Baker 1994, Puckett 1994, Sheeder et al. 2002). Recent focus has been on the atmospheric transport and deposition of nitrogen to east coast estuaries. The focus on nitrogen in east coast receiving waters is due to the presence of larger and/or more concentrated industrial and agricultural nitrogen sources and the sensitivity of the productivity of these receiving waters to nitrogen. However, studies have also evaluated atmospheric nutrient deposition for the Puget Sound region (e.g., Vong and Waggoner 1983, Vong et al. 1985, Embrey and Inkpen 1998) and within the metropolitan Seattle area (e.g., Johnson et al. 1966, Moon 1973, Ebbert et al. 1985, PSWQA 1991). A few of the Seattle area studies have been used to develop estimates of atmospheric loading of nitrogen (N) and phosphorus (P) to Lake Washington (Edmondson and Lehman 1981, Cerco and Noel 2003, Arhonditsis and Brett 2005) and Lake Sammamish (Moon 1973, Kemper 1975).

Deposition is typically characterized as "wet," "dry," or "bulk" deposition. Wet deposition occurs during periods of rain or snow in which fine aerosol and larger dust particles are scavenged from the air and deposited along with the rain water. Wet deposition is usually measured by deploying rainfall collection devices during periods of rainfall and immediately transferring the collected sample to a laboratory for analysis. Dry deposition occurs during the absence of rain or snow and occurs through the settling of particulates and impingement of fine particles on the water surface or diffusion of gasses across the air-water interface.

A number of methods can be used to measure dry deposition. Some involve measurement of the concentration and distribution of atmospheric particulates and estimating their deposition rate from equations that combine estimates of deposition velocity with concentration. A more direct method of measuring dry deposition involves the collection of dust fall in an open container during periods of dry weather. The collected material is then suspended in analyte-free water and analyzed to estimate the concentration of deposited material. Bulk deposition is the combination of dry and wet deposition and is typically measured by placing a rainfall collection device and collecting rain and dust fall over intervals ranging from weeks to months and then analyzing the wet sample for the target analytes.

There are a number of advantages and disadvantages associated with each method. For example, roosting birds can confound measurements made over periods greater than the length of an individual storm event, especially when dry or bulk sampling devices are used (long-term wet samplers often have a cover that seals the sample collector from the atmosphere during dry weather). Atmospheric exchange (gaseous) with exposed water samples can affect sample concentrations. This is particularly problematic with ammonium, which can be relatively abundant in the atmosphere (manure piles can be a significant source of ammonia) and is quite soluble in water.

In general, the importance of atmospheric sources of nutrients to receiving waters depends on the deposition rate of the nutrient and the ratio of the surface area of the receiving water to that of its drainage basin. Phosphorus tends to be primarily associated with the dry deposition of soil-derived particulates of which a portion becomes soluble in the receiving water (e.g., Eisenreich et al. 1980, Bergametti et al. 1992, Markaki et al. 2003). The atmospheric contribution of organic forms of phosphorus has received little attention. Nitrogen forms in atmospheric deposition include nitrate and ammonia nitrogen. Nitrate and ammonia occur in wet and dry deposition. The atmospheric contribution of organic forms of nitrogen has received little attention.

2.1.1 Nitrogen

The estimates of atmospheric deposition of nitrogen were developed from data collected as part of the regional atmospheric deposition monitoring network. Wet atmospheric deposition has been monitored at four rural sites in Washington as part of the National Atmospheric Deposition Program (NADP). These sites are the Hoh River Ranger Station (WA14; 5/80-present) on the Olympic Peninsula, Marblemount (WA19; 2/94-present) in the North Cascades, La Grande (WA21; 4/84-present) on the west flank of Mt. Rainier, and Mt. Rainier National Park-Tahoma Woods (WA99; 10/99-present) (see Figure 8).

Dry deposition is being measured at three sites as part of the Clean Air Status and Trends Network (CASTNet). These locations are Olympic National Park (OLY421; 99-present), North Cascades National Park (NCS415; 99-present), and Mount Rainier National Park (MOR409; 96-present) (see Figure 8).

Monthly data for precipitation and rainfall ammonia and nitrate nitrogen concentration were downloaded from the NADP website[7] (January 2006 through December 2008) and monthly deposition rates were calculated for each of the four stations. Monthly dry deposition data for ammonia and nitrate nitrogen were downloaded from the link available on the NADP website for the same period.

2.1.2 Phosphorus

To develop atmospheric P loading inputs, the data presented by Ebbert et al. (1985) and the statistical analyses of the data presented by Prych and Ebbert (1986) were evaluated. These data are the most comprehensive–they include wet and dry deposition measurements of P (and N) compounds. Unfortunately, because the data were collected in areas of Bellevue between Lake Sammamish and Lake Washington, the data are more representative of urban/residential areas rather than rural areas.

Three locations in Bellevue were sampled from March 1979 to January 1982 using wet/dry deposition samplers. The 148th Avenue SE site was located near a 4-lane arterial street, while the other two sites (Surrey Downs and Lake Hills) were single-family residential areas. Typical collection periods were at one-month intervals. However, some wet deposition collection periods were less than one day. A number of parameters were measured, including specific

[7] National Atmospheric Deposition Program. NTN (National Trends Network) in Washington. http://nadp.sws.uiuc.edu/sites/sitemap.asp?state=wa

conductance, pH, dissolved and suspended solids (wet only), total solids (dry only), dissolved and particulate organic carbon (wet only), total organic carbon (dry only), nitrate plus nitrite nitrogen, ammonia nitrogen, total ammonia plus organic nitrogen (also known as total kjeldahl nitrogen [TKN]), dissolved phosphorus (wet only), total phosphorus, and dissolved (wet only) and total recoverable lead.

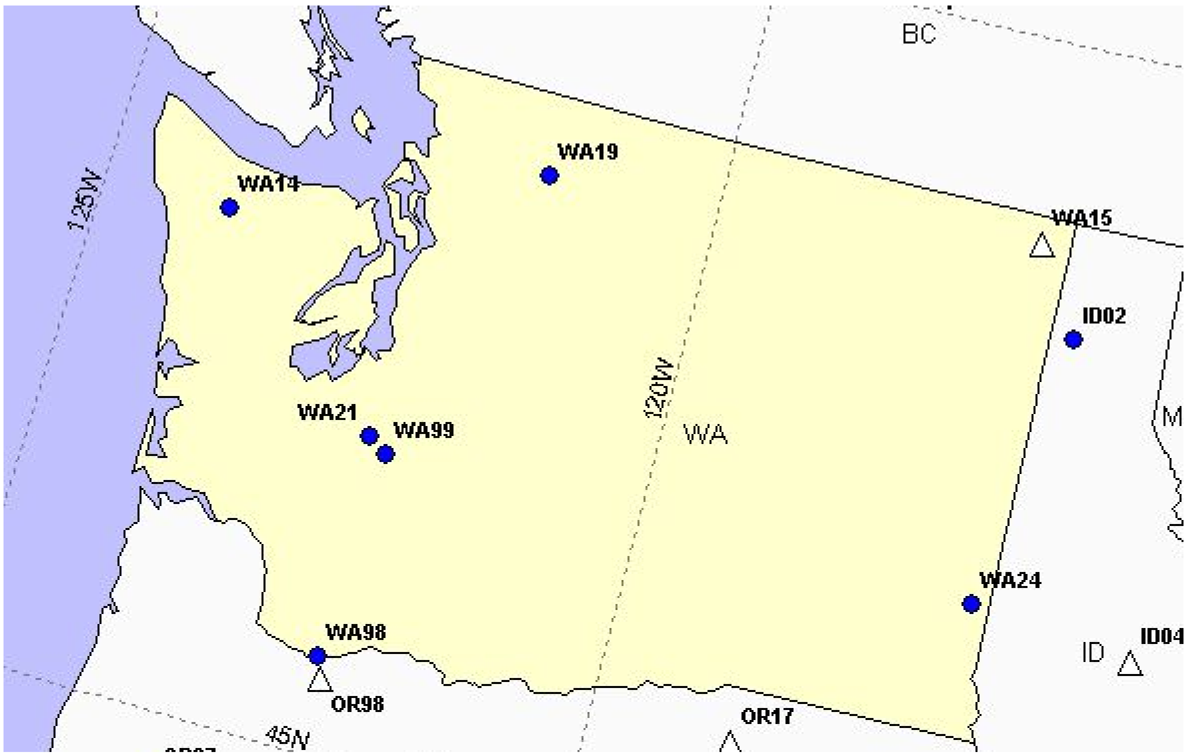

Figure 8. Map of National Atmospheric Deposition Program (NADP) and Clean Air Status and Trends (CASTNet) monitoring sites in Washington.

Note: CASTNet stations MOR409, NCS415, and OLY421, and are located near the Mt Rainier (WA99), North Cascades (WA19), and Olympic National Park (WA14) NADP monitoring stations.

Prych and Ebbert (1986) concluded that most of the characteristics of wet deposition were similar among sites and that there was little correlation among the different chemical constituents or properties except for pH and conductance. They also concluded that there was an indication that rainfall concentrations generally decreased with increasing rainfall indicating that the supply of atmospheric constituents becomes depleted as a result of rainfall washout. Dry deposition concentrations of total organic carbon (TOC), total solids, TKN, and TN were correlated with each other–but not with TP.

Prych and Ebbert (1986) also noted that there was little correlation between collector exposure time and the amount of dry-atmospheric deposition collected. This suggested that at some point during each collection period the deposition of a constituent is balanced by its removal from the collector by wind. This may be similar to the situation of particulate deposition on paved surfaces, but on the harbor surfaces all deposited material would be trapped, further enhancing the deposition rate.

Significant differences were noted among the deposition of various constituents at the three sites. However, Prych and Ebbert (1986) suggested that the differences were more an indication of deficiencies in the sampling methods–higher amounts of large organic detritus (e.g., leaves and pine needles) were caught in the Lake Hills collector due to the proximity of trees and the samplers may not have been 100 percent efficient in trapping deposited material. Note that large particulates were removed before analyses were conducted but smaller particulates likely remained.

The monthly deposition estimates developed by Prych and Ebbert (1986) were compiled to provide initial estimates of atmospheric phosphorus deposition to Quartermaster Harbor.

2.1.3 Silica

Silica deposition data have not been reported from local studies, although it would likely be a component of dry deposition. Currently, an atmospheric silica deposition rate reported by Anderson and Downing (2006) were used to estimate atmospheric silica deposition to Quartermaster Harbor. They measured a deposition rate (wet + dry) of 6.1 kg Si per hectare per year.

2.2 Stream Inputs

Stream inputs include freshwater flow to Quartermaster Harbor via large and small tributaries that deliver water and nutrients to the harbor. Four major tributaries on Vashon-Maury Island are monitored monthly for nutrient concentrations and are also continuously gauged to estimate daily flow. Two of these tributaries discharge directly to Quartermaster Harbor–Judd Creek discharges to the inner harbor and Fisher Creek enters the outer harbor–while the other two tributaries discharge to Puget Sound (Tahlequah and Shingle Mill Creeks) (Figure 9). Mileta Creek discharges to Inner Quartermaster Harbor, but it is only monitored routinely for water quality (see Figure 9).

To develop initial estimates of nitrogen, phosphorus, and silica loading to Quartermaster Harbor, monthly grab sample concentrations of ammonium, nitrate, and total nitrogen; total and soluble reactive phosphorus; and silica were interpolated to develop daily concentrations that were combined with the daily average flow data to calculate loading. With the exception of silica, estimates were based on data for 2007 and 2008. Analysis of stream samples for silica did not begin until 2009 (initiated as part of this study). These data were used to develop preliminary stream loading estimates for silica. Daily discharge for Mileta Creek was estimated by scaling the daily discharge observed in Fisher Creek based on the relative basin area of the two drainage basins. The Mileta drainage area is about 40 percent less than the Fisher Creek basin area.

The average loading from the four creeks, which are monitored for flow and water quality, was then used to calculate nutrient loading from the unmonitored drainages to Quartermaster Harbor. The unmonitored drainage area represents about 30 percent of the drainage to the inner harbor and about 70 percent of the drainage to the outer harbor. About half (52 percent) of the total drainage to the harbor is captured in the monitoring conducted on Judd, Fisher, and Mileta Creeks.

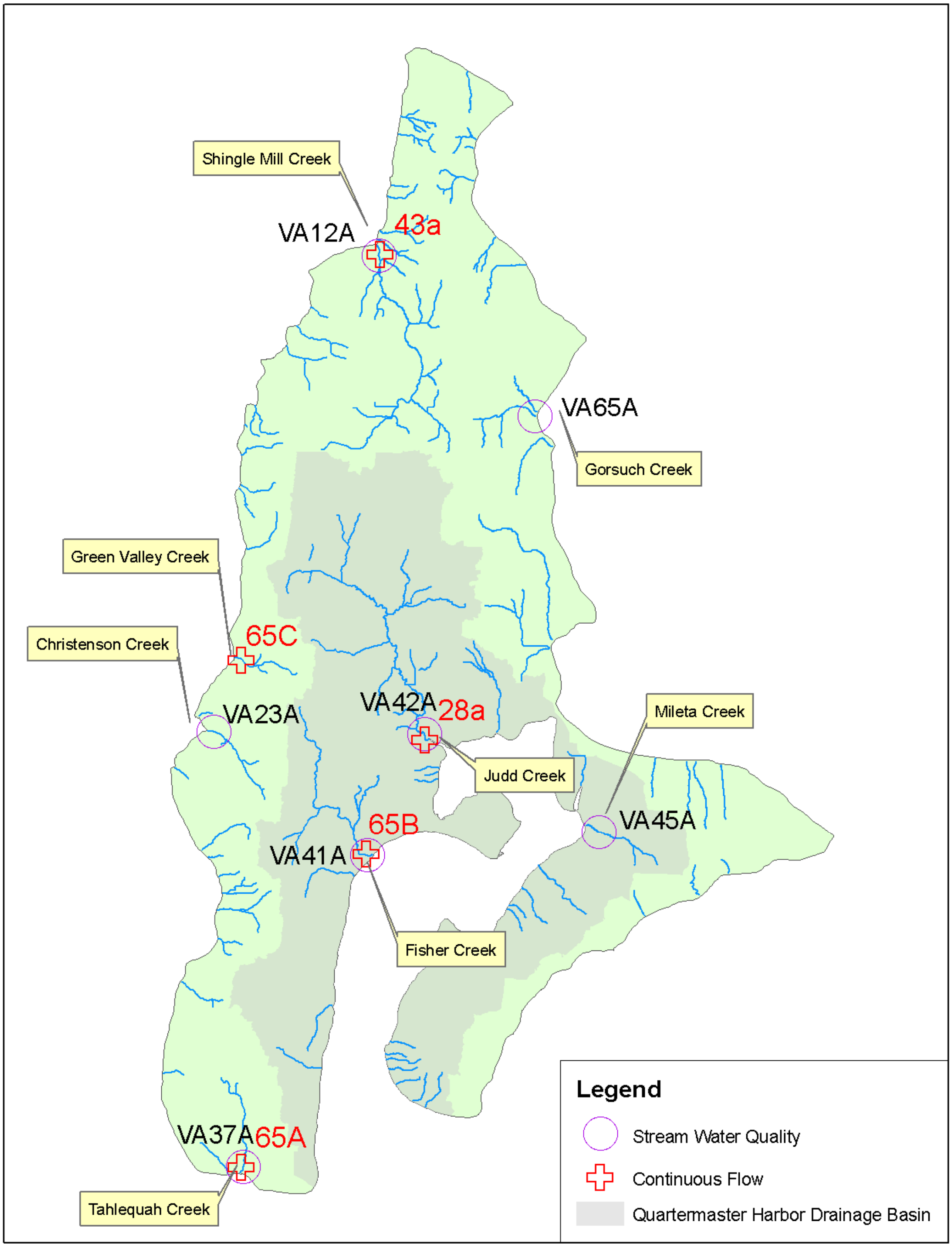

Figure 9. Map showing locations of stream discharge gauging and water quality monitoring stations.

2.3 Regional Groundwater Inputs

Ground water discharge to Quartermaster Harbor is likely to be variable in space and time because of local geology, variable hydraulic gradients near the shoreline, and the large tidal range (~ 4.5 m [15 ft]). Highly detailed groundwater level measurements and field investigations along the marine shoreline, including the use of electrical resistivity profiles and geochemical tracers, were used to estimate groundwater inputs to Lynch Cove in Hood Canal as part of the Hood Canal Dissolved Oxygen Program (Swarzenski et al. 2007, Simmonds et al. 2008). However, these types of intensive field studies are beyond the scope of the Quartermaster Harbor Nitrogen Management study. A reasonable first approximation of groundwater input to the harbor can be derived from a basin-scale water budget as outlined by Paulson et al (2007) who developed such an estimate for Hood Canal.

The estimate of groundwater input to the harbor can be derived from information on the total annual precipitation to the drainage area to Quartermaster Harbor, the annual evapotranspiration (ET) over the same area, the amount of overland runoff, including base flow, and the magnitude of consumptive water use in the drainage basin. Precipitation less ET, runoff, and consumptive water use provides an upper estimate of the total groundwater input to the harbor, at least for the period evaluated (see Equation 1 below). This is the upper limit assuming that none of the recharge to the Quartermaster Harbor drainage flows out of the watershed, consumptive use estimates affect only groundwater flow to the harbor, there is no long-term change in aquifer storage (i.e., the aquifer system is in steady state with respect to inputs and outputs), and all of the groundwater flow enters the harbor rather than entering the deeper aquifer system below harbor bottom.

Equation 1:

Groundwater Discharge = Precipitation – Evapotranspiration – Runoff – Consumptive Use

The overall water balance of the drainage to Quartermaster Harbor was developed using data from 2007 and 2008 from three precipitation gauging stations within the basin (Figure 10). One gauge was located on Vashon (station 28Y) and was used to represent rainfall on that portion of the basin. The other two gauges (stations 36U and 36V) were located on Maury Island and were used to estimate rainfall to the Maury Island portion of the drainage to the harbor. However, due to some incomplete records for the Maury gauges, only one station was used to represent each year’s rainfall total for that basin.

Consumptive water use was estimated based on the identified agricultural areas and uses identified in King County (2005b) and associated irrigation rates, which were assumed to be completely consumptive. Given the uncertainty in these irrigation rates (King County 2005b) this assumption is probably reasonable for developing initial loading estimates. The identified agricultural areas and uses are shown in Figure 11. The assumed irrigation rates were 1.4 and 2.9 inches per year for livestock areas and other agricultural uses, respectively (King County 2005b).

In addition to consumptive agricultural uses, consumptive use due to residential outdoor irrigation was developed based on a report that about 30 percent of residential water use in the

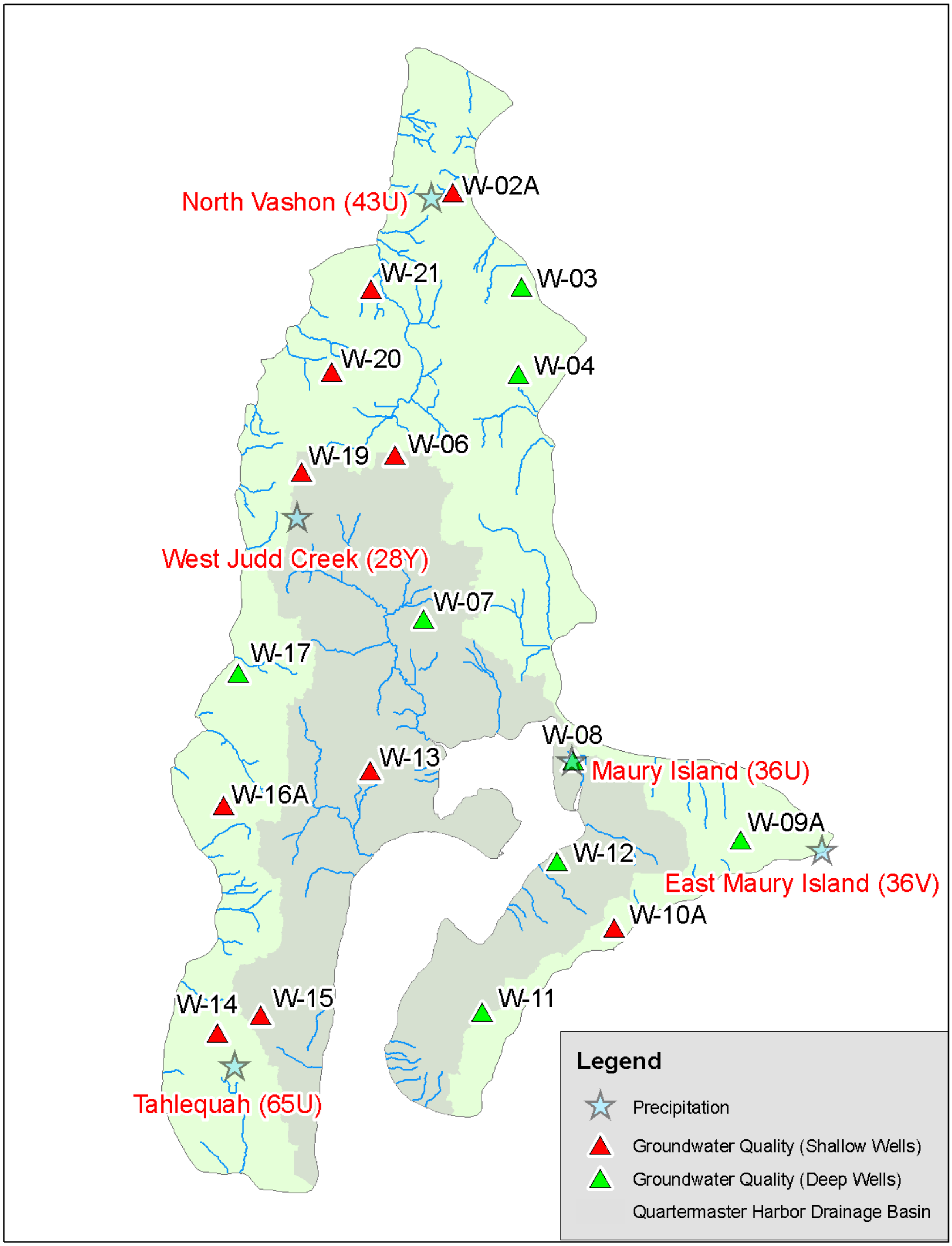

Figure 10. Map showing locations of precipitation gauging stations and shallow and deep groundwater water quality monitoring wells.

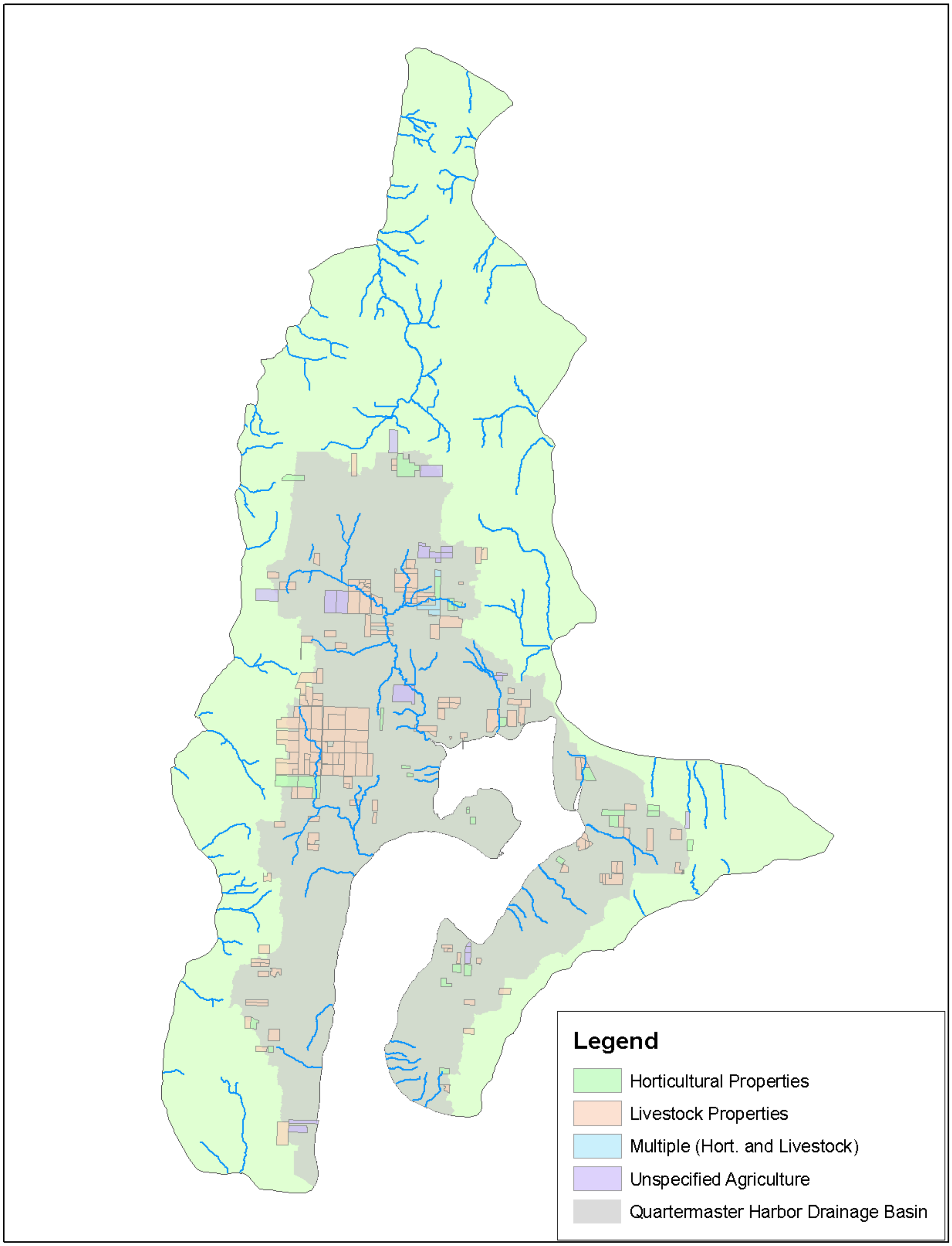

Figure 11. Map showing identified areas of agricultural activity within or adjacent to the Quartermaster Harbor drainage basin.

nearby Seattle area is used for outdoor consumptive use (American Water Works Association Research Foundation 1999). In the absence of residential outdoor water use data for VMI, this assumption was considered reasonable. The estimated total residential water use was derived from information in King County (2005b), which gave an average VMI per capita use of 76 gallons per day. This information was combined with the 2000 Census Block data, which provided an estimate of the number of households within the Quartermaster Harbor drainage area (~1,500) and combined with the average number of people per household (2.4) provided the information necessary to estimate residential outdoor consumptive use.

The estimated groundwater flow rates were combined with the available information on the nutrient concentrations in shallow groundwater wells monitored as part of the King County Water Resources Evaluation (King County 2003) in the Quartermaster Harbor drainage. “Shallow” is a relative term and here we define shallow well as those wells for which the best information available indicates that they withdraw water from the shallowest aquifer represented by Vashon advance outwash deposits - often referred to as Qva (Figure 12). The deeper aquifers below the Qva deposits generally are found below the bottom of the harbor. Therefore, the quality of the water in the shallow aquifer is likely to be most representative of the quality of the groundwater entering the harbor. The monitoring wells and their assigned aquifer units, including designations for shallow (completed in Qva or suspected of being completed in Qva) and deep wells are provided in Table 1.

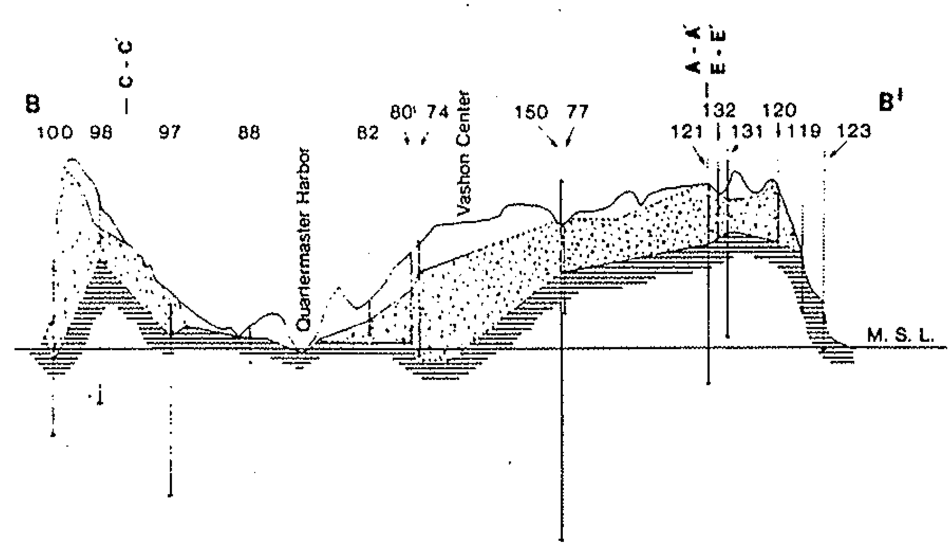

Figure 12. Geologic cross section through Vashon-Maury Island and Quartermaster Harbor.

Note: Stippled area represents the principal aquifer unit. Source: Vashon-Maury Island Groundwater Management Committee (1998)

Table 1. Groundwater water quality monitoring wells and subsurface completion information.

Well ID	Site Name	Layer [1]	Well Bottom Elevation	Depth of Well	Surface Elevation
			Feet (NAVD 1988)		
W-02a	Heights Water District	Qva/QAc	83.3	177	260.3
W-03	Glen Acres	QAc	3.6	142	145.6
W-04	Rodriques	QBC	-106.7	305	198.3
W-06	Packard/Healy	Qva	236.7	169	405.7
W-07	Toomey/Sorge	QAc	-37.2	297	259.8
W-08	Kiro/Entercomm, Inc.	QBc	-366.5	462	95.5
W-09a	White #1	QAc	-38.9	450	411.0
W-10a	Gold Beach Water Company	Qva	-7.4	114	106.6
W-11	Docton Water Association	QAc	-102.5	423	320.5
W-12	Hollymere Water System	QBc	-362.6	473	110.4
W-13	Misty Isle Farms	Qva	143.3	80	223.3
W-14	Krishnan	Qva/QAc	193.5	183	376.5
W-15	Anderson	Qva	181.8	188	369.8
W-16a	Baker/Klemka	Qva	215.6	67	282.6
W-17	Perla	QAc	3.1	220	223.1
W-19	Thorsen Rd Water Association	Qva	239.6	173	412.6
W-20	Johnson	Qva	241.0	122	363.0
W-21	Kuperberg	Qva	165.8	133	298.8

[1] Layer designations based on conceptual model and assignments for the development of the Phase II VMI groundwater model (DHI 2009). The surficial aquifer (and principal water source for most of the island's population is designated Qva, which stands for Vashon Stade outwash deposits. Less permeable confining layers separate the surficial aquifer from deeper aquifers that are designated QAc and QBc, respectively. See DHI (2009) and King County (2005b) for more details regarding subsurface geology and the groundwater conceptual modeling.

2.4 Shallow Subsurface Flow from Shoreline Septic Systems

To provide an initial estimate of nitrogen loads from shoreline septic systems, the approach used by Paulson et al. (2007) to estimate nearshore septic inputs to Hood Canal was reviewed and adapted for use in this project. The King County parcel database was used to estimate the number of occupied households along the shoreline and the 2000 Census Block data for the nearshore area were used to estimate the number of people per household. Combining the number of occupied households with the number of people per household yielded an estimate of the annual nearshore population. The population estimate was then combined with an estimate of per capita annual dissolved inorganic nitrogen (DIN; a combination of ammonia and nitrate nitrogen) and soluble reactive phosphorus load from septic systems. The per capita DIN and soluble reactive phosphorus (SRP) loads were derived from data on septic drain field effluent quality (Canter and Knox 1985) and an estimate of per capita effluent volume derived from the per capita residential water use (76 gallons per day) and percent of outdoor use noted above, which results in an estimated indoor water use and septic tank discharge rate of 51 gallons per day (193 Liters per day).

No transformation or reduction of nitrogen concentrations is assumed to occur from these nearshore systems, which is consistent with the findings of a study of nearshore septic systems along Hood Canal that found little attenuation of nitrogen from systems along the shore of Hood Canal (Atieh et al. 2008). The median estimated nitrogen removal rate based on field experiments conducted at two nearshore locations was 8.5±4.5 percent–a relatively low rate likely due to the oxygenation of the soil by infiltrating seawater (Atieh 2008). Although the septic drain field effluent is dominated by ammonium nitrogen, some nitrification likely occurs during subsurface transport to the harbor.

Table 2. Concentrations of ammonia nitrogen and phosphate phosphorus below a septic drain field summarized in Canter and Knox (1985)

Constituent	Range
Total phosphates (PO4-P)	6 - 9 mg/L
Ammonium nitrogen (NH4-N)	10 - 78 mg/L

Silica is assumed to be a negligible component of domestic wastewater and therefore, no nearshore septic loading estimate was made for this nutrient.

2.5 Benthic Nutrient Flux

Marine sediments can be a significant source of nutrients to the water column depending on the character of the sediment and conditions in the overlying water. Benthic nutrient fluxes have been recognized as a significant component of the overall nutrient budget in previous studies of

South Puget Sound embayments where low dissolved oxygen levels are of concern (Roberts et al. 2008).

Although direct measurement of benthic nutrient flux may be desired, current project resources are not sufficient to conduct such a study. Fortunately, direct measurements have been made in several South Puget Sound embayments that can be used to estimate the flux of nitrogen and phosphorus from Quartermaster Harbor sediments (Roberts et al. 2008). These South Puget Sound benthic flux estimates for nitrogen and phosphorus summarized in Roberts et al. (2008) were combined with estimates of the bottom area of the inner and outer harbor to derive initial estimates of nitrogen and phosphorus flux to the harbor during the critical dissolved oxygen period in late summer.

Benthic flux chambers were deployed in three discrete sampling events at three depths (5, 15, and 25 m) in four South Puget Sound inlets (Budd, Carr, Case, and Eld) during September and October 2007 (Roberts et al. 2008). A range of benthic flux rates and an average rate for all sampling events was reported. The sample results are summarized along with an average of estimates from other published sources in Table 3.

Table 3. Benthic nutrient flux rates measured by Ecology in South Puget Sound embayments and published estuarine/marine benthic nutrient flux data

Constituent	Range	Average	World Flux Database Average *
	(g/m^2-day)		
Ammonium nitrogen	nr	nr	0.040
Dissolved Inorganic N (DIN)	0 – 0.13	0.052	0.064
Organic Nitrogen	-0.10 – 0.34	0.038	-
Total Nitrogen	-0.07 – 0.48 (E)	0.085	-
Orthophosphate Phosphorus	-0.02 – 0.11 (E)	0.024	0.015
Total Phosphorus (TP)	-0.008 – 0.115	0.025	-
Dissolved Silica (DSi)	-	-	0.200

nr – Not reported

E – Estimate derived from figures found in Appendix F of Roberts et al. (2008).

* World Flux Database – Chesapeake Biological Laboratory (Bailey and Boynton, 2007) as reported in Roberts et al. (2008), with the exception of data for dissolved silica which came from DiToro (2001) who reported a range of 0.050 to 0.300 g Si m^{-2}-day for Chesapeake Bay.

3.0. RESULTS

The results of initial loading estimates for the five sources evaluated in this report follow below.

3.1 Atmospheric deposition

Based on the available wet deposition data from the four NADP stations, annual average (2006-2008) wet deposition of ammonium nitrogen ranged from 0.246 kg NH4-N per hectare (Olympic National Park) to 0.505 kg NH4-N per hectare (North Cascades-Marblemount). Wet nitrate deposition ranged from 0.606 kg NO3-N per hectare (Olympic National Park) to 1.254 kg NO3-N per hectare (North Cascades). The annual wet deposition results for these stations are summarized in Table 4.

Table 4. Annual average wet deposition of nitrogen estimated from NADP sites located in Western Washington

Year	Olympic National Park (Hoh River) WA14	North Cascades (Marblemount) WA19	La Grande WA21	Mt Rainier National Park (Tahoma Woods) WA99
	(kg N per hectare)			
Ammonium N (NH4-N)				
2006	0.21	0.67	0.44	0.24
2007	0.05	0.40	0.29	0.27
2008	0.30	0.50	0.42	0.19
Nitrate N (NO3-N)				
2006	0.69	1.17	0.72	0.63
2007	0.20	1.33	0.62	0.65
2008	0.63	1.30	0.64	0.47
Dissolved Inorganic N (DIN)				
2006	0.90	1.84	1.16	0.87
2007	0.26	1.74	0.91	0.92
2008	0.92	1.79	1.06	0.66

Dry deposition of ammonium nitrogen at the 2 CASTNet stations averaged 0.025 kg NH4-N per hectare and deposition of nitrate nitrogen averaged 0.126 kg NO3-N per hectare. The annual dry deposition results for these stations are summarized in Table 5.

Table 5. Annual average dry deposition of nitrogen estimated from CASTNet sites located in Western Washington

Year	Nitrate N (NO3-N	Ammonium N (NH4-N)	Dissolved Inorganic Nitrogen (DIN)
	(kg N per hectare)		
Mt. Rainier National Park (MOR409)			
2006	0.157	0.021	0.179
2007	0.106	0.019	0.125
2008	0.086	0.018	0.104
North Cascades National Park (NCS415)			
2006	0.148	0.034	0.182
2007	0.131	0.033	0.164
2008	-	-	-

Generally, nitrogen deposition is lowest in areas downwind of the major metropolitan areas around Puget Sound such as Olympic National Park and Mt Rainier National Park, with highest deposition rates measured upwind of the metropolitan area at the North Cascades National Park station. Given the limited spatial detail of the available nitrogen deposition monitoring network and the location of Quartermaster Harbor in more or less the center of the deposition monitoring stations, it seems reasonable to use an average of the station data as an initial estimate of nitrogen deposition to Quartermaster Harbor.

Deposition rates of total phosphorus averaged for the three stations monitored by Ebbert et al. (1985) in Bellevue, Washington are shown in Figure 13. Annual phosphorus deposition based on these data is 0.27 kg P per hectare.

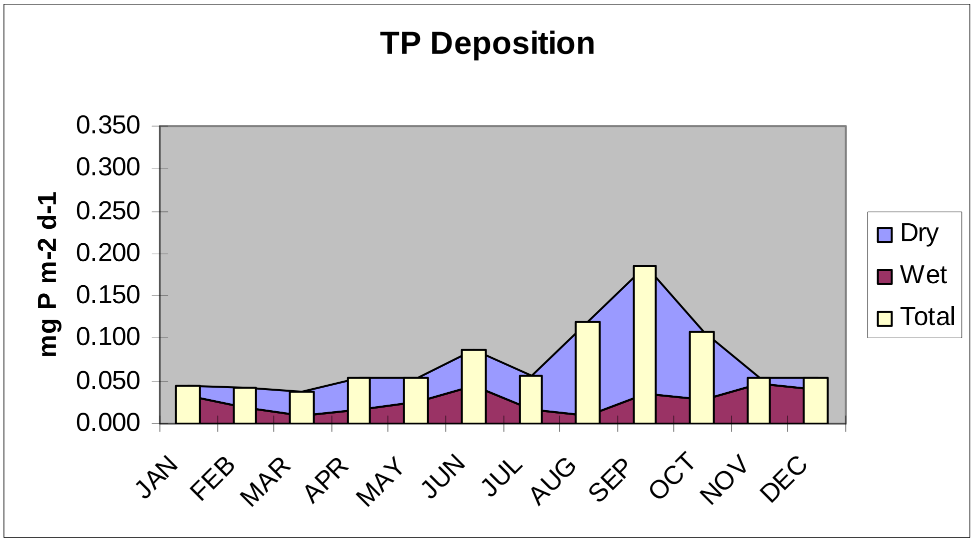

Figure 13. Graph showing monthly wet, dry, and total deposition of total phosphorus based on the study by Ebbert et al. (1985).

3.2 Stream Inputs

The available flow and water quality monitoring data from the four VMI streams used to develop nutrient loading estimates for the ungauged drainages to Quartermaster Harbor are shown in Figure 14 through Figure 17. Table 6 provides the annual nutrient loading estimates (average 2007-2008) for these tributaries based on the flow and water quality monitoring data.

The average nutrient loading based on data from these tributaries provides an initial estimate of loading from the unmonitored stream basins that deliver surface runoff to Quartermaster Harbor. Based on the monitoring data for these creeks, the majority of the nitrogen delivered from streams to Quartermaster Harbor is delivered in the form of nitrate nitrogen (~77%), with the remainder entering in the form of organic nitrogen (~22%) and ammonium nitrogen (~1%). The amount of phosphorus delivered is approximately half in dissolved form and half in particulate organic form.

Water quality data for the ungauged Mileta Creek are shown in Figure 18. Note the extremely high winter nitrate values observed in Mileta Creek relative to the other tributaries. Also note that the few available flow measurements indicate flows that are much lower than in comparably sized streams (see Figure 16 for Tahlequah Creek).

Table 6. Annual average nutrient loading estimates for Judd, Fisher, Shingle Mill, and Tahlequah Creeks for the period 2007-2008.

	TN	Org N	NO3-N	NH4-N	TP	Org P	SRP	DSi
				(kg/ha-yr)				
Judd Creek	4.88	1.35	3.49	0.04	0.18	0.11	0.07	17.5
Fisher Creek	3.85	0.89	2.93	0.03	0.18	0.10	0.08	15.2
Shingle Mill Creek	5.44	1.01	4.37	0.05	0.22	0.08	0.13	28.0
Tahlequah Creek	4.70	0.83	3.75	0.12	0.09	0.05	0.03	-
Average	4.72	1.02	3.64	0.06	0.17	0.09	0.08	20.3

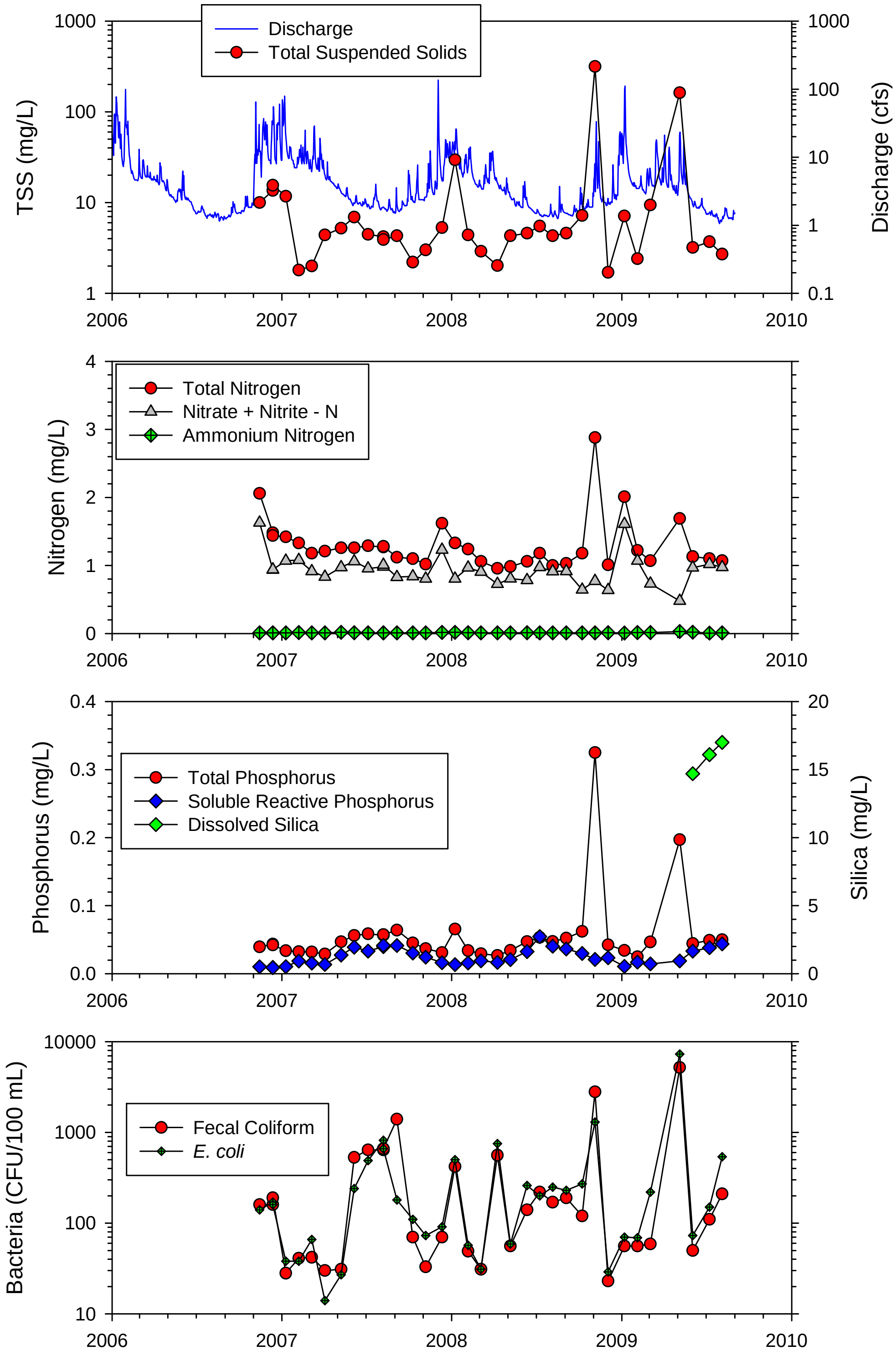

Figure 14. Graphs showing stream discharge (gauge 28a) and selected water quality data (station VA42A) for Judd Creek.

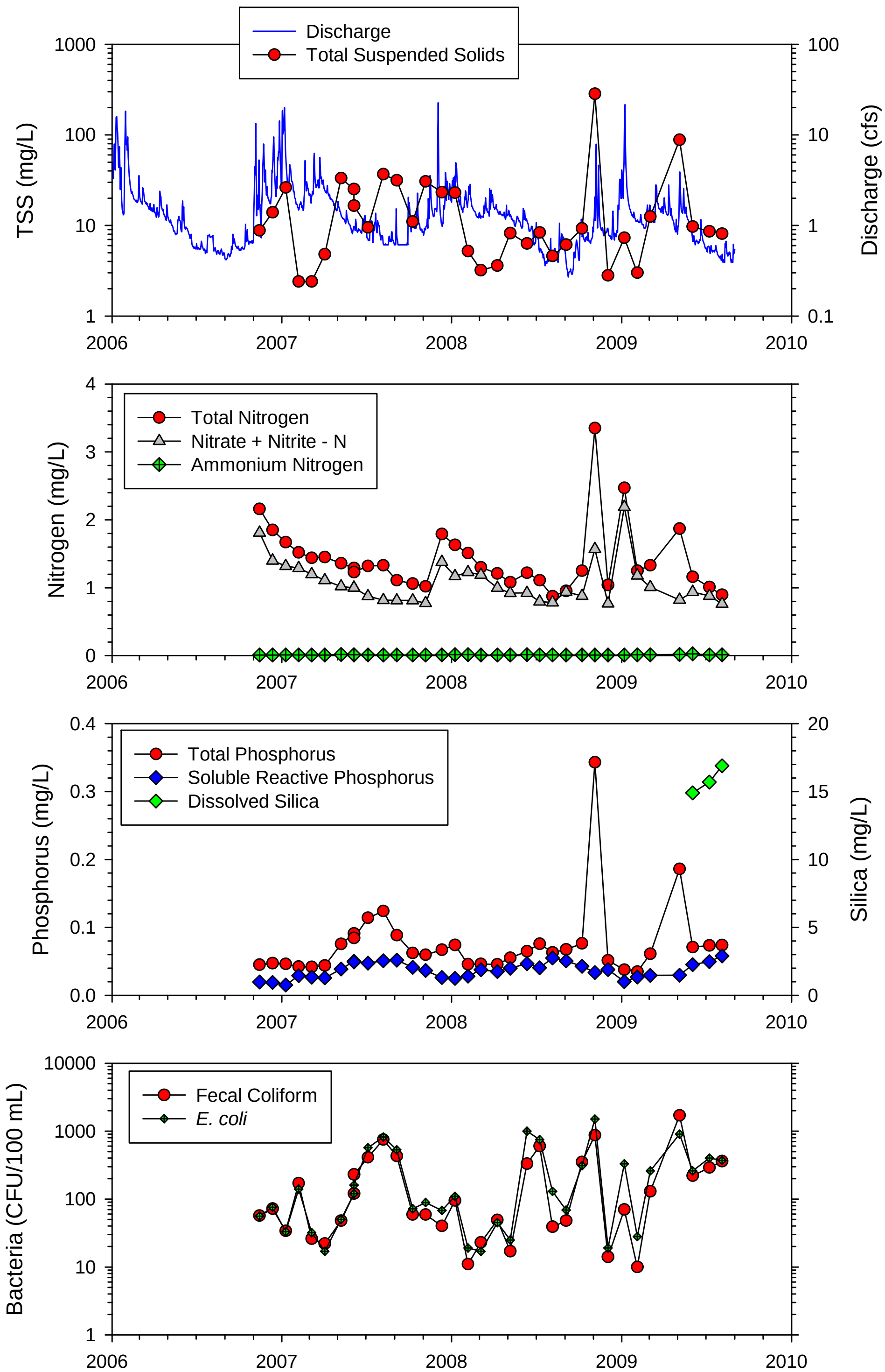

Figure 15. Graphs showing stream discharge (gauge 65B) and selected water quality data (station VA41A) for Fisher Creek.

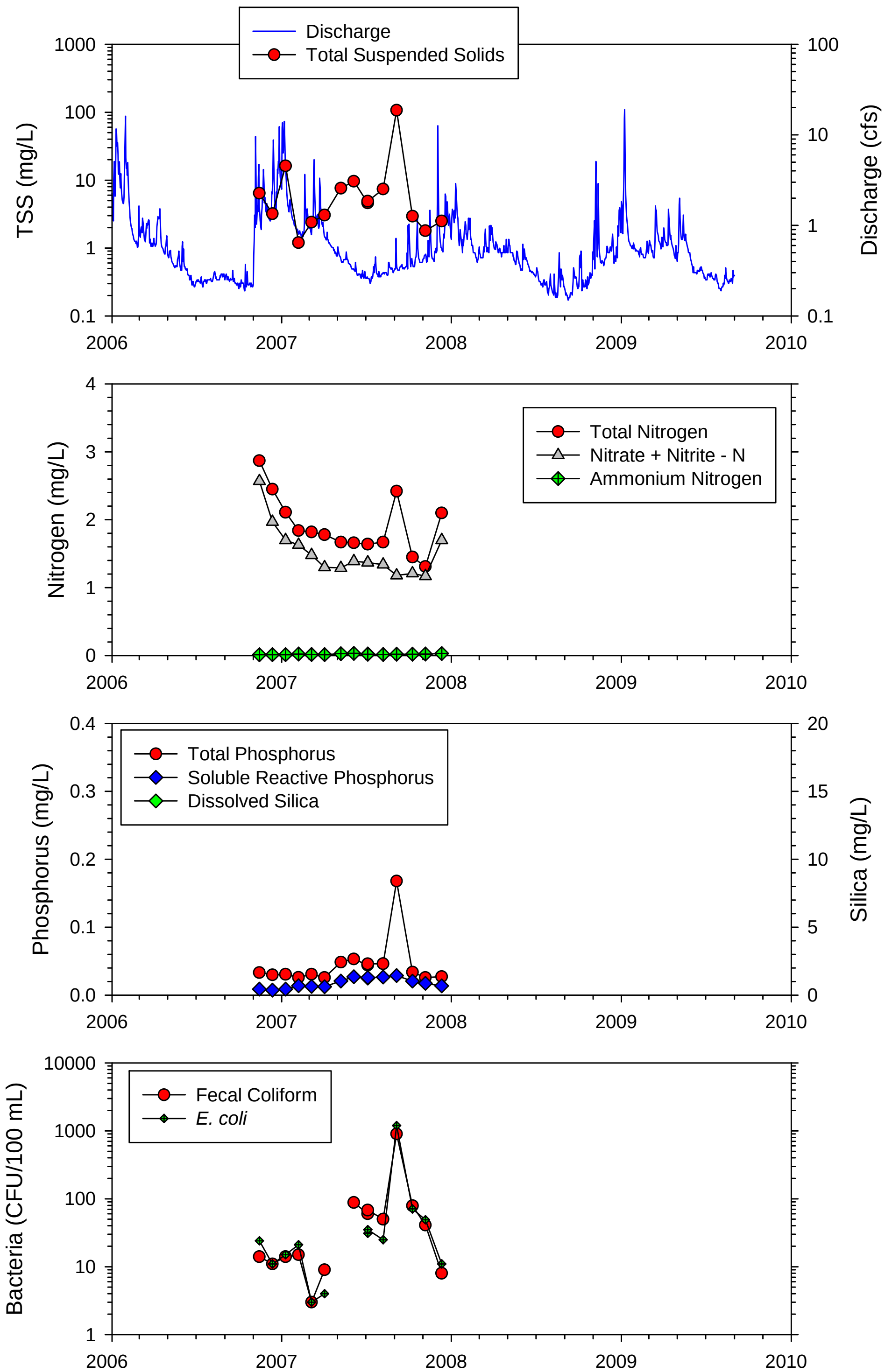

Figure 16. Graphs showing stream discharge (gauge 65A) and selected water quality data (station VA37A) for Tahlequah Creek.

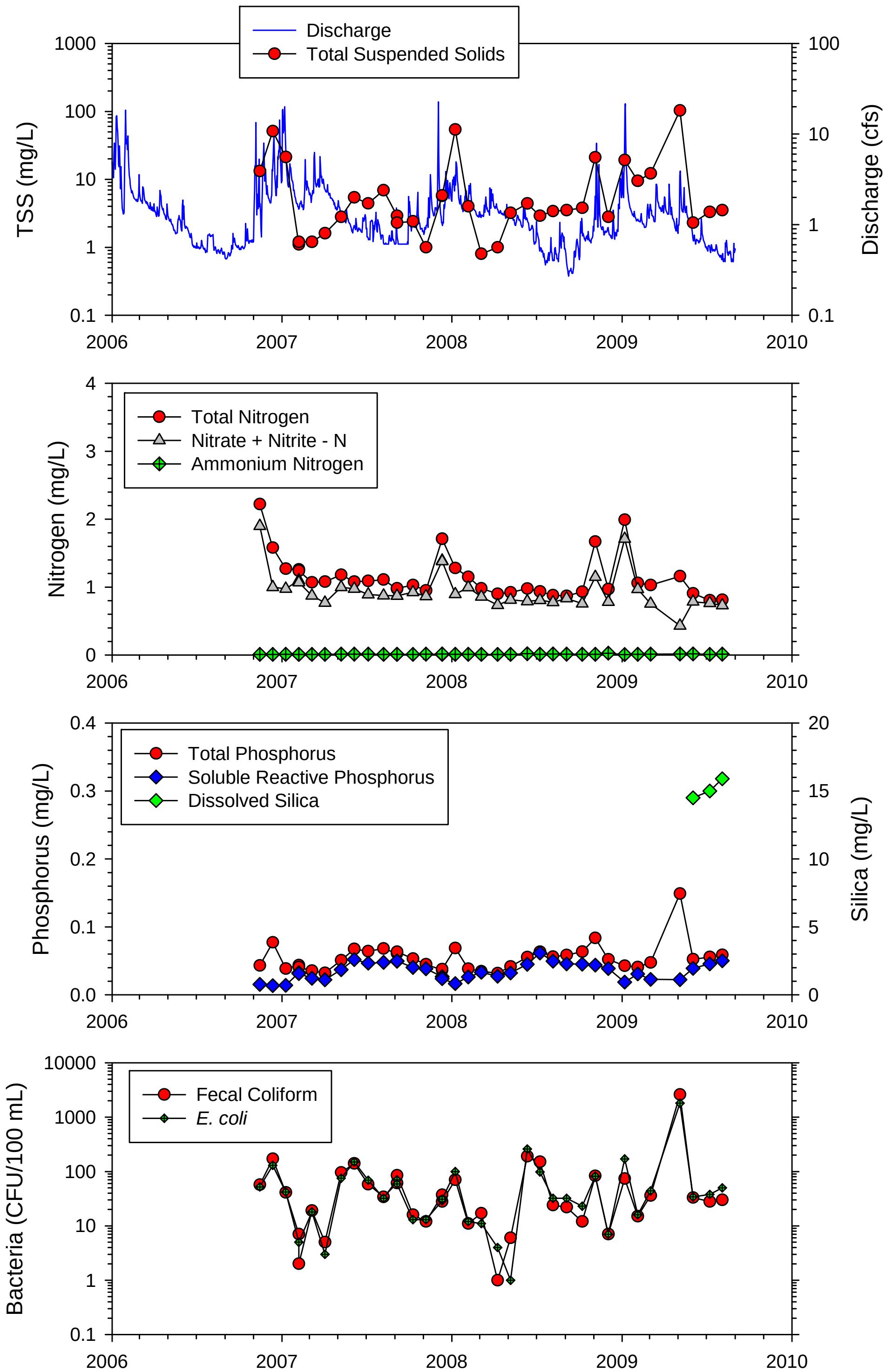

Figure 17. Graphs showing stream discharge (gauge 43a) and selected water quality data (station VA12A) for Shingle Mill Creek.

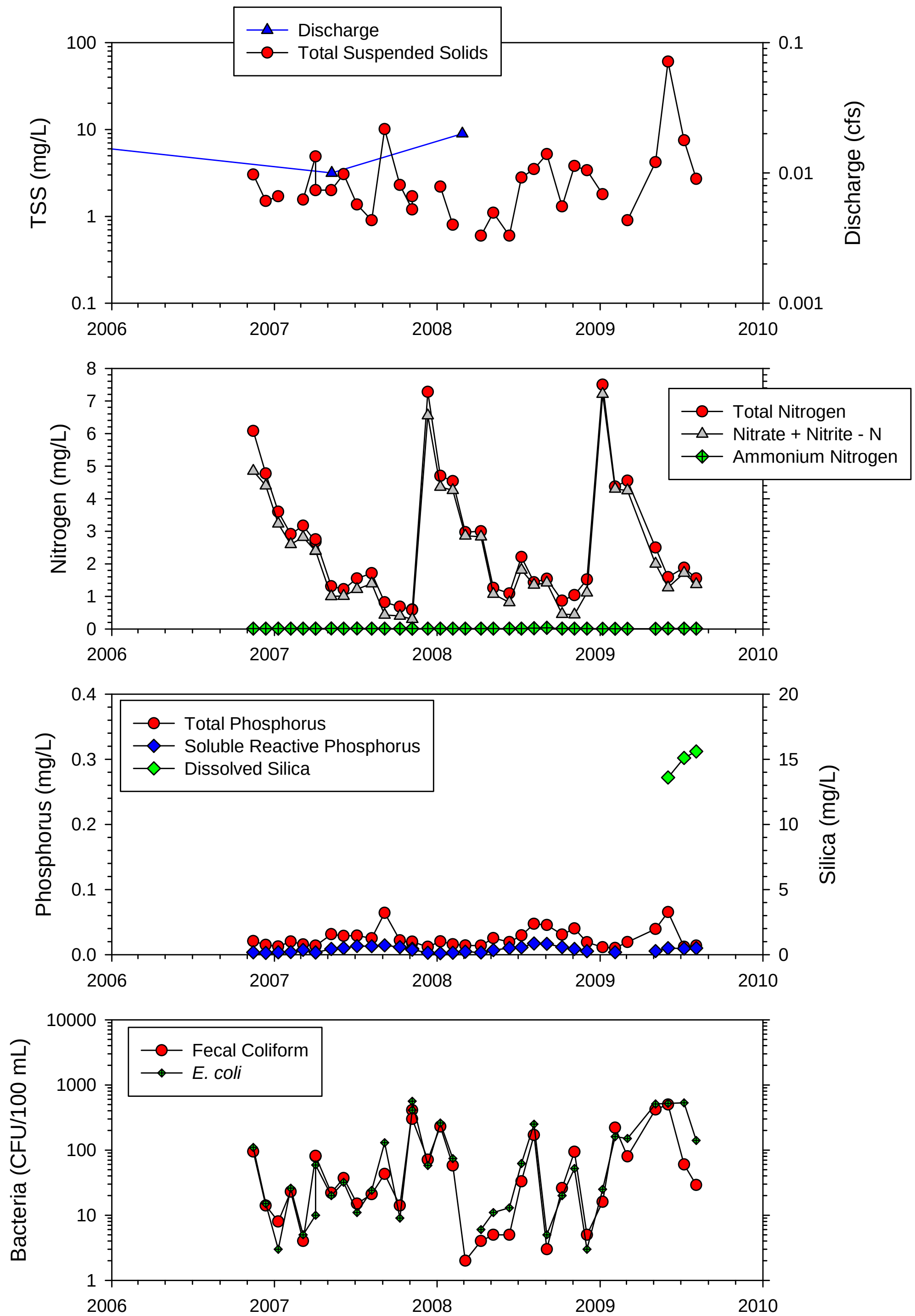

Figure 18. Graphs showing instantaneous stream discharge and selected water quality data (station VA45A) for Mileta Creek.

Table 7 provides the estimated stream loading based on the average areal loading estimates above and the area of remaining ungauged drainage to Quartermaster Harbor. Because Judd, Fisher, and Mileta Creek represent about half of the terrestrial drainage area to the harbor, the contribution from the ungauged area represents about half of the nutrient load to the harbor. The lack of observed flow data for Mileta Creek also adds some additional uncertainty to the loading estimate for this creek, which contributes much more nitrogen relative to its contributing drainage area due in part to the very high winter nitrate concentrations observed in that creek.

Table 7. Average nutrient loading estimates for Judd Creek, Fisher Creek, Mileta Creek and unmonitored drainages to Quartermaster Harbor for the period 2007-2008.

	TN	Org N	NO3-N	NH4-N	TP	Org P	SRP	DSi
				(kg/d)				
Judd Creek	17.4	4.8	12.5	0.15	0.65	0.40	0.25	72.3
Fisher Creek	5.7	1.3	4.3	0.04	0.26	0.14	0.12	29.8
Mileta Creek	4.5	0.5	3.9	0.02	0.03	0.02	0.01	8.2
Unmonitored Drainages	24.4	5.3	18.8	0.32	0.86	0.44	0.42	104.8
Total	52.0	11.9	39.5	0.53	1.80	1.00	0.80	215.1

3.3 Regional Groundwater Inputs

The annual water balance components for 2007 and 2008 for the drainage area to Quartermaster Harbor are summarized in Table 8.

Table 8. Annual water balance and estimate of groundwater input from the Vashon and Maury portions of the drainage to Quartermaster Harbor 2007-2008.

Groundwater Budget Components	Inches
A. Precip	37.6
B. ET	20
C. Runoff (island-wide avg)	15
D. Consumptive Use	0.4
D. Groundwater (D = A – B – C – E)	2.2
	cubic feet per second (cfs)
E. Groundwater	2.5

Based on the drainage area for the Vashon and Maury portions of the land surface draining to Quartermaster Harbor (29.0 and 10.4 km^2, respectively), the annual groundwater input in inches translated into a flow rate of 2.5 cfs. Following Paulson et al. (2007), the groundwater flow estimate is compared to annual groundwater flow estimates to Puget Sound from Vaccaro et al. (1998), which ranged from about 100 to 1000 cfs over a recharge area of 1,460 mi^2 (the area excluding major alluvial valleys that do not discharge to saltwater–see Vaccaro et al. 1998 p. D59). This translates into a groundwater flow rate of 0.068 to 0.684 cfs mi^{-2}. Based on the drainage area to Quartermaster Harbor (~15.2 mi^2), this results in an estimate of between 1.0 to 10.4 cfs (0.038 to 0.152 $m^3\ s^{-1}$), which brackets the initial Quartermaster Harbor groundwater estimate of 2.5 cfs.

The groundwater nutrient data collected from shallow wells throughout the island identified in Table 1 are summarized graphically in Figure 19 through Figure 24. All of the available data were used in this analysis because only four shallow wells occur in the Quartermaster Harbor drainage and there is no indication that large scale gradients in nutrient concentrations occur across the island, but rather that levels in any particular well (at least shallow ones) represent local influences and therefore best represents the potential range and central tendency of nutrient concentrations in shallow and deep groundwater within the Quartermaster Harbor drainage basin. The median nutrient concentrations based on the long term monitoring data are provided in Table 9 and associated loading estimates based on the flow and concentration data are presented in Table 10.

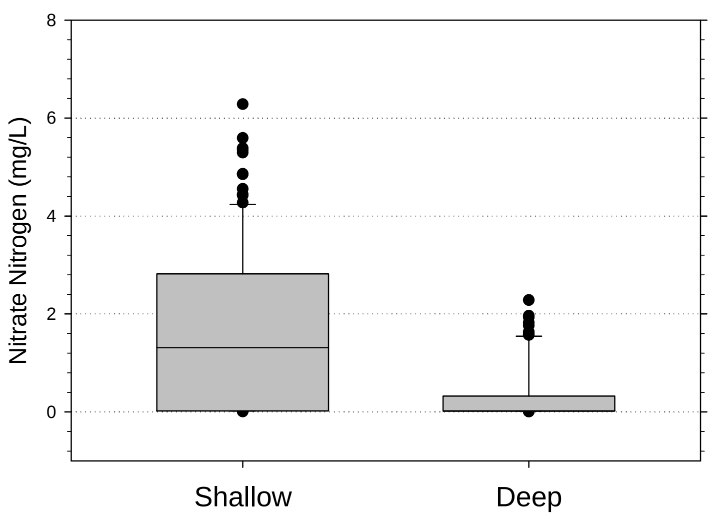

Figure 19. Box plot showing shallow and deep groundwater concentrations of nitrate nitrogen.

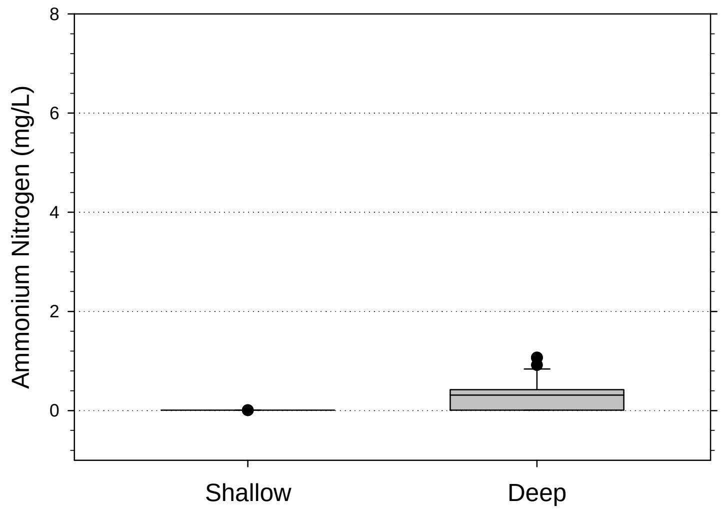

Figure 20. Box plot showing shallow and deep groundwater concentrations of ammonium nitrogen.

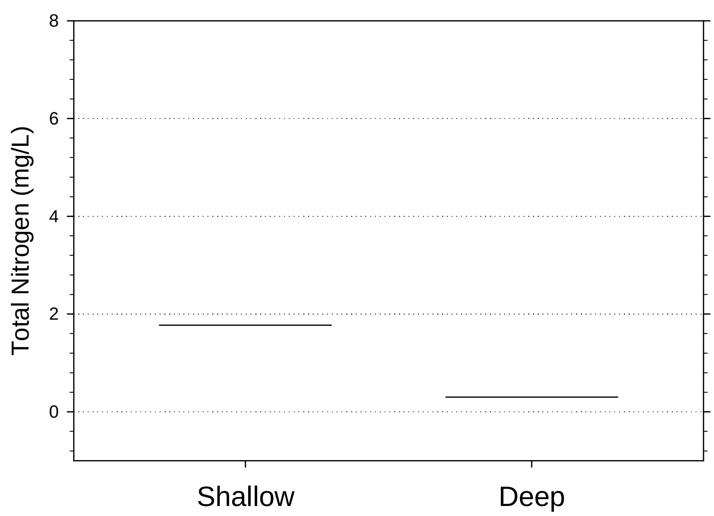

Figure 21. Box plot showing shallow and deep groundwater concentrations of total nitrogen.

Note: Total nitrogen analysis in groundwater samples did not begin until 2009.

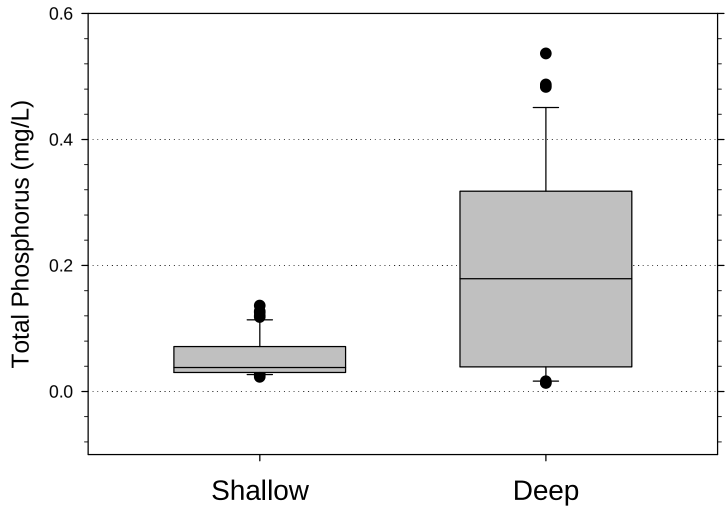

Figure 22. Box plot showing shallow and deep groundwater concentrations of total phosphorus.

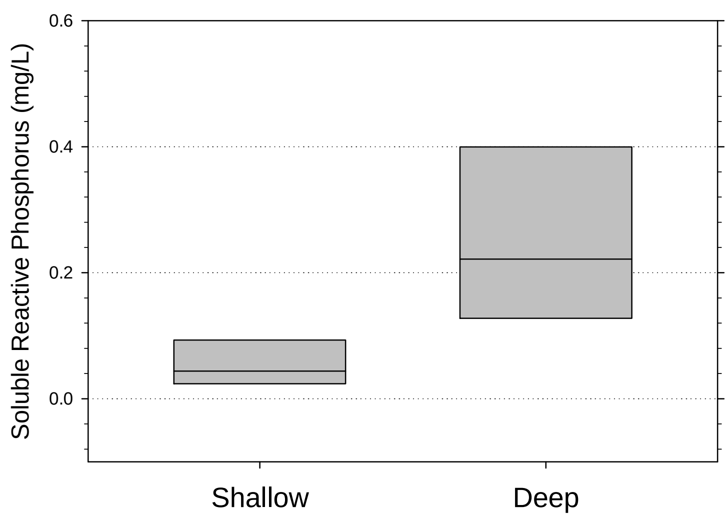

Figure 23. Box plot showing shallow and deep groundwater concentrations of soluble reactive phosphorus.

Note: Soluble reactive phosphorus analysis in groundwater samples did not begin until 2009.

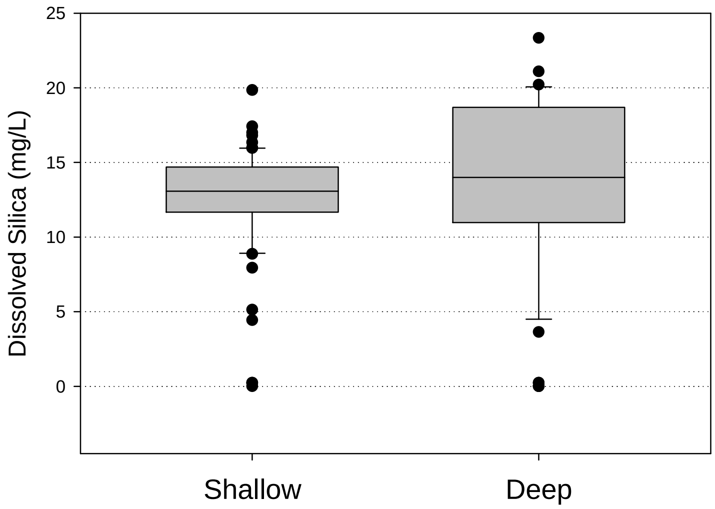

Figure 24. Box plot showing shallow and deep groundwater concentrations of dissolved silica (as Si).

Note that nitrate concentrations are generally higher in shallow groundwater, which is consistent with our understanding of the fate and transport of surface nitrogen inputs (Korom 1992) and very similar to the concentrations observed in island streams during the late summer when groundwater contribution to streamflow is significant. Ammonium concentrations are generally higher in deeper groundwater relative to the shallow system–ammonium is consistently at the detection limit in shallow groundwater, but has a median concentration of 0.3 mg N/L in deep groundwater. This may be due to dissimilatory nitrate reduction to ammonium under the conditions that occur in the deep groundwater system (Korom 1992).

Total and soluble reactive phosphorus also occur in higher concentrations in the deeper aquifer systems of the island. In general, the total phosphorus measured is equivalent to the soluble form because the phosphorus must be soluble in order to be transported in the water phase. Higher concentrations in deep groundwater are likely due to the relatively lower oxygen conditions there which favor reduced forms of iron that would otherwise precipitate and bind phosphorus to aquifer solids under more oxygenated conditions. Dissolved silica seems to be less influenced by surface sources and/or oxygen conditions and is found in similar concentrations between surface and groundwater.

Table 9. Estimated groundwater nutrient concentrations based on median of observed values in Vashon-Maury Island monitoring wells.

	TN	Org N	NO3-N	NH4-N	TP	Org P	SRP	DSi
				(mg/L)				
Shallow	1.3	0.0	1.3	0.0	0.040	0.0	0.040	13.1
Deep	0.3	0.0	0.0	0.3	0.220	0.0	0.220	14.0

Table 10. Annual average nutrient loading estimates for groundwater for the period 2007-2008.

TN	Org N	NO3-N	NH4-N	TP	Org P	SRP	DSi
			(kg/d)				
8.0	0.0	8.0	0.0	0.2	0.0	0.2	80.2

3.4 Shallow Subsurface Flow from Shoreline Septic Systems

Based on the 2000 Census Block data, there are 1,187 people living year-round in 503 households along the shores of Quartermaster Harbor. This indicates that there is an average of 2.36 people per household along the shores of Quartermaster Harbor.

Based on the current parcel data in the King County parcel database, there are 546 occupied and 276 vacant households along the shore of Quartermaster Harbor. When combined with the average number of people per household of 2.36, the year-round population is estimated to be 1,288. Using the per capita effluent volume of 193 Liters per day (51 gallons per day) and the septic drain field nutrient concentrations provided in Table 2, results in the annual nutrient loading estimates provided in Table 11. Although Paulson et al. (2007) included an estimate of summer loading due to increased occupancy of nearshore homes during the summer (using a summer occupancy factor of 1.75), we suggest that although some additional occupancy of nearshore homes along Quartermaster Harbor occurs, this increase is likely smaller than that assumed for Hood Canal and that the current estimates which range over a factor of two likely encompass estimates based on increased summer occupancy.

Table 11. Annual average nutrient loading estimates for nearshore septic systems.

	DIN	NO3-N	NH4-N	SRP	DSi
			(kg/d)		
Minimum	2	0	2	1.5	0
Maximum	19	0	19	2.2	0
Average	11	0	11	1.9	0

3.5 Benthic Nutrient Flux

Based on the estimated bottom surface area of the harbor (13.8 km^2) and the average nutrient fluxes measured as part of Ecology's South Puget Sound Study (in Table 3 above) results in the loading rates shown in Table 12. Because the Ecology flux studies were performed in late summer when nutrient flux is expected to be highest due to the combination of elevated temperatures and lower bottom water dissolved oxygen levels, these flux estimates should be considered likely overestimates of annual average flux. However, they are likely a good first approximation of later summer sediment nutrient flux during the period when harbor dissolved oxygen concentrations are lowest.

Table 12. Initial benthic nutrient flux loading rate estimates for Quartermaster Harbor

TN	DIN	Organic N	TP	SRP	DSi
		(kg/d)			
1176	720	526	346	332	2768

Note: Likely only representative of Sep-Oct benthic flux

4.0. SUMMARY AND CONCLUSIONS

Initial annual average nutrient loading estimates for Quartermaster Harbor have been developed primarily from available local and regional data sets and estimation approaches. Some of these estimates can be converted readily into seasonal and/or monthly estimates (e.g., tributary stream and atmospheric loading), while the methods used to develop other estimates will not allow for incorporation of seasonality in their inputs (e.g., nearshore septic load). The benthic flux estimate is only representative of the September-October period, although this also corresponds with the most critical period when algal growth and subsequent die-off results in low dissolved oxygen conditions in the harbor.

These initial estimates should also be viewed as just that–estimates. Uncertainties in the calculation methods, assumptions, and data are inherent in all of the calculations used to derive these estimates, but an attempt has been made to document the methods, assumptions, and data used as clearly as possible so reviewers can check our approaches and perhaps suggest improvements that could be made in the interest of reducing the uncertainty of our loading estimates.

In addition to the uncertainty associated with the data and calculations, another consideration is the representativeness of the initial period selected for analysis (primarily 2007-2008). In general, 2007 was a relatively normal year for precipitation, while 2008 was a particularly dry year (Figure 25). It is uncertain how nutrient loading from streams, groundwater, and the atmosphere respond to inter-annual variability in precipitation. Interannual variability in loading should be included in future loading estimates refined from this initial study.

The compiled nutrient loading to Quartermaster Harbor from the five sources evaluated in this report are summarized in Table 13.

Table 13. Estimated nutrient loading to Quartermaster Harbor from the atmosphere, surface streams, groundwater, nearshore septic systems, and harbor sediments

	TN	Organic N *	DIN	NO3-N	NH4-N	TP	Organic P *	SRP	DSi
					(kg/d)				
Atmospheric	33.6	28.9	4.7	3.3	1.3	1.0	0.5	0.5	23
Stream Inputs	52.0	11.9	40.0	39.5	0.5	1.8	1.0	0.8	215
Groundwater	8.0	0.0	8.0	8.0	0.0	0.2	0.0	0.2	80
Nearshore Septics	11	0	11	0	11	2.6	0	1.9	0
Benthic Flux	1176	526	720	-	-	346	12	332	2768

* The organic nitrogen deposition rate based on data from Pyrch and Ebbert (1986) was used to estimate organic N and Total Nitrogen (TN) inputs. Organic P was assumed to be 50% of the Total Phosphorus deposition estimate of Pyrch and Ebbert (1987).

Figure 26 shows the relative annual external contributions of DIN, because dissolved nitrogen is the primary nutrient of concern in Quartermaster Harbor. On an annual basis, stream inputs are the largest source of DIN (~68 %). The second largest source is estimated to be nearshore septic systems (~17 %). Atmospheric deposition and groundwater inputs are estimated to contribute 7 and 13 percent, respectively, on an annual basis.

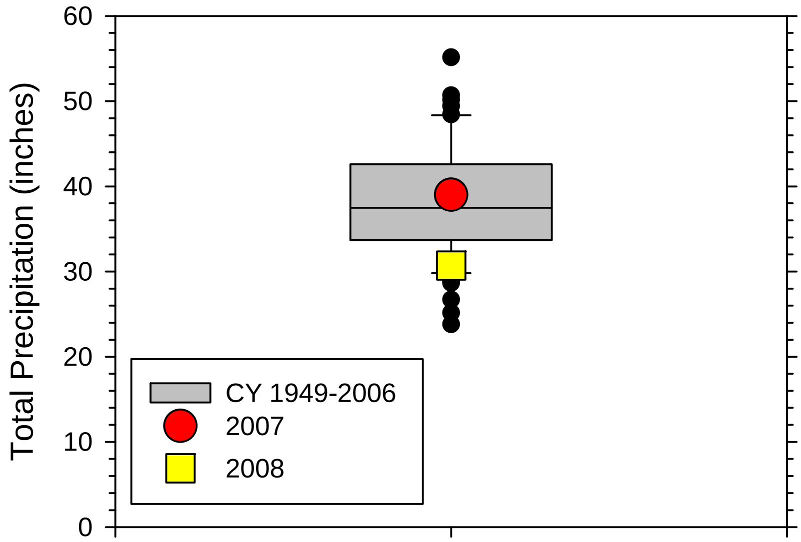

Figure 25. Box plot of annual (calendar) year precipitation measured at Seattle-Tacoma International Airport over the period 1949-2006.

Note: Total precipitation recorded in 2007 and 2008 shown for comparison to the long term record.

The estimated benthic flux based on studies conducted in similar shallow embayments in South Puget Sound (Roberts et al. 2008) indicates a DIN contribution in late summer from Quartermaster Harbor sediments that is almost 20 times higher than the largest estimated external source (tributary streams) (see Table 13). In general, stream flow and DIN concentrations are lowest during late summer, so the relative contributions from the other external sources are likely to be relatively more significant than indicated in this annual summary.

The largest estimated external source of SRP is nearshore septic systems, which were assumed to have no attenuation of soluble phosphorus (or nitrogen) inputs (Figure 27). The next largest source of SRP was estimated to be tributary streams. Again, estimated SRP input from benthic nutrient release from harbor sediments during late summer is estimated to be potentially much larger than all other external sources–over two orders of magnitude higher (see Table 13).

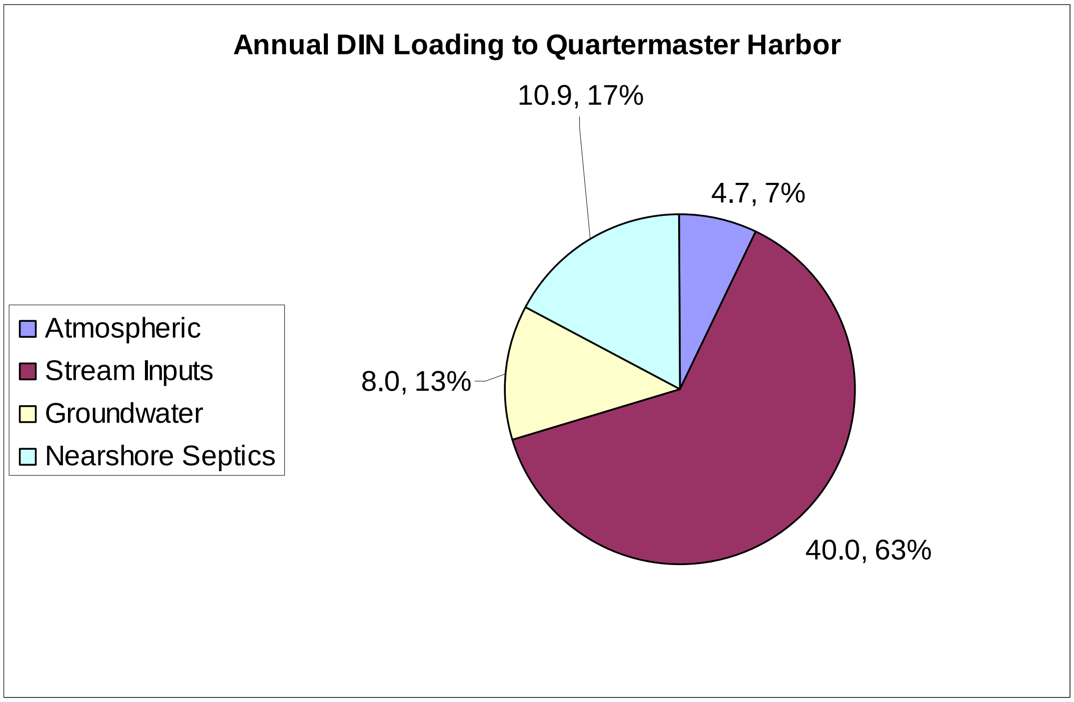

Figure 26. Pie charts showing the relative contribution of various external dissolved inorganic nitrogen (DIN) sources to Quartermaster Harbor

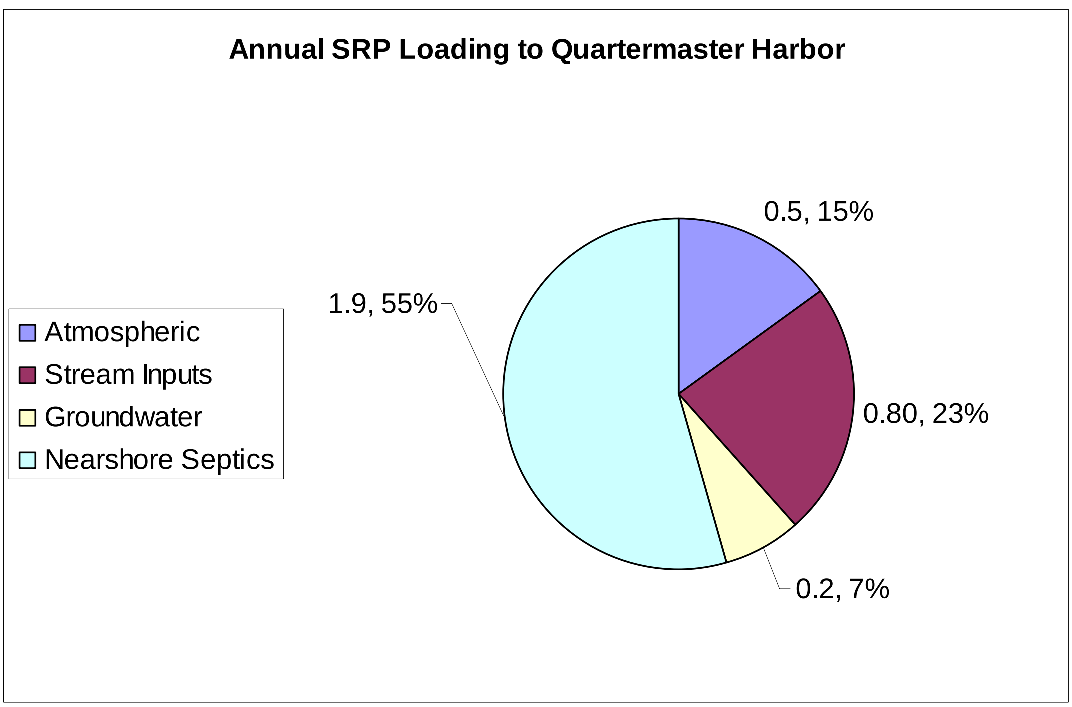

Figure 27. Pie charts showing the relative contribution of various external soluble reactive phosphorus (SRP) sources to Quartermaster Harbor

Stream inputs were estimated to be the largest external source of dissolved silica to Quartermaster Harbor (~ 68% of the total load), with groundwater input contributing an estimated 25 percent.) (Figure 28). Atmospheric input was estimated to contribute about 7 percent and nearshore septic systems were assumed not to contribute dissolved silica to the harbor. The estimated benthic flux of silica also suggested that sediments could be a significant source of this nutrient during late summer–potentially over an order of magnitude higher than the contribution from streams (see Table 13).

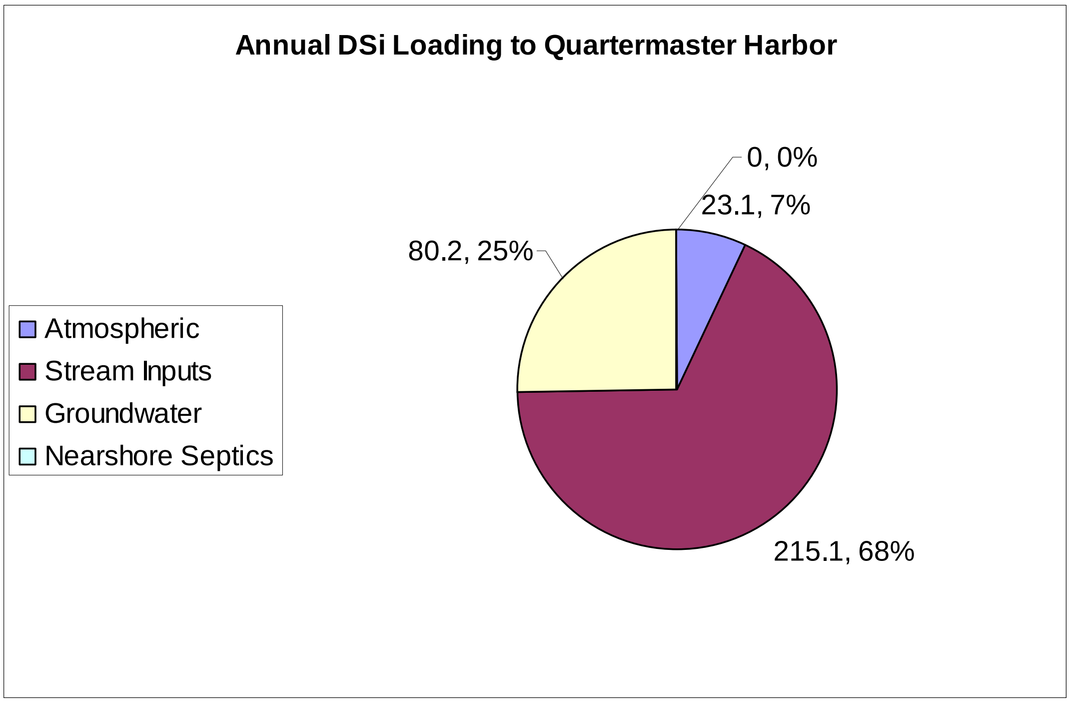

Figure 28. Pie charts showing the relative contribution of various external dissolved silica (DSi) sources to Quartermaster Harbor

5.0. RECOMMENDATIONS

Although our initial estimates indicate that harbor sediments are potentially the largest source of nutrients to the harbor during the critical low dissolved oxygen period in late summer, Paulson et al. (2007) and Steinberg et al. (unpublished manuscript) determined that DIN input from Puget Sound into Hood Canal via estuarine circulation was by far the largest source of DIN to that system during summer. Their estimates required current meter and salinity profiling data at the mouth and within Hood Canal in order to estimate the subsurface transport of nitrogen into the canal and subsequent upwelling into the surface waters where it would become available for algal growth. A current meter study has been conducted in Quartermaster Harbor (King County 2009b) with the goal of combining current meter profiling data with available salinity profiling data to estimate and model the contribution of DIN from the marine waters outside the harbor to phytoplankton growth within the harbor. It is recommended that the results of calculations of loading of nitrogen, phosphorus, and silica based on data and/or modeling be presented in an update of this report.

Benthic flux of nutrients in late summer appears to be a potentially significant source of nutrients to the harbor, but this is based on data collected from other locations in Puget Sound. Although not currently part of the Quartermaster Harbor Nitrogen Management Study scope of work, more direct measurements made in Quartermaster Harbor will likely reduce the uncertainty associated with using measurements from other locations and provide site specific data that can be used in development and testing of the water quality model that will be developed as part of this study. It is recommended that a scope and budget for a benthic flux study of Quartermaster Harbor be conducted during the first quarter of 2010.

Although discharge and water quality data were available for a number of streams on VMI, only two tributary streams to Quartermaster Harbor are monitored for flow and water quality. Tributary streams were generally found to be a significant external source of DIN to Quartermaster Harbor, but only above half of the drainage to the harbor is directly monitored. One other creek that discharges to Quartermaster Harbor, Mileta Creek, is monitored for water quality but not flow. High nitrate concentrations have been observed in Mileta Creek during winter, but it is not possible to accurately calculate the load contributed from this creek without additional flow data. It is recommended that a scope and budget for continual flow gauging on Mileta Creek be developed. It is also recommended that a scope and budget for attempting to trace the source of the elevated nitrate in Mileta Creek be developed. A plan for sampling the large number of unmonitored sources identified along the shoreline of Quartermaster Harbor–at least the largest unmonitored tributaries–should be developed for implementation in late summer 2010. Figure 29 shows the locations of unmonitored freshwater inputs to Quartermaster Harbor based on surveys conducted by Anchor Environmental (2004) and Coastal Geologic Services (2005) that identified small freshwater streams and outfalls to shoreline areas, including Quartermaster Harbor.

To a large extent, the nutrients contributed by human activity in the Quartermaster Harbor drainage basin are represented by the estimated loads from tributary streams and groundwater–as well as nearshore septic systems. In order to develop management recommendations, estimates of the relative nutrient contributions from upland septic systems, nitrogen fixation by alder, livestock and domestic animal manure, and fertilizer application will be needed. Available data are currently being compiled that will provide inputs to estimates of inputs of these sources to surface and groundwater draining to Quartermaster Harbor.

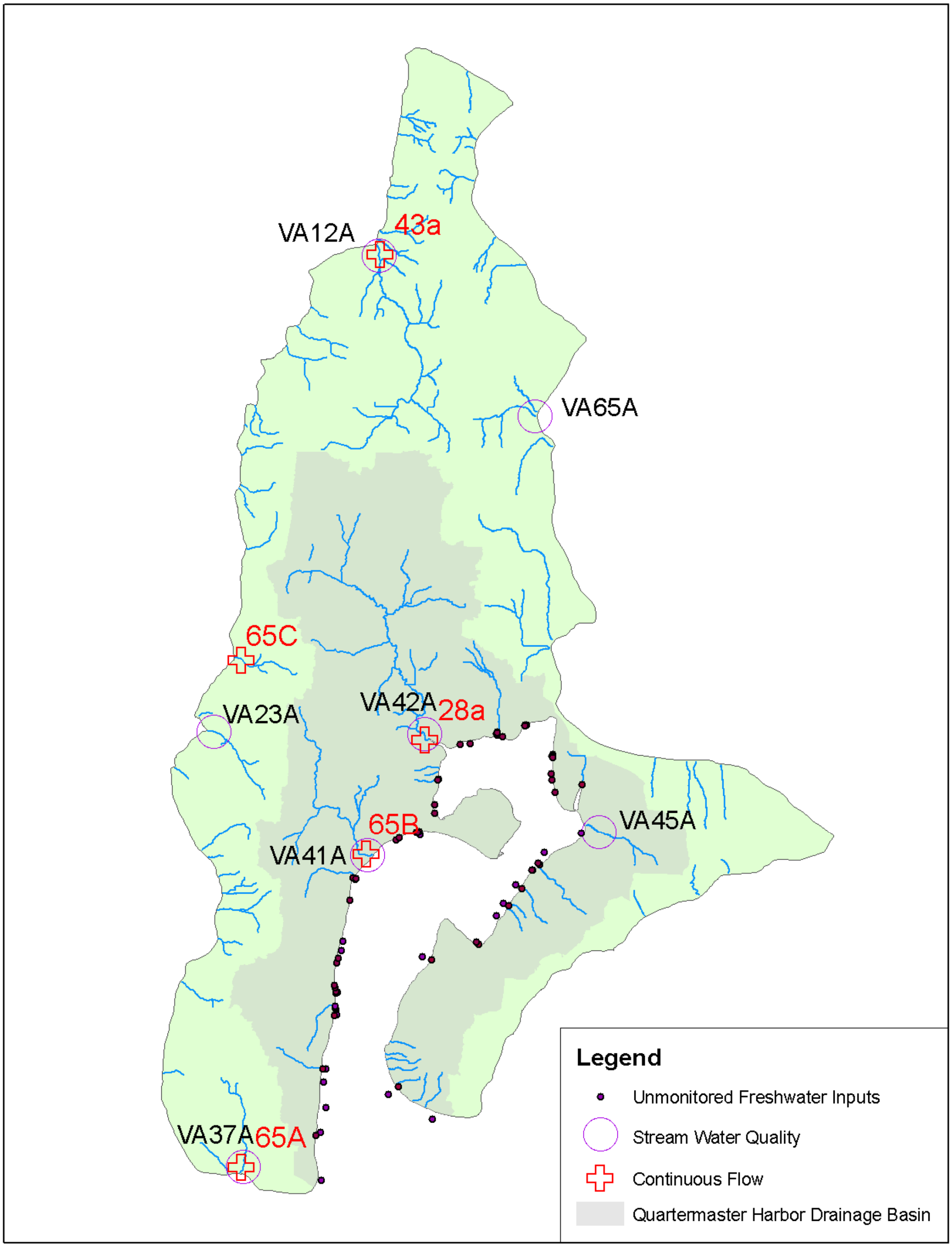

Figure 29. Map showing documented locations of freshwater inputs to Quartermaster Harbor.

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