Quartermaster Harbor Nitrogen Management Study: Final Study Report

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Quartermaster Harbor Nitrogen Management Study: Final Study Report

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

Submitted by:
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King County
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Former members: John Gerstle,Donna Klemka, Yvonne Kuperberg

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EXECUTIVE SUMMARY

In 2008, Region 10 of the United States Environmental Protection Agency (EPA) awarded King County a West Coast Estuaries Initiative (WEI) grant to conduct the Quartermaster Harbor Nitrogen Management Study, which was funded through the end of 2013. The overall purpose of this study was to determine how nitrogen from a variety of sources, including humans, affects dissolved oxygen levels in Quartermaster Harbor.

The expected long term outcomes were improved water quality management policies in the King County Comprehensive Plan and the protection and enhancement of water quality in Quartermaster Harbor. In addition, the effect of human inputs of nitrogen on dissolved oxygen levels in Puget Sound, including Hood Canal and other shallow embayments like Quartermaster Harbor, have been the subject of research and policy development for almost four decades. This study contributes to that body of knowledge.

Partners working with King County on this grant-funded study included the University of Washington-Tacoma (UWT) and the Washington Department of Ecology (Ecology). This project supported the enhancement of aquatic resource protection in an area threatened by population growth pressures. This final report summarizes the work conducted as part of the Quartermaster Harbor Nitrogen Management Study and provides an overview of study findings. Detailed findings on specific topics are contained in other project reports.

Summary of Work Completed in the WEI grant

The work products completed as part of this study included the following:

- Quality Assurance Project Plan (QAPP) to identify project tasks, field and laboratory methods and quality control procedures, and deliverable schedule
- Individual QAPPs for specific project tasks, including harbor current meter deployment, marine sediment benthic flux study, nearshore freshwater nitrogen inputs study, Mileta Creek nitrogen source tracking study, and development of hydrodynamic and water quality model of the harbor
- A number of reports documenting the tasks that were accomplished, including:
    - Initial Assessment of Nutrient Loading to Quartermaster Harbor (2010)
    - Quartermaster Harbor Nearshore Freshwater Inflows Assessment (2012)
    - Mileta Creek Nitrogen Source Tracking Study (2012)
    - Quartermaster Harbor Benthic Flux Study (2012)[1]
    - Hydrodynamic Model Report. Quartermaster Harbor Nitrogen Management Study (2013)

[1] Benthic flux refers to the biological and chemical processes that occur in sediments that result in uptake of oxygen (often referred to as sediment oxygen demand) and the release or uptake (flux) of nutrients between the water and sediment.

  - Quartermaster Harbor Marine Water Quality Data Report 2007-2011 (2014)
  - Vashon-Maury Island Water Resources – A Retrospective of Contributions & Highlights (2013)

- Monthly stream water quality data and continuous flow and temperature observations of important creeks, including Judd, Fisher and Mileta creeks
- Routine marine monitoring data and continuous mooring data at a number of stations located throughout the harbor, including stations at the Yacht Club in the inner harbor and at the Dockton marina in the outer harbor
- Public communication and outreach, primarily through public presentations and press releases (documented in Appendix A of this report)
- Recommended changes for incorporation into the 2012 update of the King County Comprehensive Plan (see Appendix A)

Some of the initial project objectives in the project work plan proved overly ambitious and were adjusted in consultation with EPA during the course of the project to better align the goals, objectives and resources of the study. The initial objectives to conduct a field study of onsite septic system (OSS) nitrogen removal effectiveness and a nitrogen source tracking study (using stable isotopes) were replaced with other focused studies that were more likely to be informative and successful. This work was reflected in the list of tasks completed above: harbor current meter study (used in calibration and testing of the hydrodynamic model), marine benthic flux study (to provide sediment nutrient release data specific to the harbor), freshwater inflows assessment (to evaluate the reliability of scaling nitrogen loading estimates) and the Mileta Creek nitrogen source tracking study (to attempt to identify the cause of seasonally elevated nitrate concentrations in this creek).

Although a hydrodynamic model (the first step in development of a receiving water quality model) of the harbor was developed as part of this study, the development of an adequately calibrated water quality model was not accomplished. A working water quality model was developed based on the hydrodynamic model, but project resources were not sufficient to fully calibrate and test the model. Therefore, the study did not determine the degree of human influence on dissolved oxygen concentrations nor evaluate the effectiveness of various nitrogen management scenarios. Nonetheless, this study does provide a solid foundation of information and a functioning, albeit un-calibrated, water quality model of the harbor that could be used by Ecology to develop a dissolved oxygen Total Maximum Daily Load study for Quartermaster Harbor – listed as Category 5 in Washington's 2012 list of impaired marine waters.[2]

[2] Category 5 - Polluted waters that require a TMDL or other Water Quality Improvement (WQI) project: the traditional list of impaired water bodies also known as the 303(d) list. Placement in this category means that Ecology has data showing that the water quality standards have been violated for one or more pollutants, and there is no TMDL or pollution control plan. TMDLs or other approved WQI projects are required for the water bodies in this category.

Summary of Study Results

This final study report summarizes freshwater (groundwater and surface water) inputs to Quartermaster Harbor, marine water quality and sources of nitrogen. It also provides recommendations for future studies to address management challenges.

Dissolved oxygen levels below the Washington State marine water quality standard (Washington Administrative Code 173-201A) have been observed in Quartermaster Harbor over the last seven years by King County. Oxygen concentrations are typically lowest in September or October. 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.

Algal biomass generally peaks during spring and summer in Quartermaster Harbor, which coincides with a reduction of nitrate concentrations to below the limit of laboratory detection as a result of algal uptake and growth. The minimum oxygen concentrations observed in late summer and fall are associated with the final decline in the summer peaks in algal biomass. These data provide evidence that phytoplankton growth in the harbor is limited by nitrogen and that additional inputs of nitrogen have the potential to fuel additional algal growth, causing even lower oxygen levels when the algae respire at night or die and are decomposed in the water column and sediments.

Historical data and information collected as part of this study suggest that human activity on Vashon-Maury Island has resulted in elevated surface and groundwater concentrations of nitrogen, particularly as nitrate. Increases observed in the most susceptible aquifers near the ground surface have not exceeded the drinking water maximum contaminant level (MCL) of 10 mg/L and concentrations appear to vary spatially to some degree in relation to susceptibility to contamination based on the Critical Aquifer Recharge Area (CARA) designations.

It is uncertain to what extent any particular source contributes to elevated nitrate concentrations in island freshwater systems, but sources include onsite septic systems, application of nitrogen containing fertilizer or manure, uncovered manure storage, animal manure/urine (urine is the primary source of nitrogen from animals, including humans) and red alder.[3] However, of these sources, onsite septic systems are clearly a contributor to nitrate in groundwater because they are designed to deliver soluble nitrogen below the soil surface to be diluted into the local groundwater system before reaching a stream or the marine shoreline. An onsite septic system does not need to fail in order to discharge inorganic nitrogen to groundwater and ultimately to receiving waters. Upgrading conventional septic systems, particularly systems along the shoreline limited by area and soil quality, would be costly. Development of local decentralized systems or connection to the existing centralized wastewater treatment system on the island is not a new idea and

[3] Red alder is a nitrogen fixing tree common in disturbed areas, including second and third growth forests.

was evaluated as recently as 2008 by King County (Harbor Communities Wastewater Management Options).[4]

There remains a great deal of uncertainty regarding the human contribution, particularly human activity on Vashon-Maury Island, to nitrogen and other factors that may cause low dissolved oxygen concentrations and harmful algal blooms in Quartermaster Harbor. The current best estimates of the relative contribution of nitrogen sources to the harbor developed as part of this study and information generated in other related studies of Puget Sound suggest that only a portion of the observed low dissolved oxygen in late summer is due to human influence. This is consistent with other studies in Puget Sound.

However, the state anti-degradation standard for dissolved oxygen is based on a determination of an explicit effect of no more than 0.2 mg/L decline in oxygen due to human influence. Determination of whether or not this threshold has been exceeded has been a challenge throughout Puget Sound, particularly for work conducted on this issue in Hood Canal.

The approach that is typically taken to determine the human contribution to the observed low oxygen levels, and one that was originally intended for this project, is to develop and calibrate a numerical eutrophication model and compare current condition and natural condition model scenarios to assess compliance with the anti-degradation standard for dissolved oxygen (no more than 0.2 mg/L decline due to human influence). This approach is challenging for a number of reasons, especially considering the occurrence of species of potentially harmful algae and complicated interactions with sediment and weather conditions. Managing water quality under this level of uncertainty presents challenges that should be acknowledged and addressed.

Additional scientific information that could help address some of these challenges in Quartermaster Harbor includes the following:

- Review current fresh and marine monitoring programs and recommend changes to ensure that sampling designs are robust to detecting change, particularly with respect to separating natural variability from anthropogenic effects
- Investigate the causes of fish kills, including analyses of key water quality and planktonic variables and analysis of fish tissues by pathologists
- Standardize and perform trend analysis of paralytic shellfish poison (PSP) monitoring data collected by the Washington State Department of Health
- Use the existing Ecology Puget Sound/Georgia Basin model to supply boundary conditions to the current Quartermaster Harbor hydrodynamic/water quality model or increase the resolution of the Puget Sound/Georgia Basin model within Quartermaster Harbor

[4] These planning efforts were intended to address concerns regarding contamination of shellfish beds with human pathogens now being addressed by the Marine Recovery Area (MRA) designation http://www.kingcounty.gov/healthservices/health/ehs/wastewater/mra/quartermaster.aspx

- Collect and analyze sediment cores to attempt to better identify the history of carbon, nutrients and phytoplankton (and levels of anoxia) since before extensive inhabitation and development
- Conduct a study that attempts to separate the relative contribution of alder, OSS, fertilizer and domestic animal waste to harbor nitrogen loading
- Develop groundwater susceptibility/vulnerability maps based on available nitrate data and land characteristics specific to Vashon-Maury Island

1.0 INTRODUCTION

In 2008, Region 10 of the United States Environmental Protection Agency (EPA) awarded King County a West Coast Estuaries Initiative (WEI) grant to conduct the Quartermaster Harbor Nitrogen Management Study, which was funded through the end of 2013. The goal of this study was to support the protection and restoration of Quartermaster Harbor–a high value, coastal aquatic resource on Vashon-Maury Island in Puget Sound. Partners working with King County on this grant-funded study included the University of Washington-Tacoma (UWT) and the Washington Department of Ecology (Ecology). This project supported the enhancement of aquatic resource protection in an area threatened by population growth pressures. This final report summarizes the work conducted as part of the Quartermaster Harbor Nitrogen Management Study and provides an overview of study findings.

1.1 Study Area

Quartermaster Harbor, located between Vashon and Maury Islands in Puget Sound, is sheltered from the wind and waves and receives runoff from about 40 percent of Vashon-Maury Island (Figure 1). It is a shallow embayment that comprises approximately 12.1 km^2 (3,000 acres) of water surface area in an inner and outer harbor. Inner Quartermaster Harbor is especially sheltered and Judd Creek, located in the northwestern portion of the inner harbor, is the largest freshwater input. Inner Quartermaster Harbor is shallow, with greatest depths of 5 to 6 m (16 to 20 ft) relative to mean lower low water. Outer Quartermaster Harbor water depths range from about 11 to 46 m (36 to 150 ft).

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. 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.[5]

The island is composed of glacially-derived sediment deposits. The predominant geology is glacial till. Glacial till covers approximately 68 percent of the island. The remaining 32 percent of the island is composed of glacial outwash and alluvial deposits. All of the island

[5] Washington Department of Natural Resources Maury Island Aquatic Reserve: http://www.dnr.wa.gov/ResearchScience/Topics/AquaticHabitats/Pages/aqr_rsve_maury_island.aspx

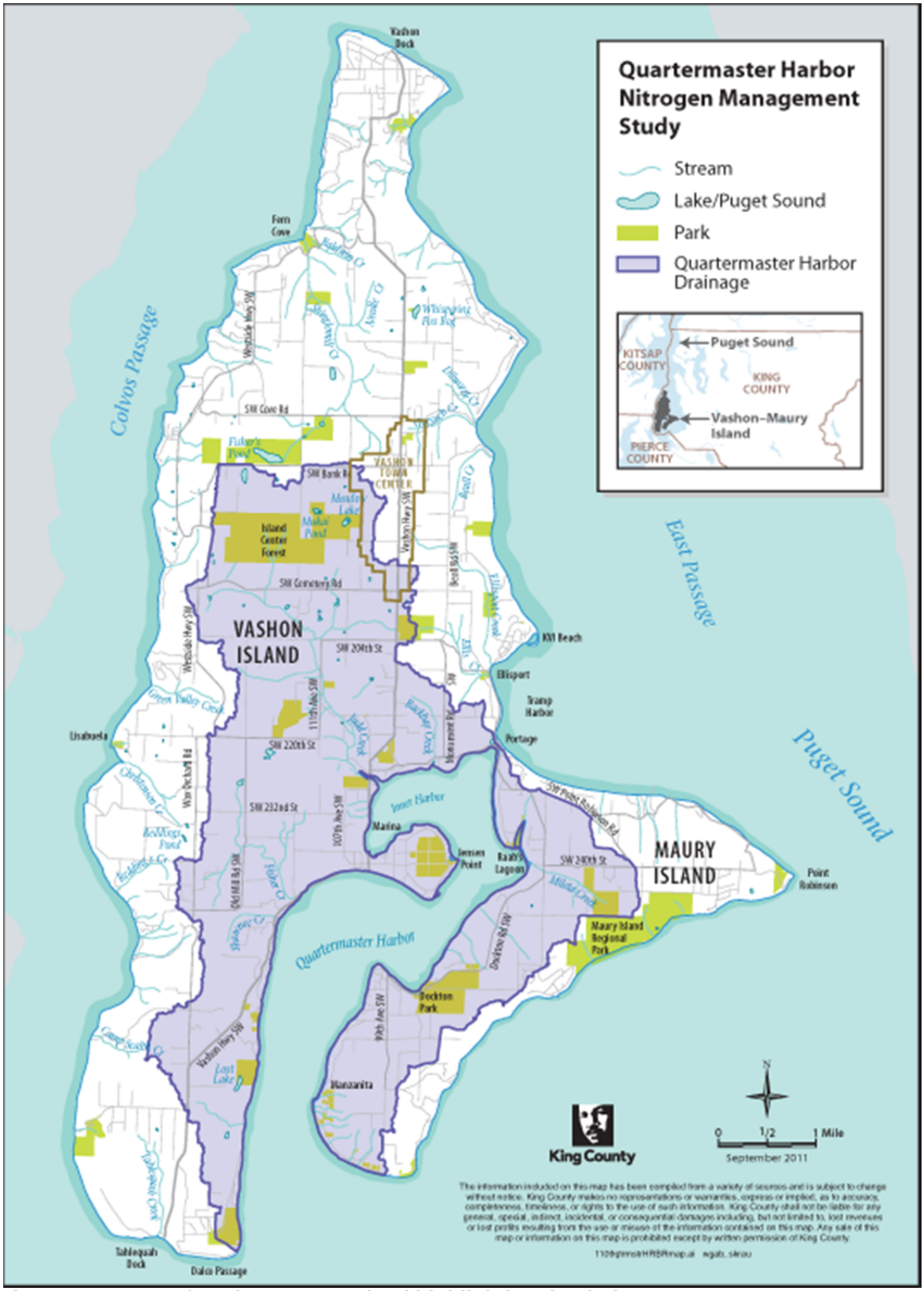

Figure 1. Map of Vashon-Maury Island highlighting the drainage area to Quartermaster Harbor.

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. Land cover is predominately forest with other cover being non-forest vegetation and developed land.

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 Vashon-Maury Island was certified by Ecology and the Vashon-Maury Island Groundwater Protection Committee (GWPC) was formed in 2001 along with a county-wide 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 2013a). In 2004, King County designated three categories of Critical Aquifer Recharge Areas (CARAs) for rural areas of the county including Vashon-Maury Island.[6]

Like much of rural Puget Sound, nearly all the residents in the study area treat domestic wastewater with onsite septic systems (OSSs). A watershed plan for Vashon-Maury Island 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 Vashon-Maury Island, including the western shoreline along outer Quartermaster Harbor as Marine Recovery Areas (MRAs) based on information indicating that shellfish harvesting in those areas was threatened or restricted because of contamination originating from septic systems.[7]

1.2 Project Overview

Dissolved oxygen levels below the Washington State marine water quality standard (Washington Administrative Code 173-201A) have been observed in Quartermaster Harbor over the last seven years by King County (Figure 2). Oxygen concentrations are typically lowest in September or October. 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.

Quartermaster Harbor was one of 19 areas of Puget Sound judged to be relatively sensitive to anthropogenic nutrient inputs (Rensel Associates and PTI 1991). Nitrogen and phosphorus are essential nutrients for marine plants and phytoplankton. Excess nutrients,

[6] For a description of the three CARA categories see http://your.kingcounty.gov/ddes/cao/Manual/II-CARA.pdf.
[7] See Public Health – Seattle and King County Vashon-Maury Island Marine Recovery Area (http://www.kingcounty.gov/healthservices/health/ehs/wastewater/mra.aspx).

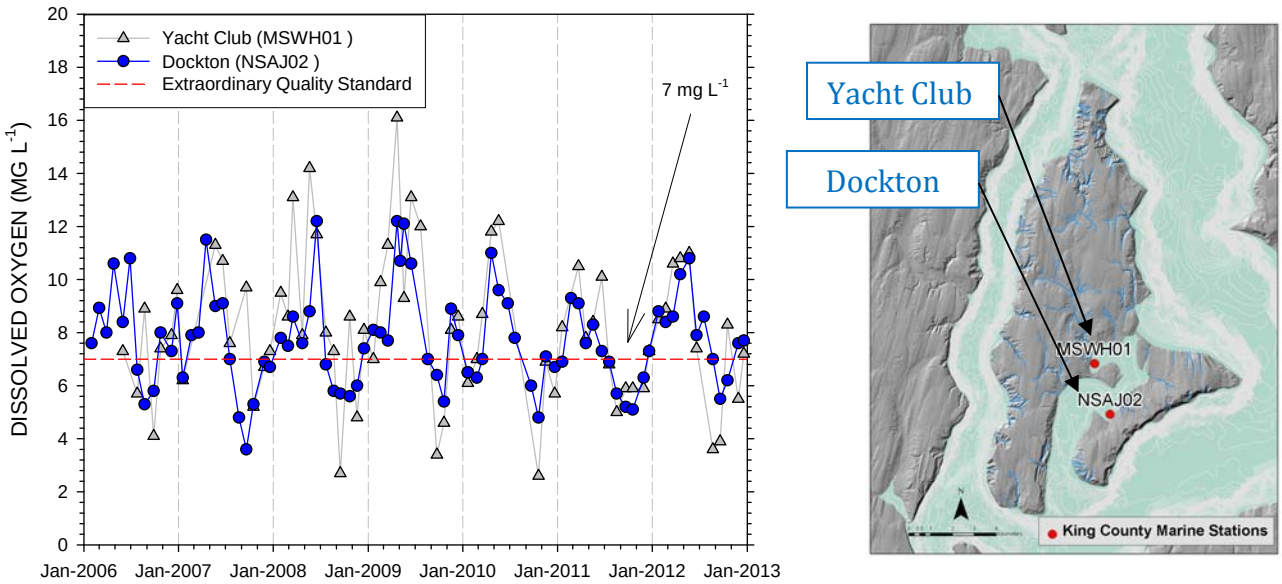

Figure 2. Monthly dissolved oxygen concentrations measured in bottom waters of Quartermaster Harbor by King County.

nitrogen compounds in particular, can lead to excessive phytoplankton and algae growth which can deplete oxygen concentrations when the algae respire at night or die and are decomposed by bacteria in the water column and sediments (Figure 3). 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).

The interactions between nitrate (the most abundant form of nitrogen available for phytoplankton growth), algal biomass and dissolved oxygen in inner Quartermaster Harbor are illustrated in Figure 4. Algal biomass generally peaks during spring and summer, which coincides with a reduction of nitrate concentrations to below the limit of laboratory detection as a result of algal uptake and growth. The minimum oxygen concentrations observed in late summer and fall are associated with the final decline in the summer peaks in algal biomass. These data provide evidence that phytoplankton growth in the harbor is limited by nitrogen and that additional inputs of nitrogen have the potential to fuel additional algal growth, causing even lower oxygen levels when the algae respire at night or die and are decomposed in the water column and sediments.

1.3 Goals and Objectives

The overall purpose of this study was to determine how nitrogen from a variety of sources affects dissolved oxygen levels in Quartermaster Harbor. The expected long term outcomes were improved policies in the King County Comprehensive Plan and the protection and enhancement of water quality in Quartermaster Harbor.

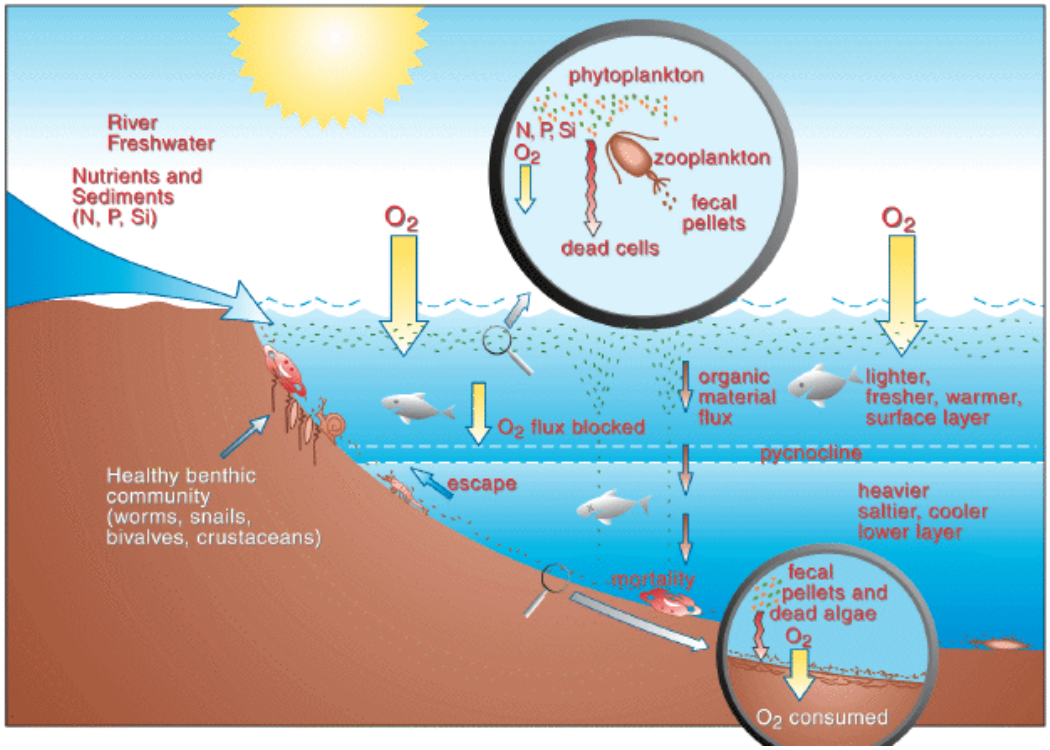

Figure 3. Conceptual diagram of marine nutrient-oxygen dynamics.

Source: Downing et al. (1999)

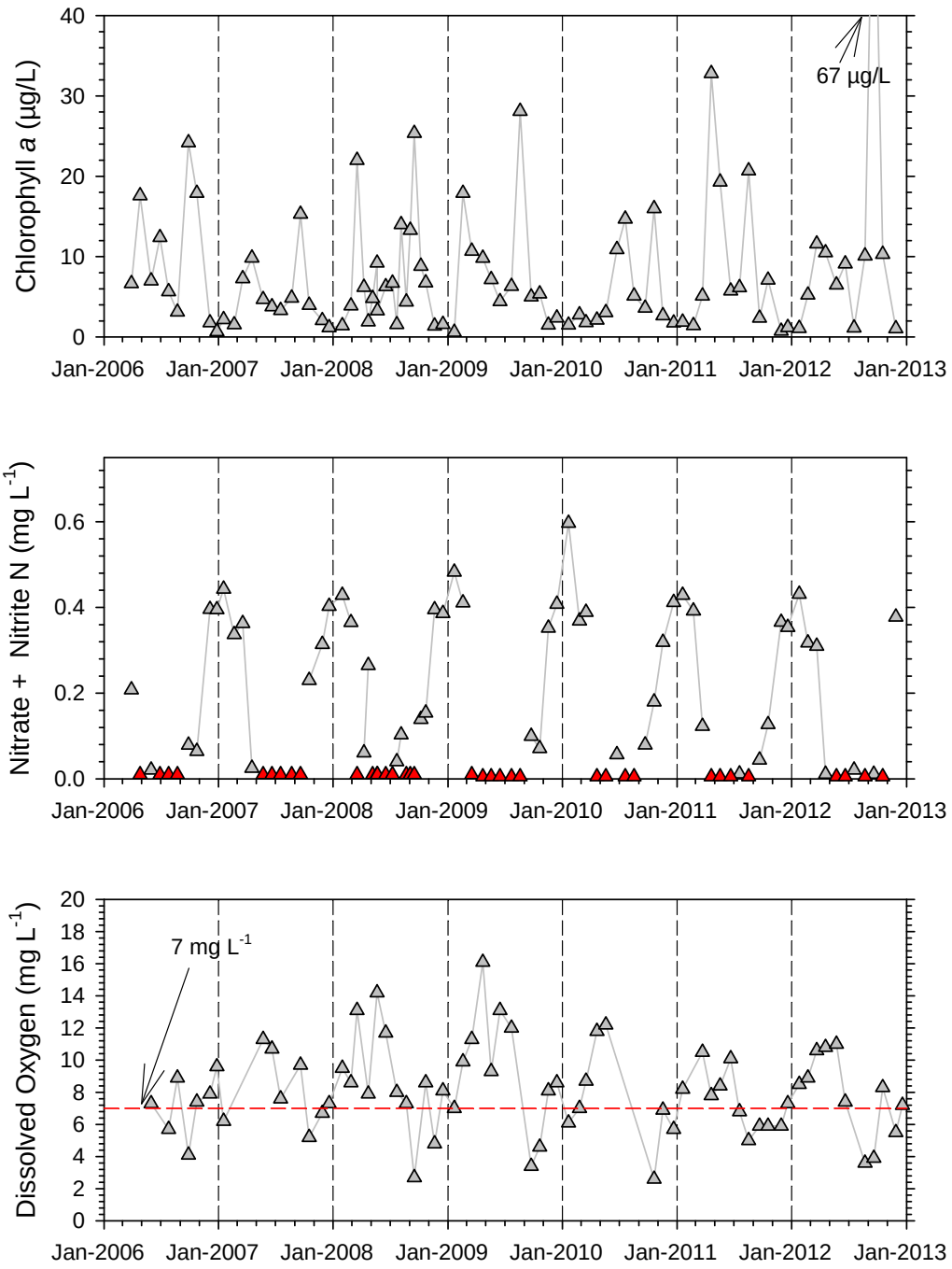

Figure 4. Monthly concentrations of surface water algal biomass (based on measurements of chlorophyll *a*), surface concentrations of nitrate nitrogen, and bottom water dissolved oxygen concentrations at the Yacht Club (Station MSWH01) in Inner Quartermaster Harbor.

Note: Red triangles in the center panel represent nitrate concentrations that were below the laboratory detection limit of 0.02 mg/L. The state standard for dissolved oxygen is shown as a dashed red line in the bottom panel.

Some of the initial project objectives described in the Quality Assurance Project Plan (King County 2009a) proved overly ambitious and were adjusted in consultation with EPA during the course of the project to better align the goals, objectives and resources of the study. For example, the initial study proposal included a field study of island OSS nitrogen removal effectiveness and a nitrogen source tracking study using stable isotopes. Upon further consideration and consultation with EPA and review of existing information, these studies were considered to be too experimental and/or too difficult to implement successfully, and were replaced with four other focused studies that were more likely to be informative and successful:

- Hydrodynamic study (current meter deployments) of the harbor to support the development and testing of a marine circulation/hydrodynamic model (King County 2009b)
- Marine benthic flux study to provide local estimates of sediment nutrient release during the critical period of low dissolved oxygen (King County 2010a)
- Nearshore freshwater inputs study to provide information on the nutrient levels and inputs from small, previously unmonitored tributaries and outfalls to the harbor (King County 2010b)
- Mileta Creek nitrogen source tracking study to provide more information regarding seasonally high nitrate levels in this creek (King County 2010c)

Estimates of nitrogen loading directly to the harbor were developed as part of this study and include inputs from tributaries, nearshore septic systems, atmospheric deposition, marine vessels, bottom sediments and inputs from the exchange of Puget Sound water at the entrance to the harbor.

Other objectives of the study were to develop a receiving water quality model of the harbor to evaluate scenarios designed to determine the degree of human influence on dissolved oxygen concentrations and to evaluate the effectiveness of various nutrient management scenarios (King County 2010d). The hypothetical nutrient input reductions were to be tied to planning level estimates of the costs of achieving those reductions, with recommendations for policies and management actions.

Although a hydrodynamic model (the first step in development of a receiving water quality model) of the harbor was developed as part of this study (Albertson 2013), the development of an adequately calibrated water quality model of the harbor was not accomplished. A working water quality model was developed based on the hydrodynamic model, but project resources were not sufficient to fully calibrate and test the model. Therefore, the study did not determine the degree of human influence on dissolved oxygen concentrations nor evaluate the effectiveness of various nutrient management scenarios. Nonetheless, this study does provide a solid foundation of information and a functioning, albeit un-calibrated, water quality model of the harbor that could be used by Ecology to

develop a dissolved oxygen Total Maximum Daily Load study for Quartermaster Harbor – listed as Category 5 in Washington's 2012 list of impaired marine waters.[8]

1.4 Organization of Report

This final study report provides a summary of all the work conducted as part of the Quartermaster Harbor Nitrogen Management Study. Section 2.0 of this report, provides an introduction to the concept and current understanding of marine eutrophication with an emphasis on Puget Sound and Quartermaster Harbor. Section 3.0 describes the historical and current conditions in the watersheds on Vashon-Maury Island that drain to Quartermaster Harbor. An overview of results and conclusions from the surface and groundwater monitoring efforts is presented in Section 4.0. Section 5.0 provides an overview of the available marine water and sediment quality data, with an emphasis on relationships between nitrogen, phytoplankton biomass and dissolved oxygen; including a summary of benthic nitrogen flux measurements made in Quartermaster Harbor as part of this study. Section 6.0 provides a summary of the methods and results of Quartermaster Harbor nitrogen loading estimates developed as part of this study, including estimates of nitrogen released from harbor sediments described in Section 5.0 and an estimate of the nitrogen input delivered through the harbor entrance boundary with Puget Sound.

Study conclusions and recommendations are provided in Section 7.0. Appendix A provides a summary of the outreach and education activities undertaken as part of this study and the changes incorporated into the 2012 Comprehensive Plan related to nitrogen management on Vashon-Maury Island.

[8] Category 5 - Polluted waters that require a TMDL or other Water Quality Improvement (WQI) project: the traditional list of impaired water bodies also known as the 303(d) list. Placement in this category means that Ecology has data showing that the water quality standards have been violated for one or more pollutants, and there is no TMDL or pollution control plan. TMDLs or other approved WQI projects are required for the water bodies in this category.

2.0 MARINE EUTROPHICATION

Nitrogen is one of the earth's most abundant elements and it is also an essential plant and animal nutrient. Ironically, much of the nitrogen in the biosphere exists in a form that is unavailable to most life forms – nitrogen gas (N_2). Through a process called nitrogen fixation, N_2 is converted to a form of nitrogen called nitrate (NO_3-N) that is available for uptake by plants, including marine phytoplankton. In the natural environment, nitrogen fixation is carried out by a variety of specialized bacteria. Other natural processes such as lightning can also fix nitrogen from the atmosphere. The nitrogen cycle is completed by the decomposition of organic matter, which generates ammonia (NH_3-N). Ammonia can be converted via bacterially mediated processes to nitrate, which in turn is denitrified by certain bacteria to N_2.

Over the past several decades, humans have modified the global nitrogen cycle primarily through the combination of industrial fixation of atmospheric nitrogen for fertilizer and the use of this fertilizer to maintain and improve crop yields to feed the growing human population (Vitousek et al. 1997, Galloway et al. 2004). Globally, other significant human sources of nitrogen include increased cultivation of nitrogen fixing crops and fossil fuel combustion (Galloway et al. 2004). Much of these additional inputs of nitrogen to the environment are delivered to groundwater, streams, rivers, lakes, estuaries and coastal marine waters.

The nutrient enrichment of receiving waters is known as *eutrophication*. The nutrient of most concern in marine and estuarine waters is typically nitrogen, which under certain conditions can be the limiting factor for marine algae and plant growth (Howarth and Marino 2006). Increased inputs of nitrogen can under certain conditions result in excessive growth of aquatic plants and/or algae and may also affect which species, some of which can be harmful, are favored.[9] The process by which harmful species, particularly species of phytoplankton, are preferred remains poorly understood (Horner et al. 1997, Smayda and Reynolds 2001, Anderson et al. 2002, Gilbert et al. 2005). Whether nutrient enrichment results in excessive plant or algal growth in any particular estuary depends on a number of natural characteristics that affect an estuary's susceptibility to additional nutrient inputs. These characteristics include spatial and temporal variation in light availability, zooplankton grazing, vertical mixing, flushing, salinity, temperature and nutrient regeneration (Rensel Associates and PTI 1991, Bricker et al. 2007).

Around the world, the impacts of the modification of the nitrogen cycle by humans have been observed, particularly in coastal marine and estuarine ecosystems where phytoplankton were historically limited by the availability of nitrogen (Howarth and Marino 2006). The impacts that have been identified include increases in algal and aquatic

[9] Note that there are a number of other potential causes of excessive algal growth and/or increases in the amount and extent of oxygen depletion. These other causes in include loss of higher trophic levels, anthropogenic inputs of oxygen demanding substances, algal growth limitation by nutrients other than nitrogen (Sharp 2010).

plant biomass and productivity; reductions in transparency; increased incidences and duration of harmful algal blooms; degradation of sea grass and kelp beds and coral reefs; increases in extent and severity of hypoxic and anoxic waters; and reduced populations of fish and shellfish (Scavia and Bricker 2006, Smith 2006). In the U.S., significant problems related to estuarine eutrophication have been observed in Chesapeake Bay, Long Island Sound and the northern Gulf of Mexico (Bricker et al. 1999), although as more information becomes available it appears that many U.S. estuaries exhibit symptoms of eutrophic conditions (Bricker et al. 2007).

Concerns regarding the eutrophication of Puget Sound have been raised at least since the 1970s, although initially the nutrient of concern was dissolved phosphate, driven to a large extent by the lack of nitrogen data (Duxbury 1975, Collias and Lincoln 1977). At that time, no significant effect of a population increase from about 750,000 to almost 2 million people between 1930 and 1970 was detected on the oxygen concentration in the main basin of Puget Sound. Duxbury (1975) did acknowledge that human influence might be registered in densely populated, small, confined embayments. These studies also highlighted the importance of interannual variability in coastal upwelling as a major factor controlling nutrients and dissolved oxygen concentrations in the sound.

The initial attention to the potential for eutrophication of Puget Sound led to more extensive monitoring, including routine measurements of nitrate (the dominant nutrient form of nitrogen) and chlorophyll *a* – a surrogate measure of phytoplankton biomass. In the late 1980s, an effort was made again to evaluate the available data for trends, both spatial and temporal, especially for trends in nutrients, dissolved oxygen and indicators of phytoplankton growth (Tetra Tech 1988). In general, dissolved oxygen concentrations appeared to have increased or not changed significantly over time. A few areas were judged to be sensitive to the deleterious effect of algae blooms due to their physical conditions and/or their proximity to large human population centers:

- Sinclair Inlet
- Budd Inlet
- Oakland Bay
- South Hood Canal

Citing evidence of water quality problems related to nutrient enrichment and phytoplankton blooms, as well as depletion of dissolved oxygen and related fish kills in poorly flushed embayments of Puget Sound, a report was prepared that reviewed the state of knowledge regarding nutrient-phytoplankton relationships in Puget Sound and quantified the relative sensitivity of various areas of the sound to additional inputs of nutrients (Rensel Associates and PTI 1991).

Based on the analyses presented in their report, primarily analyses of the frequency of water column depletion of nitrogen available for phytoplankton growth, Rensel Associates and PTI (1991) expanded the list of potentially nutrient sensitive areas to include several other locations in Puget Sound. Quartermaster Harbor was also listed as potentially

sensitive to nutrient additions, but at that time no nitrogen data were available for the harbor. Quartermaster Harbor was listed on the basis of a study of the occurrence of *Alexandrium catenella* in the harbor, a motile dinoflagellate that can produce toxins that accumulate in shellfish tissue and cause paralytic shellfish poisoning (PSP) (Nishitani et al. 1988).

Interest in the potential for the eutrophication of Puget Sound continues and has lead to at least four major studies:

- Hood Canal Dissolved Oxygen Program[10]
- South Puget Sound Dissolved Oxygen Study[11]
- Puget Sound/Salish Sea Model[12]
- Deschutes River Watershed (including Budd Inlet) Water Quality Improvement Project[13]

Final study reports are available for the Hood Canal and Budd Inlet studies. The Budd Inlet study is summarized in Roberts et al. (2012) and the Hood Canal study is described in a number of online report chapters (http://www.hoodcanal.washington.edu/news-docs/publications.jsp). In addition, a report synthesizing available information related to the assessment of the relative human influence on Hood Canal dissolved oxygen was published (Cope and Roberts 2013). Overall, these studies indicate that oxygen levels in Puget Sound are naturally less than the applicable absolute water quality standard at certain places and times during the year and that the maximum human influence on the "natural" (i.e., without human influence) oxygen levels is on the order of 0.5 mg/L in isolated portions of Budd Inlet (Roberts et al. 2012). Budd Inlet currently receives point and nonpoint source inputs of nitrogen (Roberts et al. 2012). Cope and Roberts (2013) determined that humans are not responsible for the fish kills that have occurred near Hoodsport in Central Hood Canal, nor for the low dissolved oxygen levels observed in this area. The relative influence of humans on dissolved oxygen in Lynch Cove at the most southern end of Hood Canal was determined to be relatively uncertain, but somewhere between 0.03 and 0.3 mg/L relative to the naturally occurring dissolved oxygen concentrations.

Draft reports of the South Puget Sound and Puget Sound/Salish Sea studies have been prepared and made available for review (Ahmed et al. 2013, Roberts et al. 2013). The South Puget Sound Study determined that the maximum human influence on dissolved oxygen was 0.4 mg/L in the inner portions of Budd, Carr, Eld and Totten inlets caused primarily by direct permitted point source discharges of treated wastewater to Puget Sound – including inputs to Central Puget Sound (Ahmed et al. 2013).

[10] Hood Canal Dissolved Oxygen Program (http://www.hoodcanal.washington.edu/)
[11] South Puget Sound DO Study (http://www.ecy.wa.gov/puget_sound/dissolved_oxygen_study.html)
[12] Puget Sound/Salish Sea Model (http://www.ecy.wa.gov/programs/wq/PugetSound/DOModel.html)
[13] Deschutes River Watershed Project (http://www.ecy.wa.gov/programs/wq/tmdl/deschutes/index.html)

The Puget Sound/Salish Sea study identified a somewhat smaller effect of humans on dissolved oxygen levels in Puget Sound. A maximum effect of 0.2 mg/L was noted in the inner portion of Case Inlet. As in the South Sound study, the majority of the human influence was due to existing point source wastewater discharges to Puget Sound. The Puget Sound/Salish Sea study also evaluated the effect of future increases in the Puget Sound population (without additional treatment requirements) and climate change on dissolved oxygen. These scenarios indicated the potential for a much larger influence of humans, primarily as the result of unchecked increases in nitrogen loading from wastewater to Puget Sound, of up to a 1.1 mg/L decline of dissolved oxygen from predicted natural conditions (Roberts et al. 2013).

The relatively small effect of the total increase in nitrogen loading from all current human sources on dissolved oxygen in the main basin of Puget Sound (0.04-0.08 mg/L) and in Hood Canal (0.02-0.04 mg/L) estimated by Roberts et al. (2013) is supported by analyses of sediment cores conducted by Brandenberger et al. (2008). Cores collected from Hood Canal and the main basin of Puget Sound revealed the effects of land use changes, including forest clearing and urbanization, but they did not record any increasing trend in hypoxia in the last 100 years that would be expected in response to land use changes and growth of the human population in the Puget Sound basin (Brandenberger et al. 2009).

That the response of the main basin of Puget Sound and Hood Canal was contrary to what was expected (i.e., greater impact of nitrogen inputs on DO levels) is consistent with the evolving conceptual model of coastal eutrophication (Cloern 2001). The initial conceptual model of coastal eutrophication was based on experience with freshwater systems and assumed a proportional relationship between the magnitude of nutrient loading and response reflected in increased primary production and biomass and a decline in dissolved oxygen. More recent research has lead to a more complex conceptual model that includes a filter that modulates the response of a particular coastal marine system to nutrient loading (Figure 5). The potential responses are also expanded to include changes in nutrient ratios that may play a role in altering the phytoplankton community or promoting toxic and/or harmful algal blooms and a long list of potential indirect effects that include fish kills, changes in water transparency and alteration of food web structure (see Figure 5).

In the main basin of Puget Sound, the main filter appears to be a general tendency for light limitation of spring and summer phytoplankton growth, which moderates the effect of nutrient inputs to the sound (Duxbury 1975, Winter 1975). The main driver historically of oxygen levels in the main basin of Puget Sound are decadal climate cycles that affect the ventilation of Puget Sound and the oxygen content of coastal marine waters exchanged through the Strait of Juan de Fuca (Brandenberger et al. 2008).

Also consistent with the conceptual model of Cloern (2001) is the finding by Brandenberger et al. (2008) that there do appear to be some shifts in the primary producer community identified in the sediment cores, including increased relative abundance of species generally associated with eutrophication over the last several decades such as *Pseudo-nitzschia*, which is capable of producing the toxin domoic acid. *Alexandrium* is another toxin producing species that, although present historically in coastal marine

waters, has spread to Puget Sound since the 1960s along with the observed frequency of exceedances of paralytic shellfish toxin levels (Moore et al. 2009).

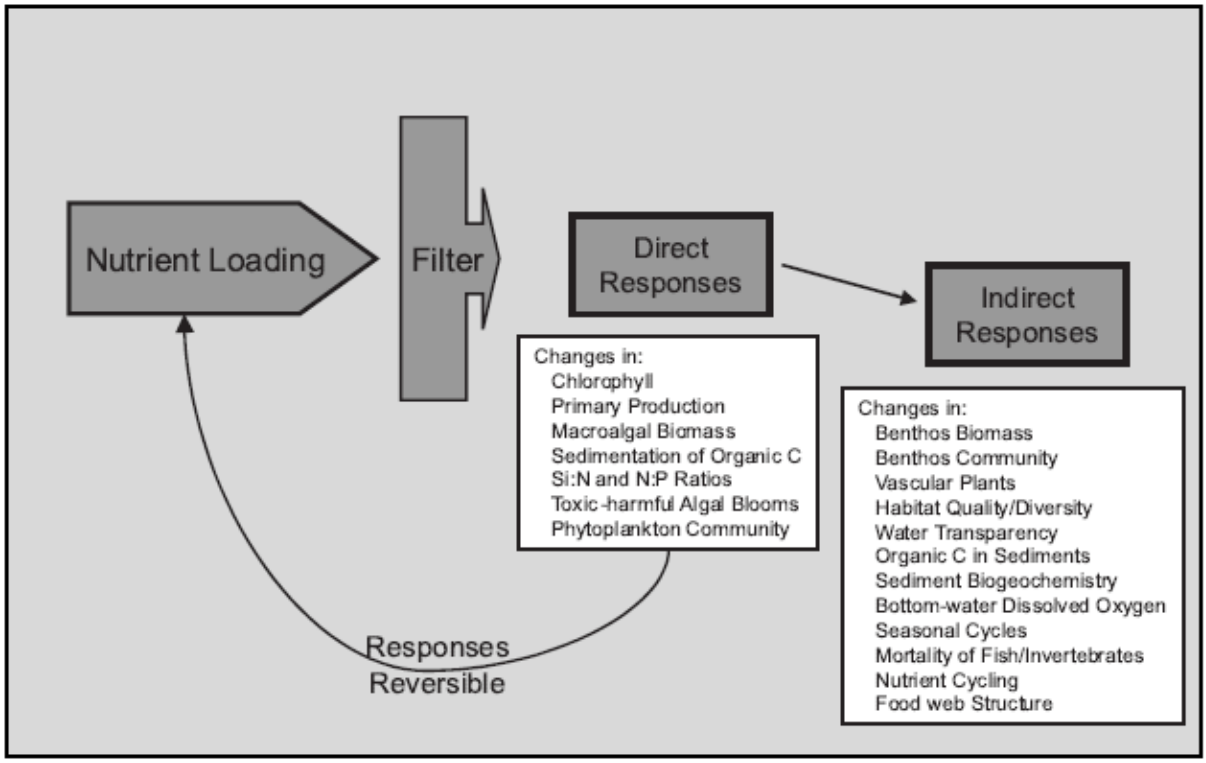

Figure 5. Schematic representation of the contemporary (Phase II conceptual model of coastal eutrophication proposed by Cloern (2001).

Source: Cloern (2001)

Perhaps the most challenging thought provided by Cloern (2001) in response to the question posed regarding "How can this science advance?" is that our view of the problem is too narrow and needs to consider that nutrient enrichment does not operate as an independent stressor, but rather operates in the context of many other stressors. These additional stressors include habitat loss, invasive species and climate change. This broader view that includes multiple stressors and responses requires a more sustained and integrated research and monitoring effort (Cloern 2001).

3.0 HISTORICAL CONTEXT

Research has highlighted the role that past land use activity may play in affecting the current environmental conditions (Harding et al. 1998, Foster et al. 2003). Of specific relevance to this study are the recent findings published by Sanford and Pope (2013) who showed a delay in nitrogen load reduction to Chesapeake Bay due to the lag resulting from nitrogen application at the land surface and transport via groundwater to receiving waters. To provide historical context for the current conditions on the island and in the harbor, the following historical overview is provided.

The history of Vashon-Maury Island 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 Department 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.

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. In 1841 the U.S. Exploration Expedition, led by Captain Charles Wilkes, 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 low tide (Blumenthal 2009). Although the journal entry of one participant (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. Turnbeaugh (1976) suggests that the overtopping occurred at the highest spring tides. 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 driven them from the area. The first permanent settlers established themselves on the northern shore of Quartermaster Harbor in 1877.

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. Upland areas were being logged and converted to farms and areas for sheep grazing. With the exhaustion 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 Vashon-Maury Island 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.

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[14]), 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 Vashon-Maury Island to work in Seattle and Tacoma.

3.4 Residential Development

The forest prior to European-American settlement was dominated by Douglas fir, western hemlock, and western red cedar, 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. Forest regeneration following the initial clearing by the early 1900s has been documented for Judd, Fisher and Tahlequah creeks as part of another EPA WEI grant-funded study (King County 2013b; Figure 6).

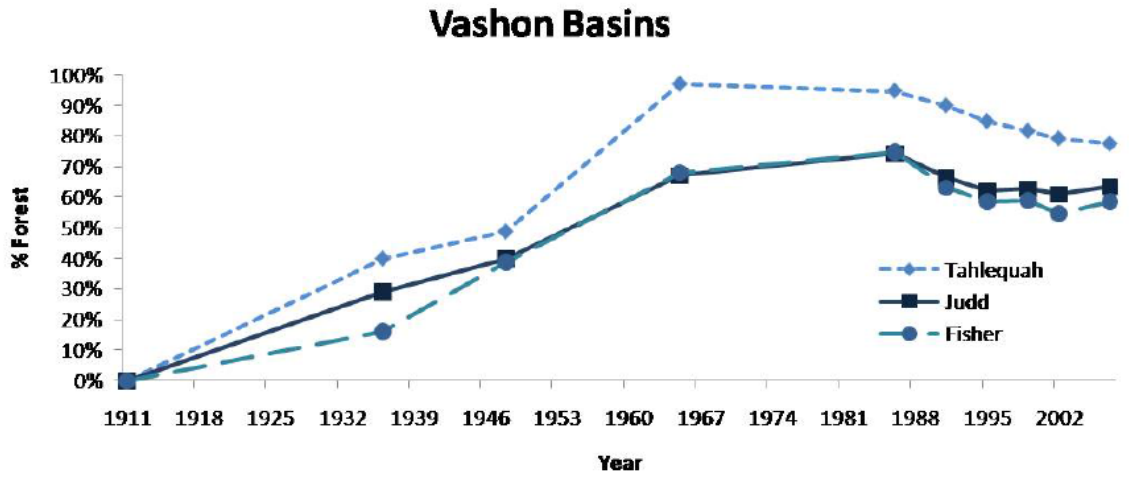

Figure 6. Graph showing change in forest cover in selected basins on Vashon-Maury Island, 1911-2007.

Source: See Appendix D in King County (2013b)

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

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 1920-2010 indicates the steady progression in the number of people settling on the island. Since 1920, the population has increased about four fold (Figure 7).

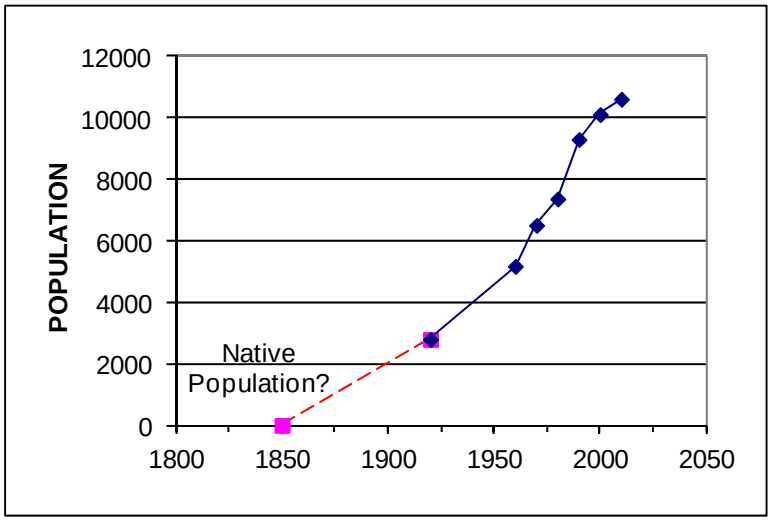

Figure 7. Graph showing the population change on Vashon-Maury Island, 1920-2010.

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 8). 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.

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.

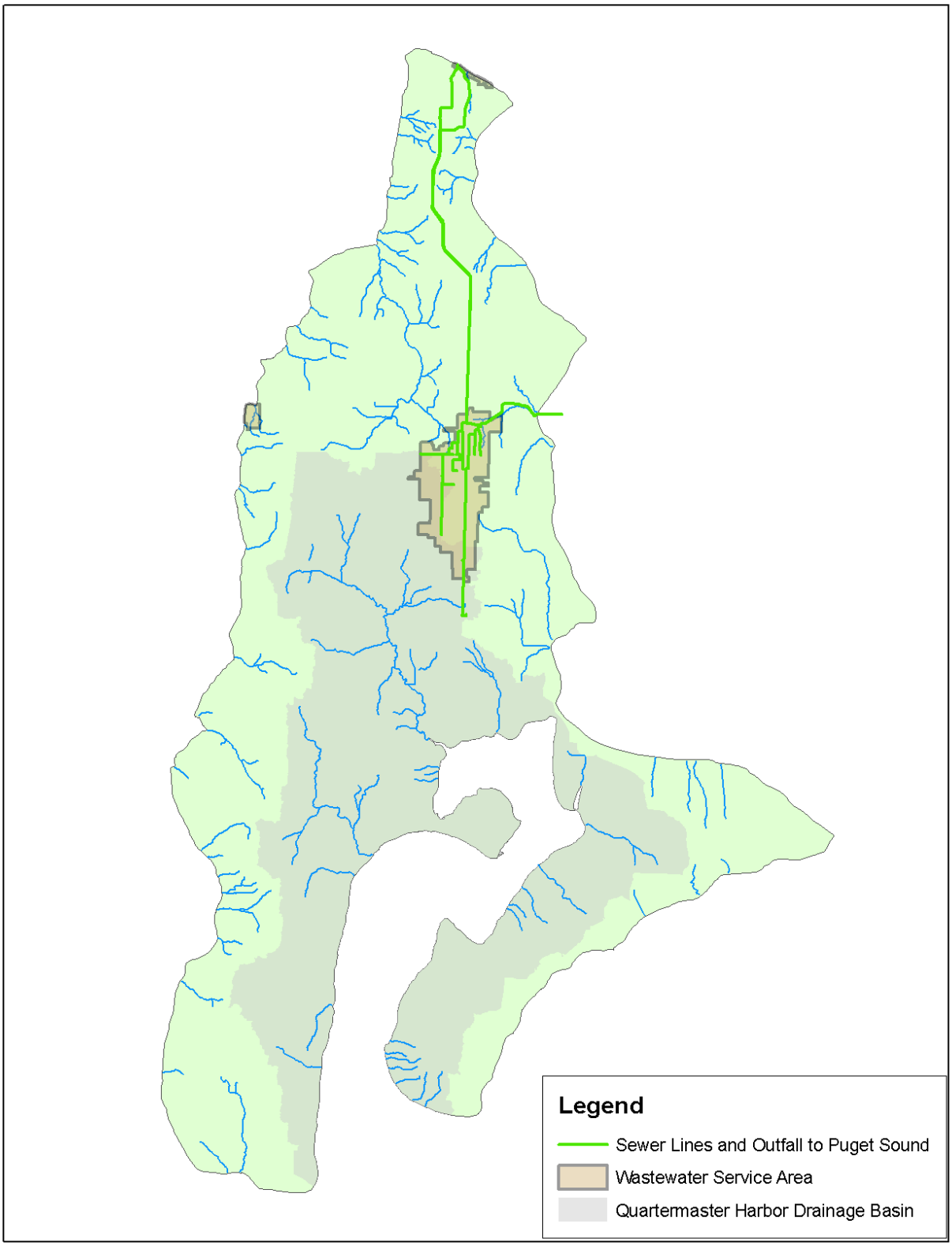

Figure 8. Map showing current service area for the Vashon Island Wastewater Treatment System.

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, 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 (Figure 9). 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 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).

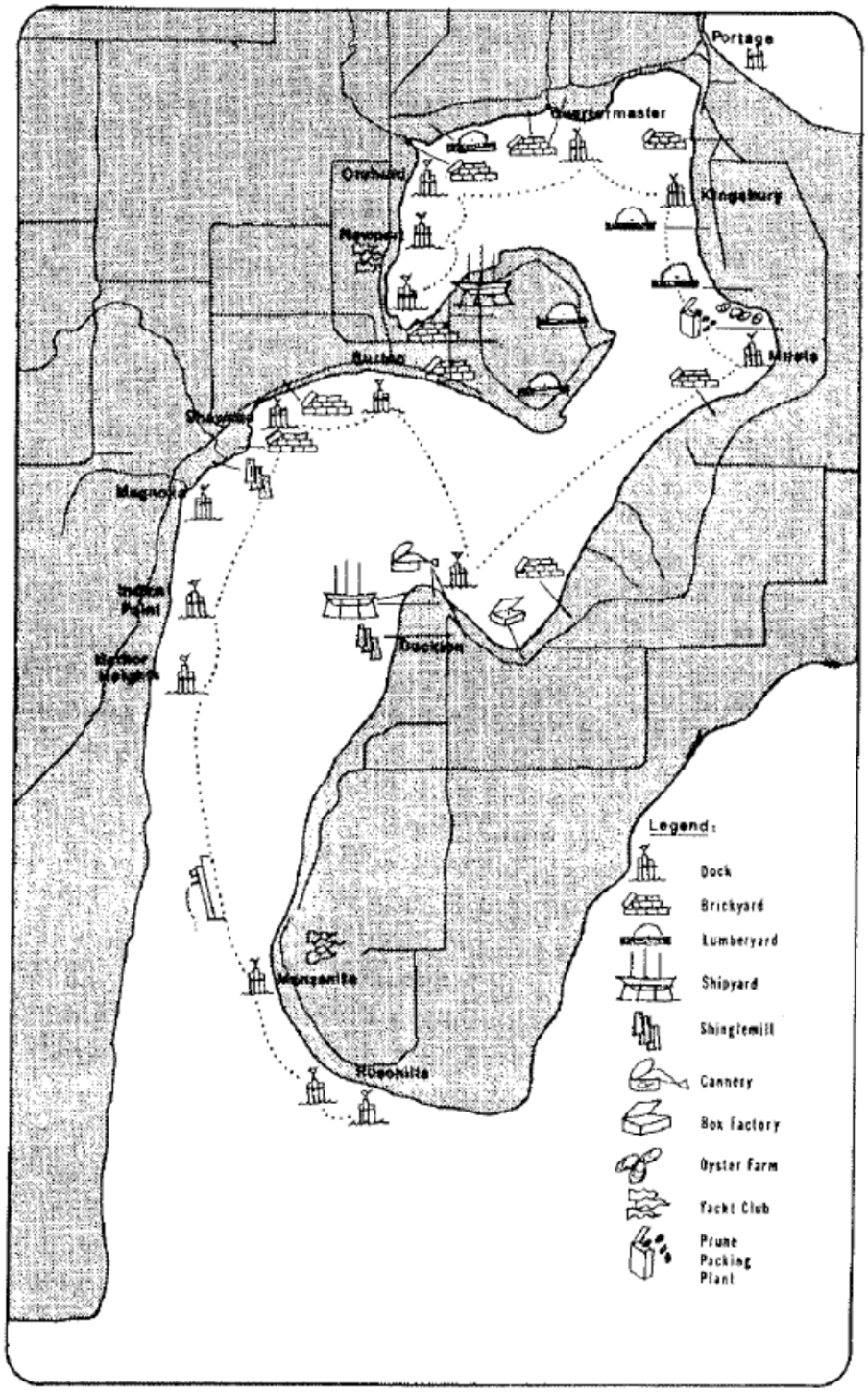

Figure 9. Map showing early distribution pattern of development activities around Quartermaster Harbor.

Source: University of Washington (1976)

4.0 FRESHWATER

Freshwater inputs to Quartermaster Harbor include a number of tributary streams and groundwater seepage. This section provides an overview of available data on the quantity and quality of surface water and groundwater inputs to the harbor. For a complete overview of the data and research on the island's freshwater resources conducted to date, the reader is referred to King County (2013a).

4.1 Surface Water

Tributary 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 have been monitored monthly for nutrient concentrations and have been 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 10). Mileta Creek discharges to inner Quartermaster Harbor and has been monitored routinely for water quality, but continuous flow data have only been collected since the beginning of 2010 (see Figure 10).

Water quality observations included monthly measurements of total suspended solids (TSS), nutrients (total and soluble forms of nitrogen and phosphorus), indicator bacteria, specific conductance, alkalinity, temperature, pH and dissolved oxygen. Nutrient analyses included total nitrogen, nitrate+nitrite nitrogen (hereafter referred to as nitrate), ammonia nitrogen, total phosphorus, soluble reactive phosphorus and dissolved silica. Indicator bacteria measurements included fecal coliform and *Escherichia coli*. The available flow and water quality data for these five tributaries are illustrated in Figure 11 through Figure 15.

In general, the temporal patterns in flow were typical of rural streams in King County, with highest flows during the winter rainy season and lowest flows during late summer when rainfall is least. Temporal patterns in the water quality measurements and their relationships with variations in flow were also fairly typical. For example, high flows were often associated with spikes in TSS, total nitrogen, total phosphorus and indicator bacteria driven by washoff of particulate matter and instream erosion and transport during storms. Other constituents increased during low flow as the result of the dominance of groundwater base flow as the source of those primarily dissolved constituents (e.g., dissolved silica and soluble reactive phosphorus), which was also reflected in an increase in specific conductance and total alkalinity associated with summer base flow.

With the exception of the effect of storm events on particulate nitrogen concentrations, total nitrogen was comprised primarily of nitrate, while ammonia nitrogen concentrations were relatively low or below the laboratory limit of detection. Seasonal patterns in total nitrogen and nitrate concentrations were also evident, although the details differed among streams. Generally, the highest concentrations were observed in late fall as basin soils became saturated and delivered shallow subsurface flows containing nitrogen stored

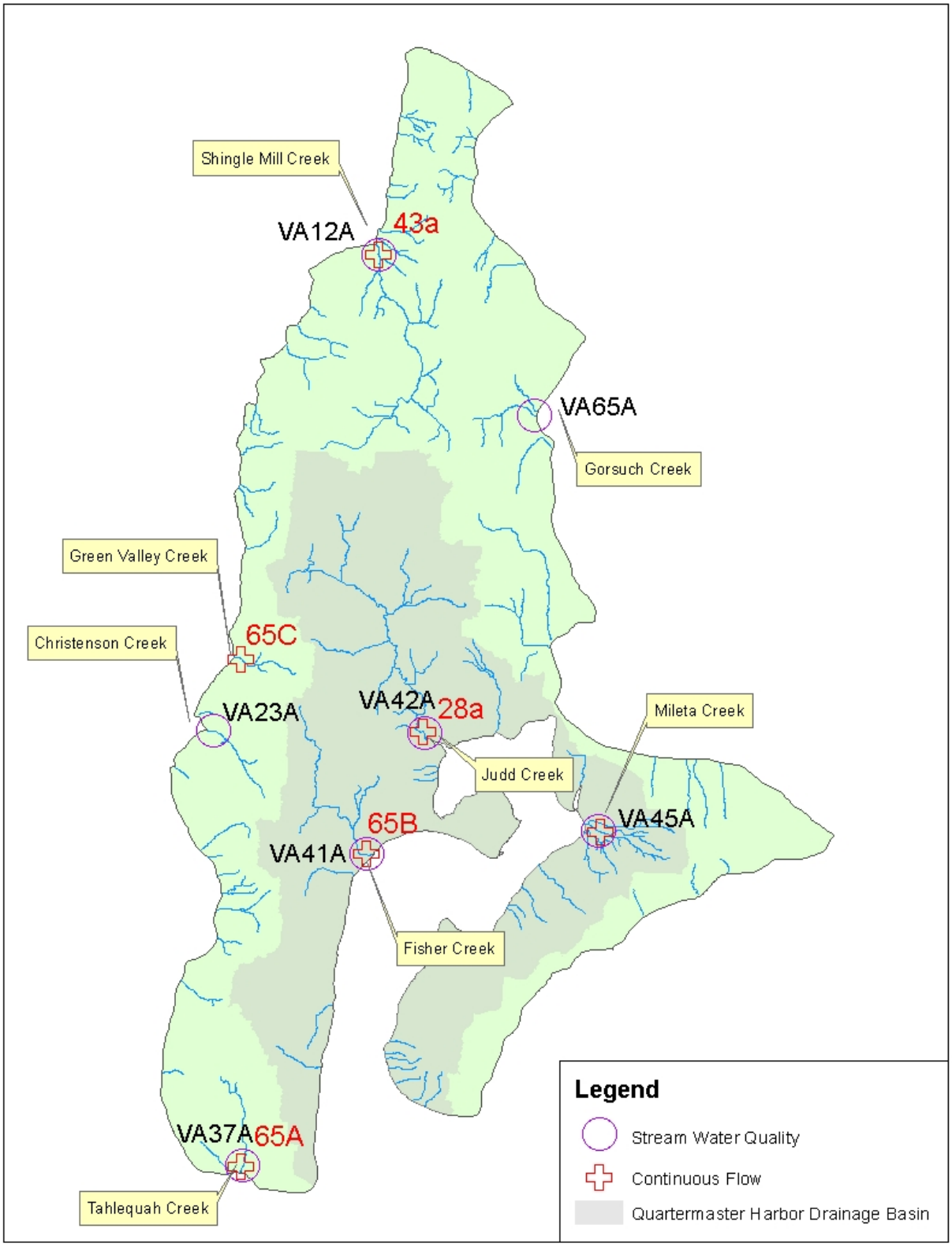

Figure 10. Map showing locations of stream discharge gauging and water quality monitoring stations.

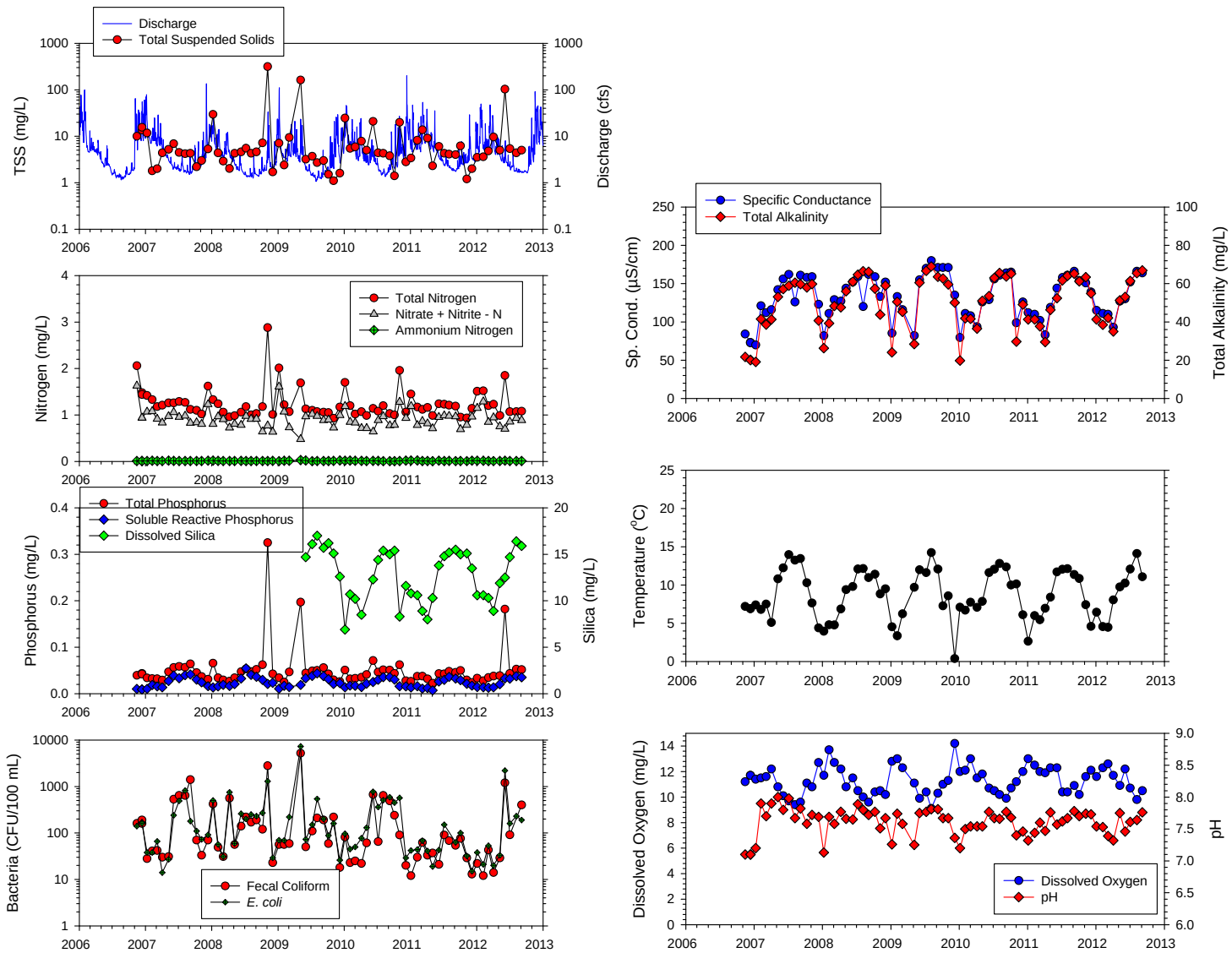

Figure 11. Graphs showing stream discharge (gauge 28a) and water quality data (station VA42A) for Judd Creek.

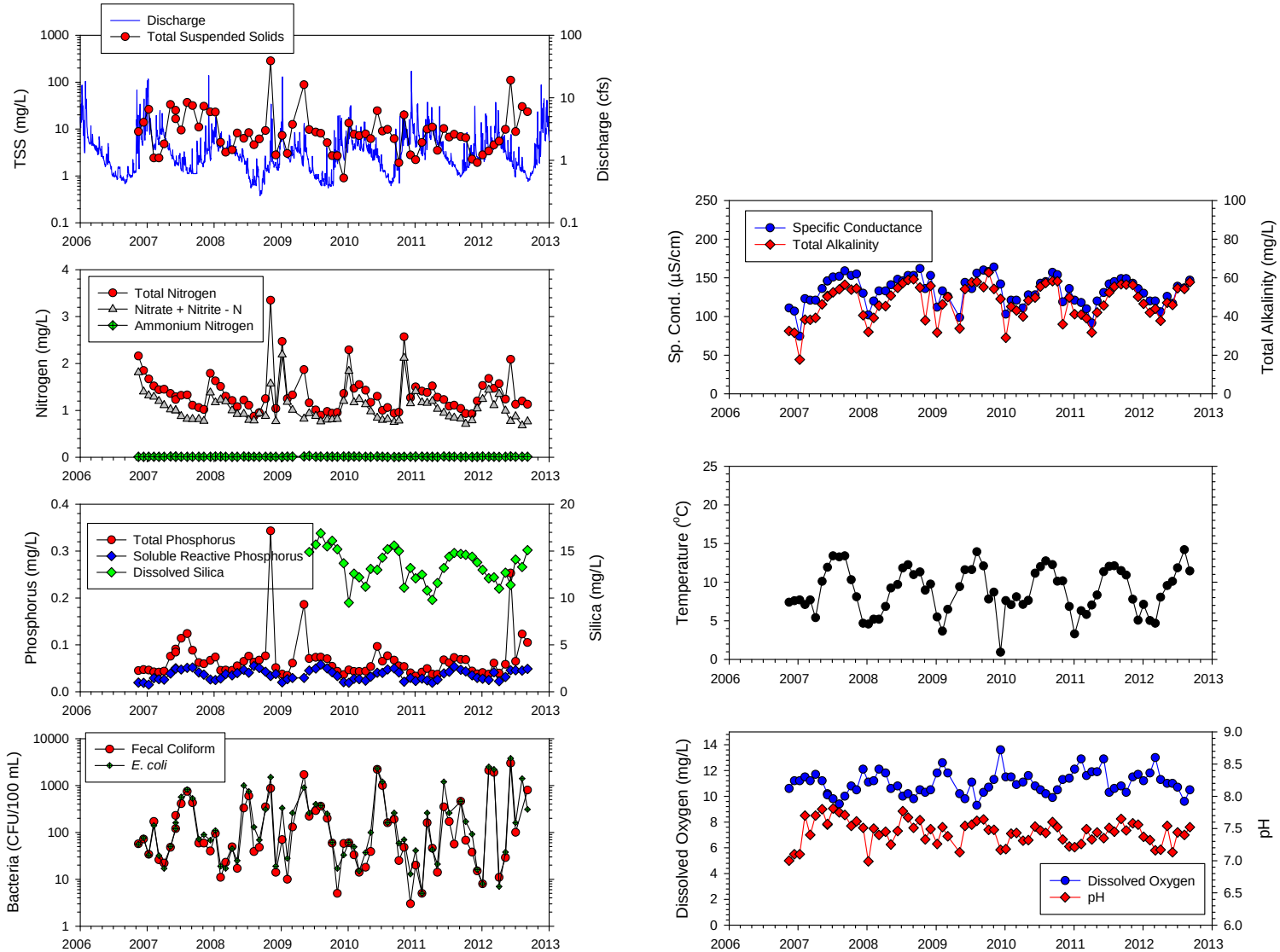

Figure 12. Graphs showing stream discharge (gauge 65B) and water quality data (station VA41A) for Fisher Creek.

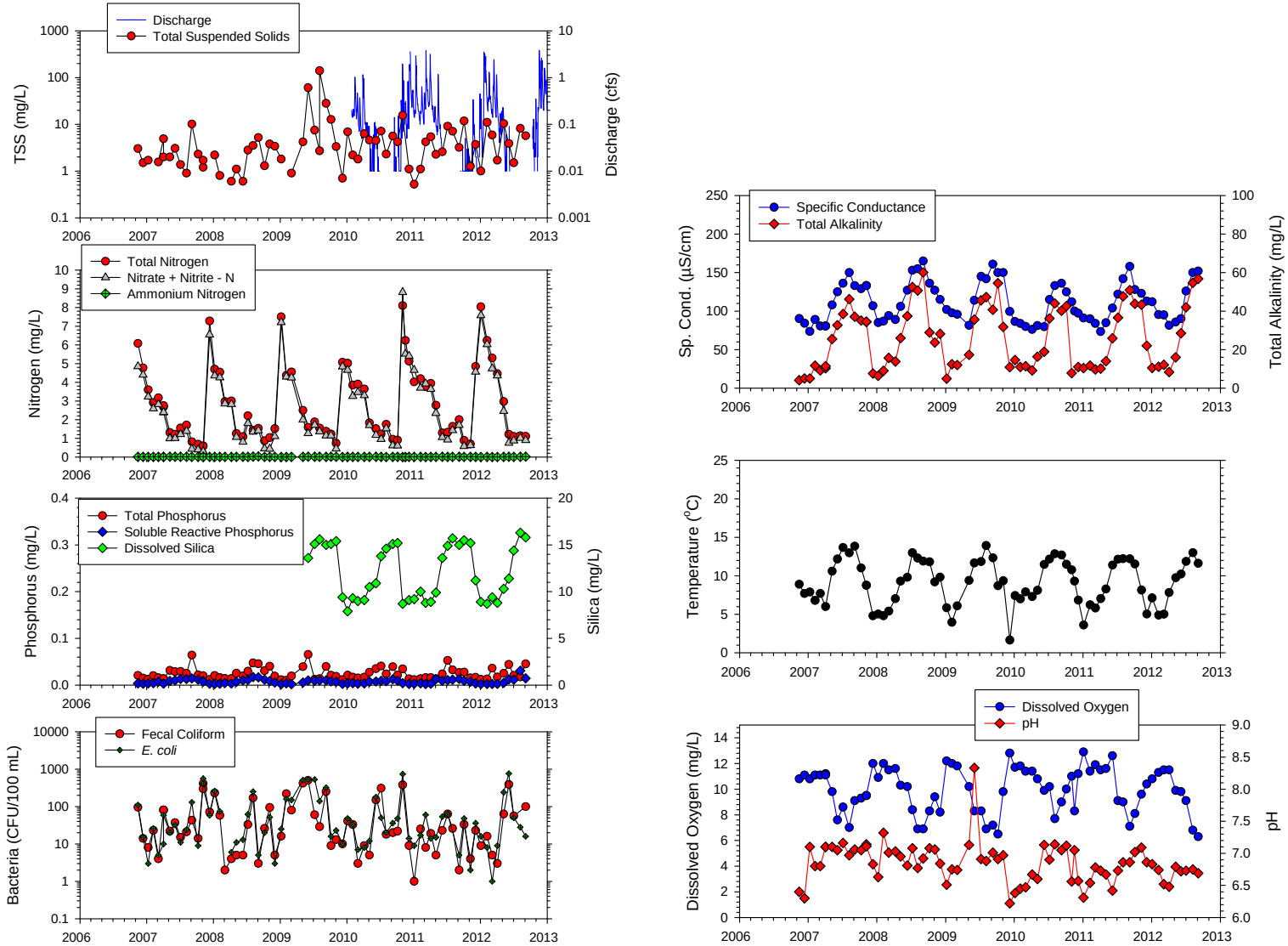

Figure 13. Graphs showing instantaneous stream discharge and water quality data (station VA45A) for Mileta Creek.

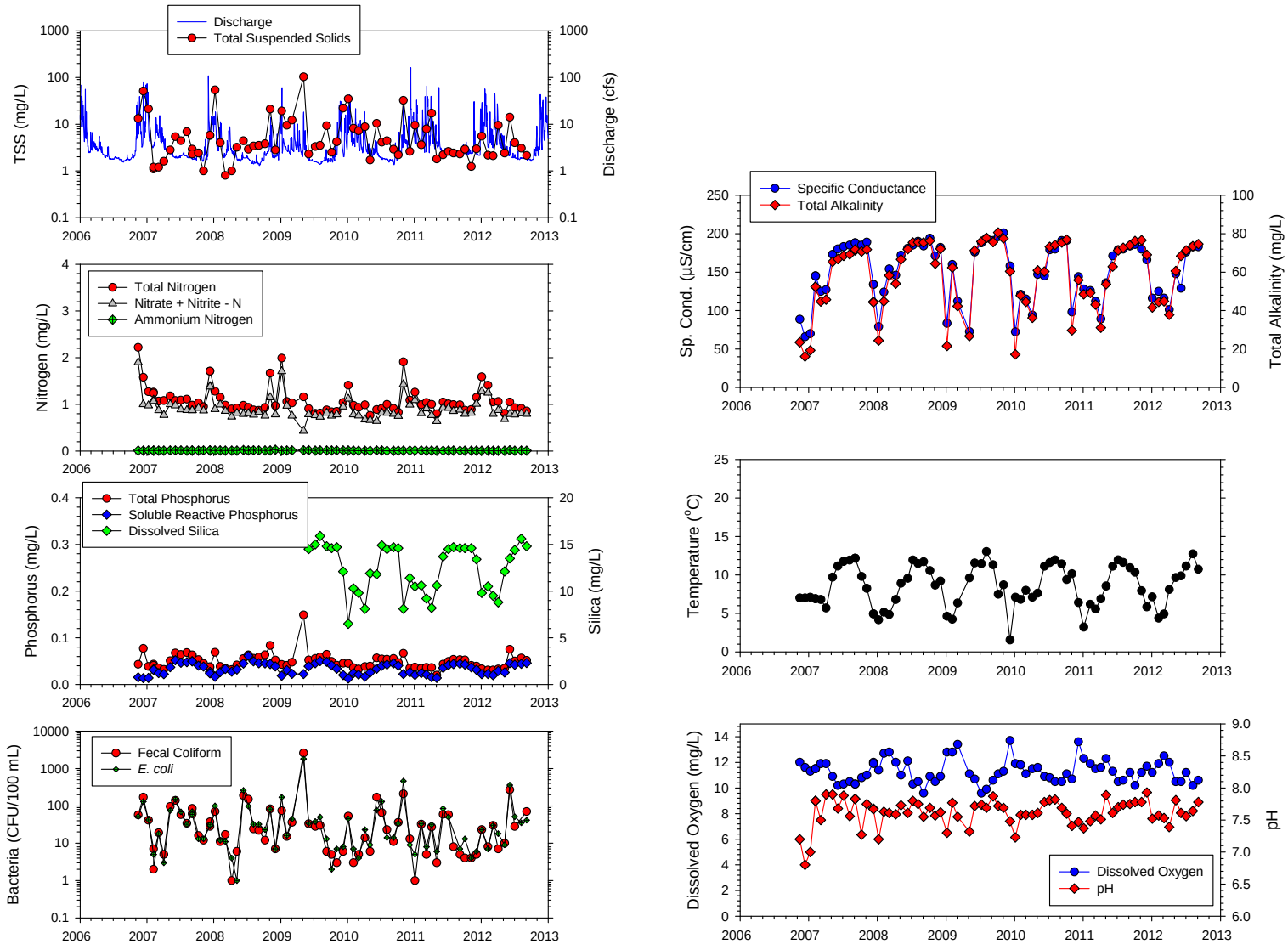

Figure 14. Graphs showing stream discharge (gauge 43a) and water quality data (station VA12A) for Shingle Mill Creek.

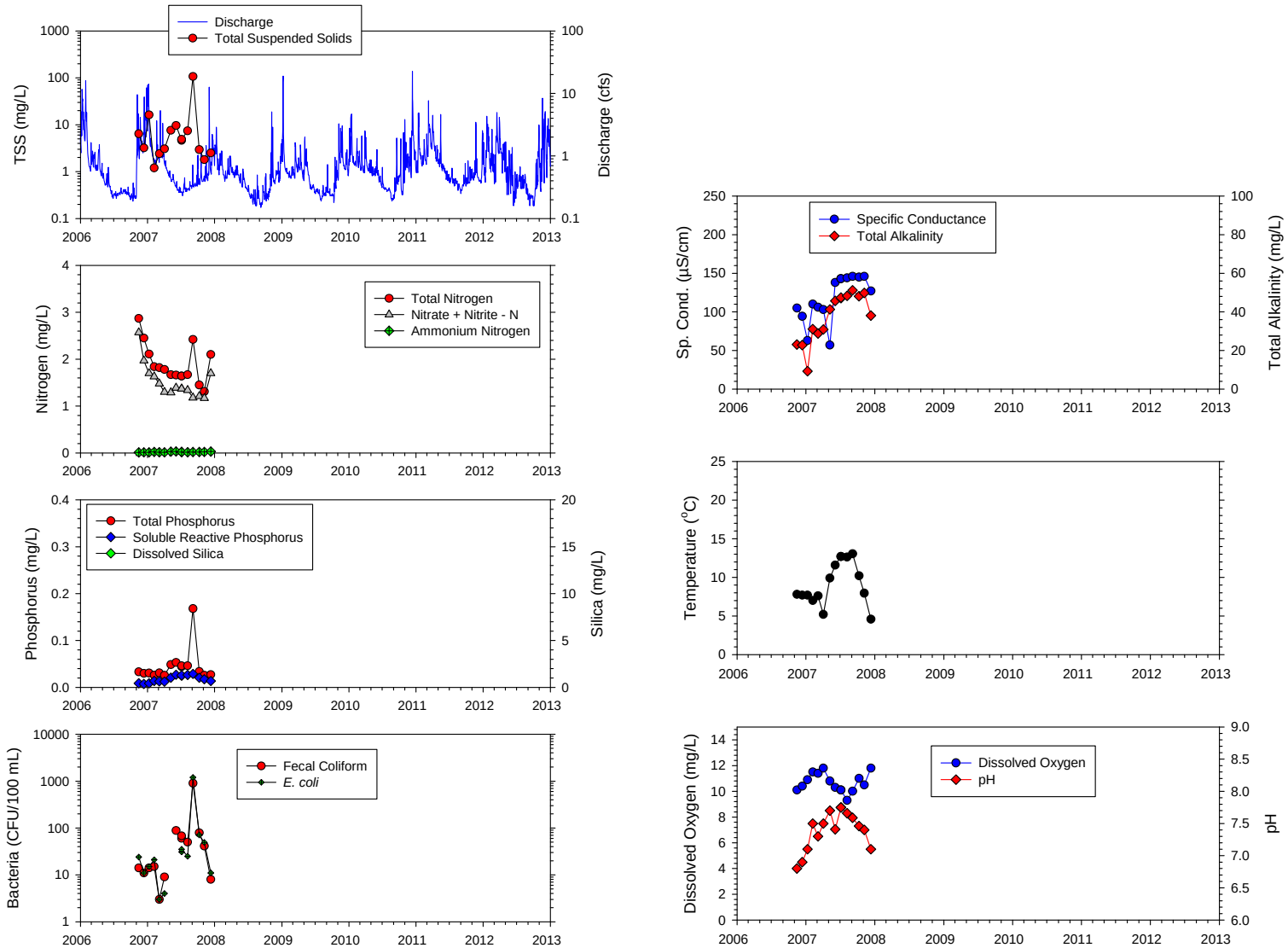

Figure 15. Graphs showing stream discharge (gauge 65A) and water quality data (station VA37A) for Tahlequah Creek.

during the summer (Figure 16). Concentrations remained high during winter when plant uptake was lowest, but typically fell to the lowest levels in summer when plant uptake was greatest and soils were generally dry and accumulating nitrogen. Low nitrate concentrations were also associated with the decline in summer base flow.

The most distinctive spatial pattern in stream nitrogen concentrations is the occurrence of relatively high levels of nitrate in Mileta Creek that peak in late fall with the first soil saturating rains and remain relatively high throughout the summer (Figure 17).

An attempt was made as part of this study to identify the source of elevated nitrate (King County 2012a). No specific source was identified, although potential sources (a golf course, an abandoned chicken farm and an old heron rookery) were ruled out as likely sources. These suspected sources were not located on the branch of Mileta Creek where the elevated nitrate concentrations were observed.

Although not unequivocally established, the similar seasonal nitrate concentration pattern suggested that the elevated concentrations may be the result of a combination of soil, subsurface hydrology and the accumulation of nitrate and subsequent release from storage of nitrogen from red alder – a tree known to fix nitrogen – that is found in the Mileta Creek basin and is distributed throughout disturbed forests in the Puget Sound basin (Davis 1973, Bechtold et al. 2003, Compton et al. 2003, Cairns and Lajtha 2005, Steinberg et al. 2011, Ward et al. 2012). It was also noted that although Mileta Creek is likely one of the largest Maury Island creeks draining to the harbor, the total contribution of nitrogen is relatively small. Consider that the flow during late fall/winter when peak nitrate concentrations occur is less than 1 cfs and that the peak daily flow in this creek has not exceeded 4 cfs.

Of most interest to the issue of low dissolved oxygen concentrations in the harbor during late summer/fall is the concentration (and mass loading) of nitrogen delivered by tributary streams at this time of year. Because the harbor was known to receive freshwater input from many small unmonitored tributary sources, another sampling study conducted as part of this grant focused on measuring flow and nitrogen concentrations in these previously unmonitored sources during October of 2010 (King County 2012b). Although the range was larger, the median nitrate concentration measured in October 2010 in small freshwater inflows was similar to the median nitrate concentration measured in October in the three largest tributary streams to Quartermaster Harbor from 2007 to 2010 - ~0.8 mg/L (Figure 18). Although there was no distinctive spatial pattern in small tributary nitrate concentrations, the highest four observed concentrations were measured in springs that discharged along the western shoreline just south of the Burton Peninsula. These springs are below the Burton Springs and Burton Group A water supply systems that have experienced an increase in nitrate levels as the result of historical land management activities associated with farming and livestock production (CDM 2007, King County 2013a).

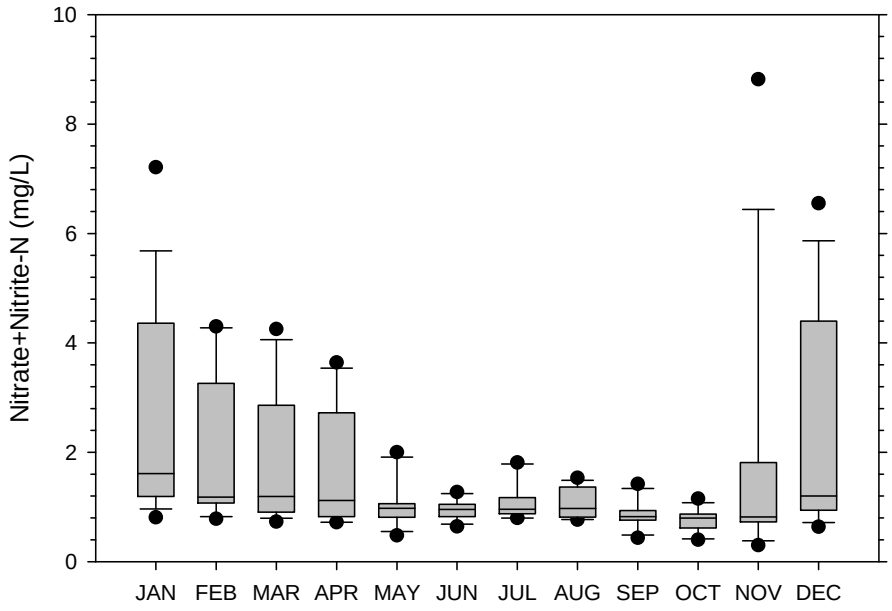

Figure 16. Box plot of monthly (November 2006 through December 2010) nitrate+nitrite nitrogen concentrations measured in routine monthly water quality samples from the three creeks that discharge directly to Quartermaster Harbor (Judd, Fisher, and Mileta creeks).

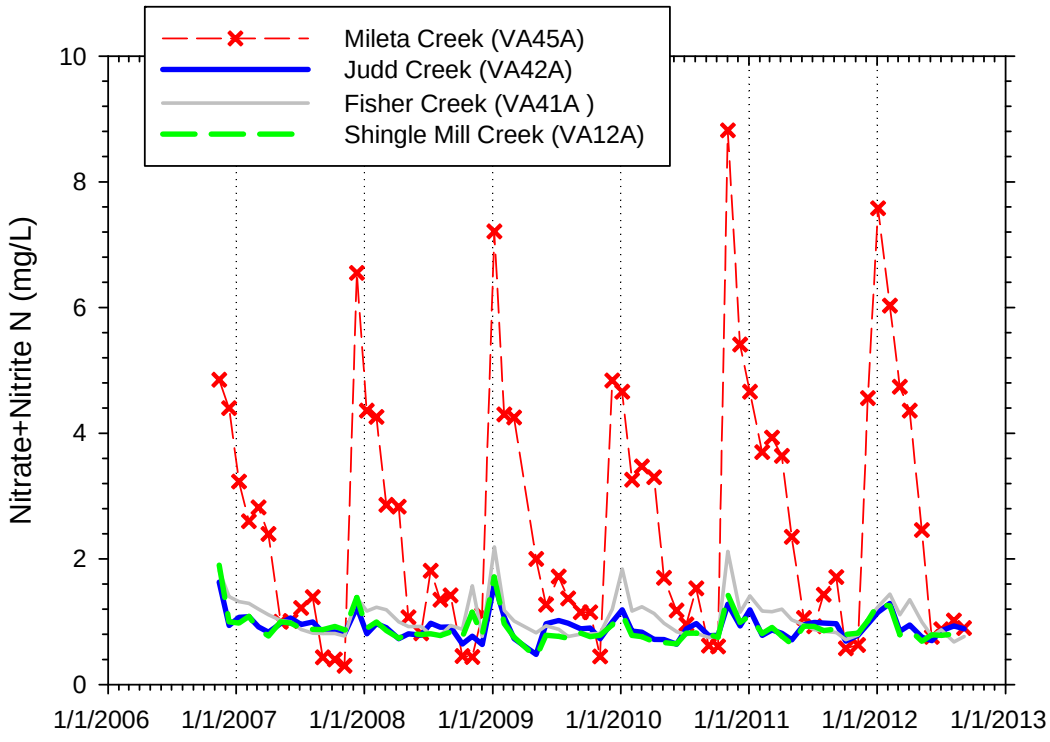

Figure 17. Nitrate+Nitrite nitrogen concentrations measured in routine monthly water quality samples from four Vashon-Maury Island Creeks collected from November 2006 to September 2012.

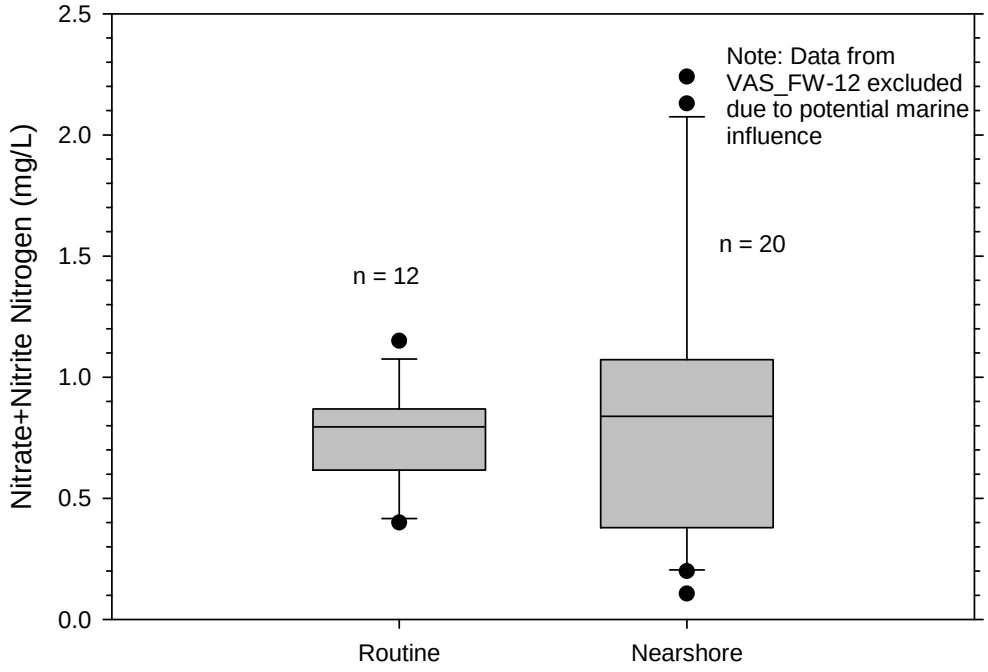

Figure 18. Box plot comparing nitrate concentrations observed at freshwater inputs along the shore of Quartermaster Harbor in October 2010 and the concentrations measured in October from 2007 to 2010 in the three routinely monitored tributaries – Fisher, Judd and Mileta creeks.

4.2 Groundwater

Because of the long standing interest in groundwater on the Vashon-Maury Island, residents rely almost exclusively on groundwater for water supply. Because of drinking water system monitoring and reporting requirements, a great deal is known about the quality and quantity of the island's groundwater system. For a complete overview of the data and research conducted to date, the reader is referred to King County (2013a).

In general, the island is overlain primarily by glacial till and smaller pockets of recessional outwash and advance outwash deposits.[15] Deeper glacial deposits include varying layers of fine grained (less permeable) and coarse grained deposits (more permeable). The nomenclature describing the main island aquifers has changed over time, but for the purposes of this report, the groundwater quality data have been separated into "Shallow" and "Deep" aquifer categories. "Shallow" aquifer data represent the groundwater sources in closest proximity to land surface activities, particularly in those locations where these

[15] The shorthand for these on geologic maps and in the text are as follows: Qvr = Vashon recessional outwash deposits, Qva = Vashon advance outwash deposits, Qpfc = Pre-Fraser coarse grained deposits, Qpoc = Olympia coarse grained deposits.

aquifers are exposed at the land surface (i.e., are not overlain by a protective layer of less permeable till). "Deep" aquifer data represent aquifers that have one or more less permeable layers of till and so are less susceptible to activities at the land surface (Table 1). These "Shallow" aquifers were originally termed the Principal Aquifer because most of the individual wells and smaller water systems rely on these aquifers for water supply. The "Deep" Aquifer is generally tapped by larger water utilities on the island.

In addition to differentiation by susceptibility, the Shallow Aquifers are also the dominant source of water to island streams, particularly in the Quartermaster Harbor drainage basin. The available geologic information also indicates that in particular, the Shallow Aquifer Vashon advance outwash deposits are likely the main conduit for groundwater input to Quartermaster Harbor and may be limited primarily to inner harbor and the inner portion of the outer harbor near Burton Peninsula (Figure 19 and
Figure 20).

Table 1. Various definitions of Vashon-Maury Island aquifer units, including the definitions used in this study.

This report	Carr/Associates (1983)	VMI GWMC (1998)	WRE
Shallow Aquifer	Principal Aquifer	Zone 1	Zone 1 - shallow Vashon recessional outwash deposits (Qvr) & Principal/ Main Vashon advance outwash deposits (Qva) & alluvium deposits (Qal)
		Zone 2	
Deep Aquifer	Deep Aquifer	Zone 3	Zone 2 - Deep 1 Pre Fraser coarse grained deposits (Qpfc)
		Zone 4	Zone 3 - Deep 2 Olympia coarse grained deposits (Qpoc) and deeper units

VMI GWMC = Vashon-Maury Island Groundwater Management Committee
WRE = Water Resources Evaluation (see King County 2013a)

In support of this study, groundwater quality data were compiled from King County monitoring wells (Figure 21). The monitoring data from these wells indicates that nitrate is generally higher in the Shallow Aquifer, while the concentrations of soluble reactive phosphorus and ammonia are generally higher in the Deep Aquifer (Figure 22). Ammonia concentrations in wells completed in the Shallow Aquifer were generally below the limit of detection indicating that the inorganic nitrogen was in the form of nitrate.

Because of the limited number of King County monitoring wells representing the quality of the Shallow Aquifer on the island, additional monitoring data reported to the Washington State Department of Health from municipal and small private water supply systems was also compiled and wells classified into Shallow and Deep aquifer categories. In general, nutrient data reported to the Department of Health are limited to nitrate because of a Maximum Contaminant Level standard for the protection of human health, which is 10 mg/L.

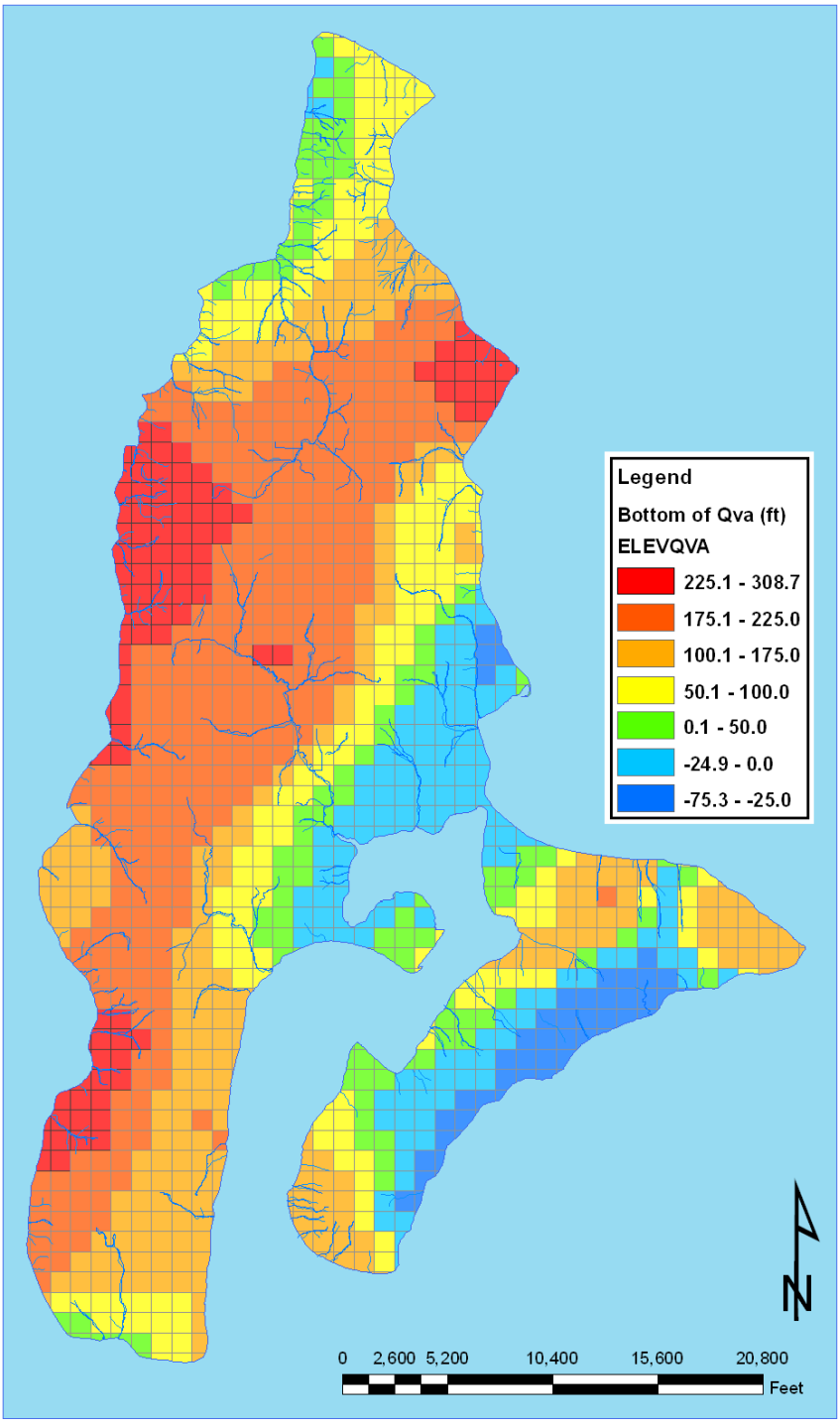

Figure 19. Estimated bottom elevations of the Vashon advance outwash geologic layer (elevation datum is NAVD88 – 2.9 ft is equal to Mean Lower Low Water).

Source: King County (2005)

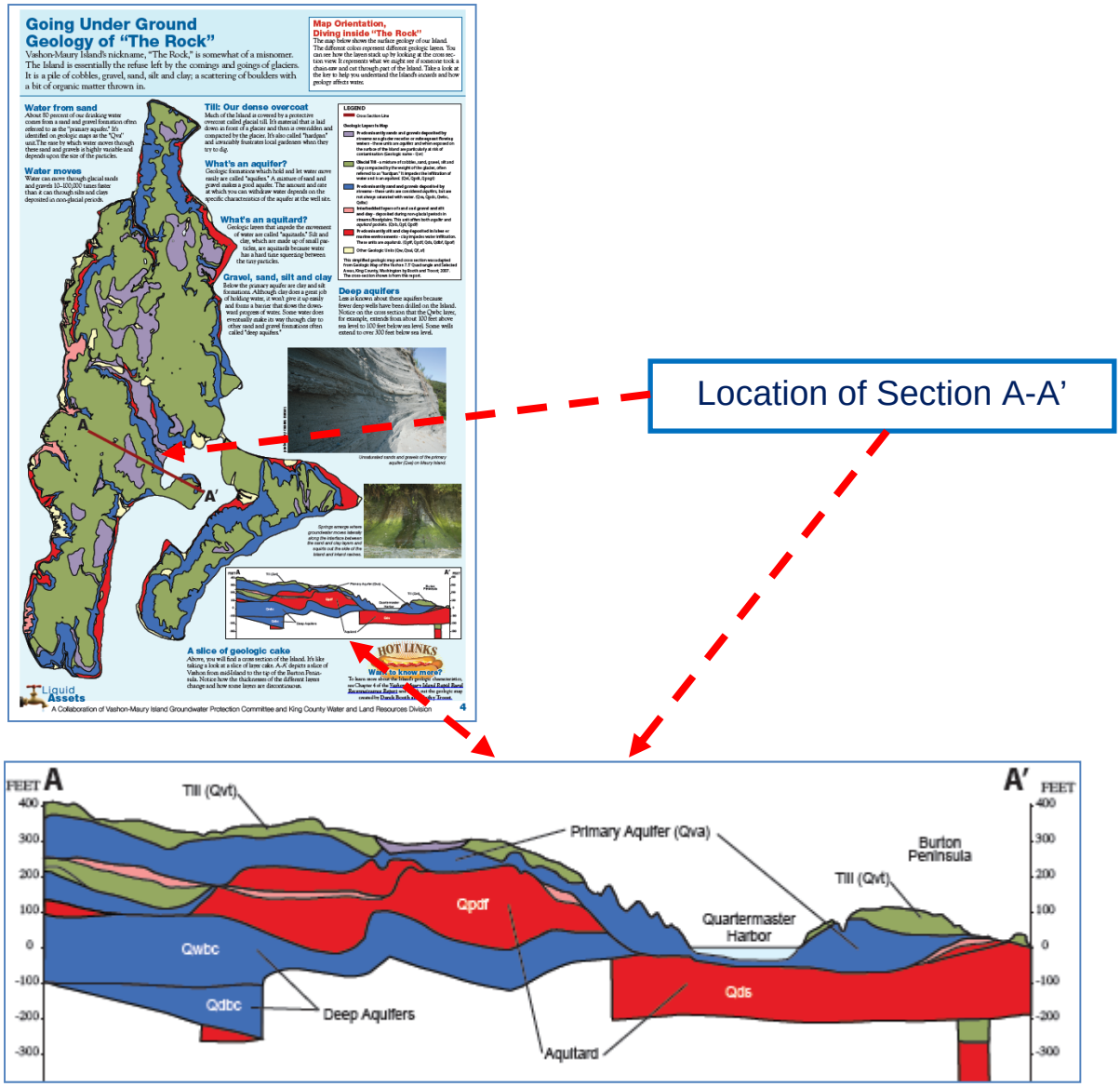

Figure 20. Geologic cross section from west to east (left to right) through inner Quartemaster Habor and Burton Peninsula.

Source: King County – Our Liquid Assets: Going Underground
http://your.kingcounty.gov/dnrp/library/water-and-land/groundwater/liquid-assets-brochure/p4-going-under-ground-geology-of-the-rock.pdf

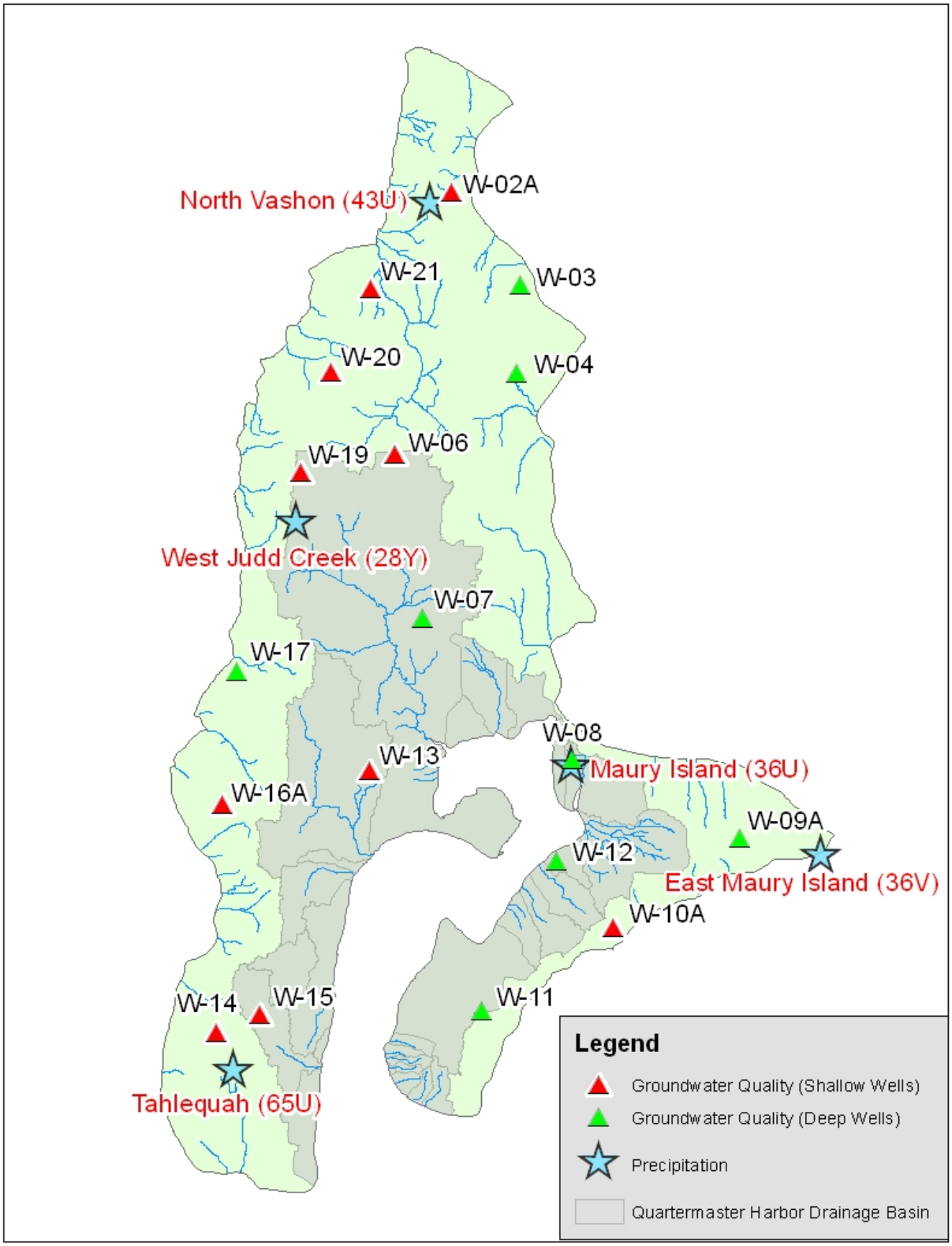

Figure 21. Map showing locations of precipitation gauging stations and shallow and deep groundwater water quality monitoring wells.

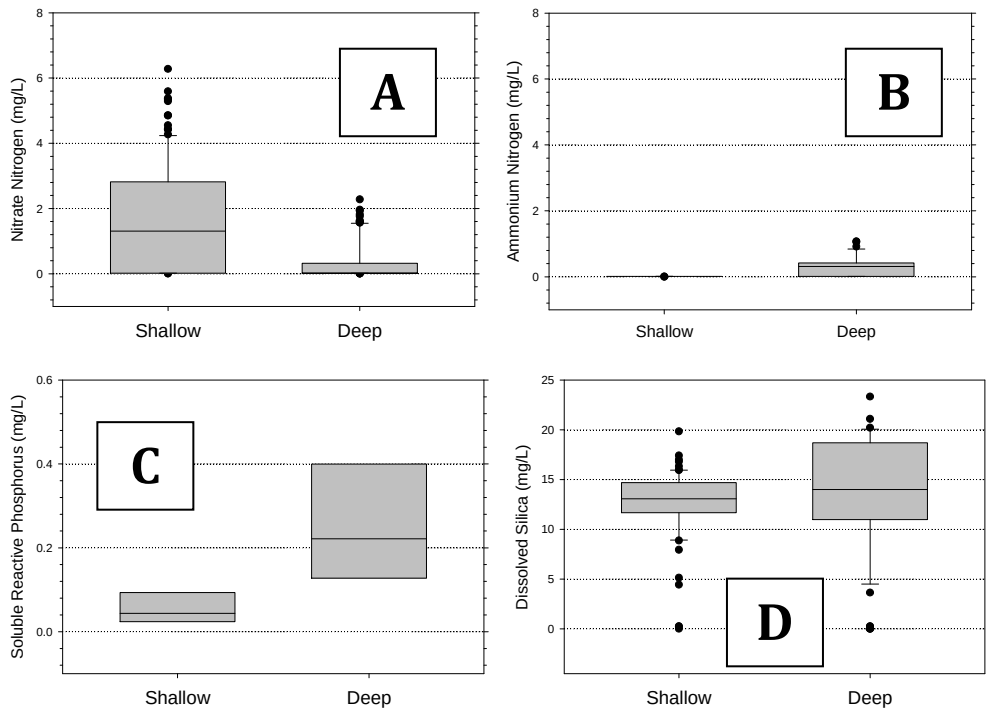

Figure 22. Box plots showing Shallow and Deep groundwater concentrations of dissolved nutrients: A) nitrate, B) ammonia, C) soluble reactive phosphorus and D) dissolved silica.

This expanded dataset confirmed that nitrate concentrations in the Surface Aquifer are generally higher, with a median concentration of approximately 0.6 mg/L (
Figure 23). As noted above, this concentration is very similar to the median concentration observed in streams during late summer base flow and similar to the median concentration observed in freshwater inputs to the harbor from small tributary sources in October 2010. Similar concentrations in groundwater and stream base flow are typical of permeable soils and oxygenated groundwater (Spahr et al. 2010).

No large scale spatial pattern was evident in the distribution of nitrate concentrations in the Shallow Aquifer across the island, although there did appear to be an association of elevated concentrations of nitrate associated with areas identified as CARA Category 1, which is the category used to identify groundwater recharge areas most susceptible to contamination (Figure 24).

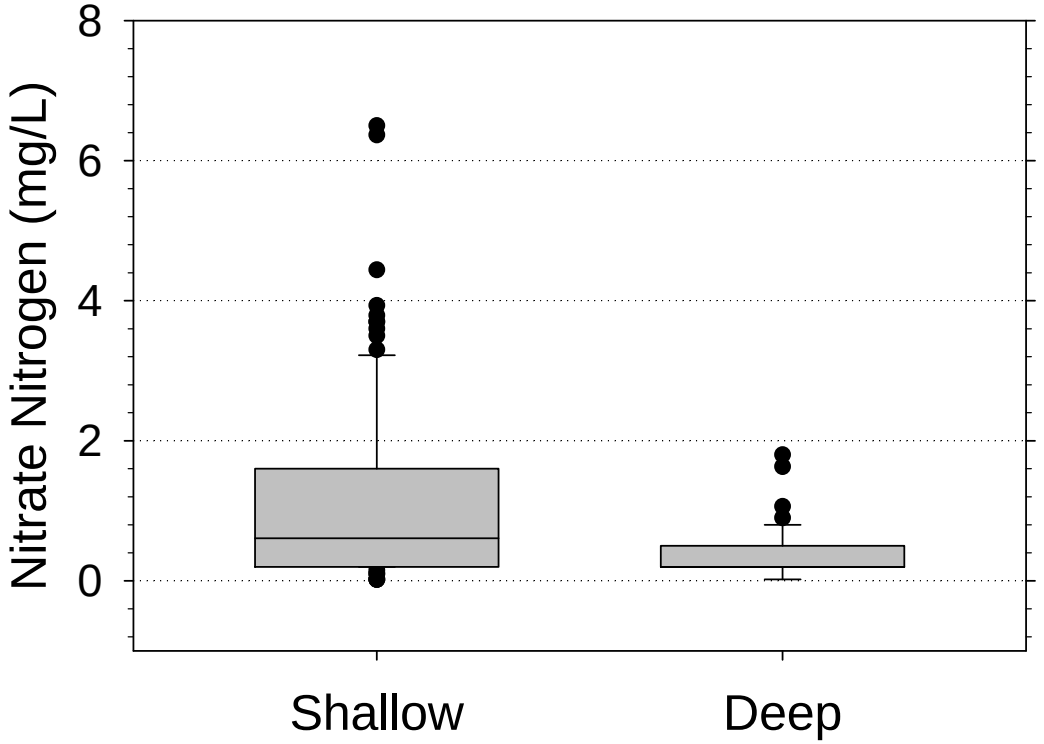

Figure 23. Box plot showing Shallow and Deep groundwater concentrations of nitrate nitrogen in King County routine monitoring wells and available data compiled for Group A and Group B water supply systems.

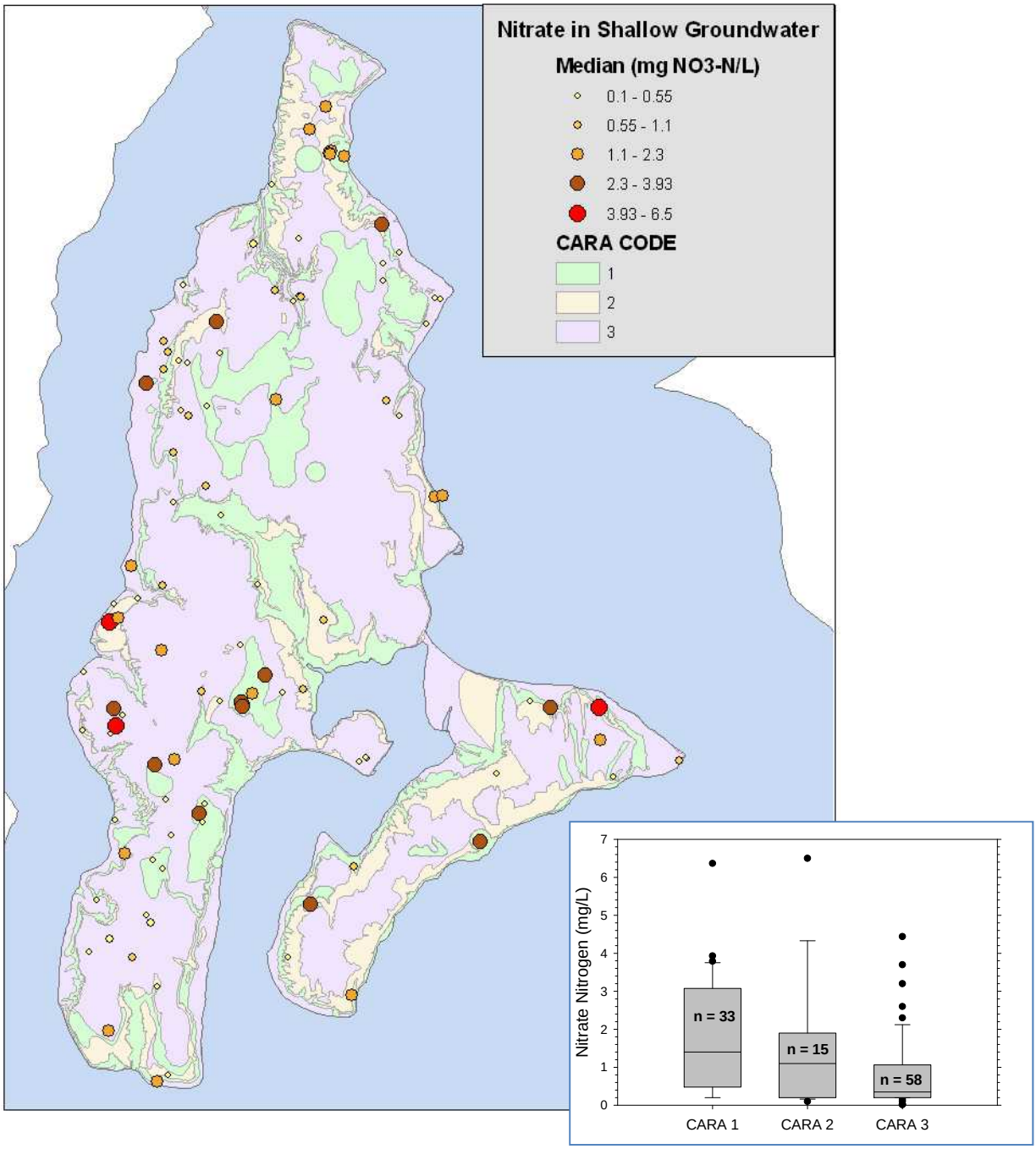

Figure 24. Map and associated box plot showing nitrate concentrations measured in Shallow Aquifer wells and Critcal Aquifer Recharge Area (CARA) categories.

Note: CARA Category1 = highly susceptible to contamination, Category 2 = medium susceptibility to groundwater contamination and Category 3 = low susceptibility to groundwater contamination.

4.3 Synthesis

Of ultimate interest is whether or not the observed levels of nitrate in island streams or aquifer systems are elevated above natural background conditions, and if so, by how much? Smith et al. (2003) described the challenges to estimating natural background concentrations of nutrients, including the lack of pristine reference sites in industrialized countries like the United States. They further distinguished *natural background conditions* from *background* or reference conditions based on data available from relatively undeveloped, but culturally impacted, sampling locations.

Based on logistic regression models developed to evaluate the risk of groundwater nitrate contamination throughout the Puget Sound basin by Tesoriero and Voss (1997), the probability of detecting elevated nitrate concentrations (>3 mg/L) in shallow groundwater on Vashon-Maury Island is relatively low. However, their assessment was directed more at identifying areas of Puget Sound that might be at risk of reaching concentrations close to the 10 mg/L MCL for nitrate in drinking water supplies. Their models were based on vulnerability due to proximity to urban and agricultural areas and susceptibility based on well depth for coarse-grained, alluvial and fine-grained surface geology. Although not terribly useful for determining if the observed nitrate concentrations in island freshwater systems are elevated above historical background, this information does suggest that in general, widespread nitrate contamination above 3 mg/L is not likely to occur on Vashon-Maury Island at this time.

However, long term groundwater monitoring data at specific locations on Vashon-Maury Island do provide an indication that localized increases in nitrate have occurred, including an increase in the Burton groundwater supply mentioned previously (Figure 25).
Given the availability of a relatively large data set and that a number of island wells in the Shallow Aquifer have concentrations above 2 mg/L (20 of 108 wells), it might be useful to develop an island-specific nitrate risk contamination model following the example of Tesoriero and Voss (1997) or Nolan and Hitt (2006).

Another potential source of information regarding background concentrations would be historical pre-development observations of nitrate levels or observations from a relatively undisturbed system with similar characteristics somewhere in the Puget Sound basin. Although Carr/Associates (1983) suggested that the natural background concentration of nitrate in island groundwater was near the laboratory limit of detection (stated as <0.01 mg/L), it is unclear how this was established. Their estimate of background nitrate concentration may have been based to some extent on concentrations measured in the Deep Aquifer, which very likely has naturally lower concentrations than the Shallow Aquifer.

Another source of information regarding likely background concentrations of nitrate is based on data collected from reference streams and rivers as part of the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) program and extrapolated using temporal and spatial regression equations (Smith et al. 2003). Data were stratified by 14 major ecoregions in the United States, with the Western Forested Mountains ecoregion

encompassing the Puget Sound basin. Their analyses suggest an average background stream nitrogen concentration between about 0.08 and 0.2 mg/L after accounting for the anthropogenic influence of atmospheric nitrogen inputs. This estimate is very similar to a range of natural background nitrate concentration estimates developed by Ecology for Puget Sound eutrophication studies, which also included estimates based on nitrogen deposition measured at a location relatively uninfluenced by humans (Mohamedali et al. 2011a and Mohamedali et al. 2011b).

Another potential indication of background surface water nitrate concentrations comes from data collected by King County from Griffin Creek – a relatively undeveloped, forested tributary to the Snoqualmie River. The Griffin Creek basin is predominantly second growth coniferous forest with very little agricultural activity or human habitation (Wilhelm et al. 2013). Nitrate concentrations measured monthly in Griffin Creek since 2011 had a similar seasonal pattern to concentrations in Vashon-Maury Island streams – peak in late fall/winter, elevated winter concentrations and lower concentrations during summer – but the overall concentrations were lower in Griffin Creek (Figure 26).

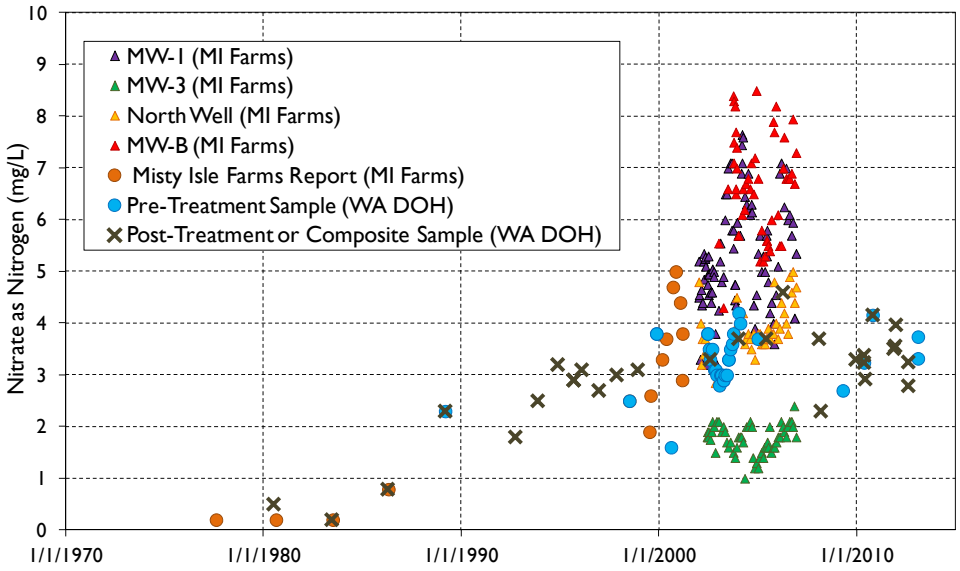

Figure 25. Response of nitrate in shallow groundwater wells to upland land clearing and agricultural activities.

Note: Pre-treatment, composite and post-treatment sample designation set by public water system. For example, treatment may include chlorination (Source: King County 2013a)

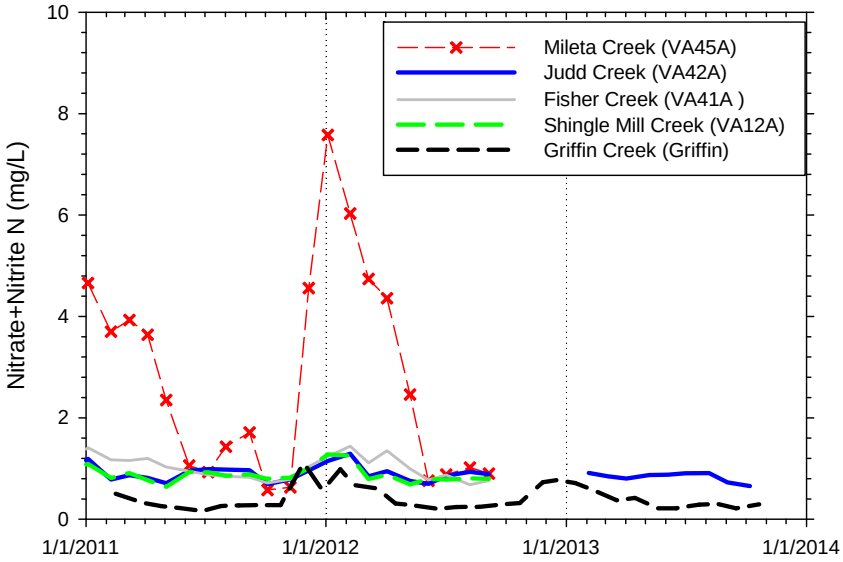

Figure 26. Graph comparing monthly stream nitrate concentrations in Vashon-Maury Island Creeks with relatively undeveloped Griffin Creek.

5.0 MARINE WATER

As noted above, Quartermaster Harbor has been the focus of several previous studies focused on water quality, circulation and harmful algal blooms (e.g., Turnbeaugh 1976, University of Washington 1976, Nishitani et al. 1988). This section provides an overview of available information on the water quality and circulation of Quartermaster Harbor. For a complete overview of marine water quality data collected by King County and UWT, the reader is referred to King County (2014).

The sections below are organized as follows. The next section (Section 5.1) discusses in more detail the dissolved oxygen standards relevant to Quartermaster Harbor. Section 5.2 provides an overview of the physical characteristics of the harbor, including circulation and flushing characteristics. Section 5.3 presents an overview of the available data on dissolved oxygen, nitrogen and phytoplankton and Section 5.4 describes the available data describing the role of sediment nutrient release and dissolved oxygen demand in the harbor. The last section provides a synthesis of the current understanding of the relationships among circulation/flushing and nutrient/phytoplankton/dissolved oxygen dynamics with an emphasis on the critical late summer period when harbor oxygen concentrations are typically lowest.

5.1 Water Quality Standards

Water quality standards have been adopted by Washington to meet the requirements of the Federal Water Pollution Control Act Amendments of 1972 (later amended to be the Clean Water Act).[16] These standards are for the protection of designated uses of state waters, which include use by aquatic life, use by humans for recreation, use for water supply and other miscellaneous uses. Miscellaneous uses include use as wildlife habitat, harvesting of aquatic life by humans as well as use for commerce and navigation, boating and aesthetics.

Although eutrophication of marine waters has the potential to affect aquatic life (via direct effects on dissolved oxygen and via indirect effects such as changes in phytoplankton community structure and promotion of harmful algal blooms), state water quality standards for the protection of marine aquatic life have only been established for dissolved oxygen (Washington Administrative Code 173-201A-210). The establishment of water quality standards for dissolved oxygen differs with respect to the development of standards for synthetic contaminants in two important ways (U.S. EPA 2000). One difference is that low oxygen concentrations can occur naturally. The second difference is that when levels are found to be influenced significantly by humans it is controlled indirectly by reducing human inputs of nutrients and/or oxygen demanding wastes.

The state marine dissolved oxygen standard for a particular waterbody depends on the category assigned in the standards (Table 2). Quartermaster Harbor is categorized as Extraordinary and the applicable standard is that dissolved oxygen concentrations do not

[16] Water Quality Standards for Surface Waters of the State of Washington (revised January 2012): http://www.ecy.wa.gov/biblio/0610091.html

go below 7.0 mg/L more than once every ten years. When dissolved oxygen concentrations go below the applicable standard due to natural conditions, then human influence considered cumulatively may not cause the dissolved oxygen to decrease more than 0.2 mg/L below the natural level. The standard is meant to apply to the dominant aquatic habitat of the area and not to shallow, stagnant, backwater areas.

Another requirement of the Clean Water Act, found in Section 303(d), is that states must routinely perform a water quality assessment of surface waters of the state using available data and submit a list of impaired waters in need of a water cleanup plan. The most recent state assessment approved by EPA in December 2012 placed Quartermaster Harbor in Category 5 for impairment for dissolved oxygen. Category 5 is reserved for waterbodies where Ecology has credible data that water quality standards have been exceeded and there is no water cleanup plan already developed. Waterbodies designated as Category 5 require the development of a Water Quality Improvement project. A Water Quality Improvement project can lead to a Total Maximum Daily Load (TMDL) or lead to an approach known as Straight to Implementation.[17]

Because the data available for the assessment represent current conditions and natural conditions in Quartermaster Harbor can be part of the cause of low dissolved oxygen, a Water Quality Improvement Project would typically require the development of a calibrated water quality model to establish if human influence on dissolved oxygen concentrations is greater than 0.2 mg/L (e.g., Roberts et al. 2012, Ahmed et al. 2013).

Table 2. Washington marine dissolved oxygen standards (WAC 173-201A-201).

Category	Lowest 1-Day Minimum
Extraordinary	7.0 mg/L
Excellent quality	6.0 mg/L
Good quality	5.0 mg/L
Fair quality	4.0 mg/L

The allowance of no more than a 0.2 mg/L decrease due to human influence is part of the anti-degradation policy of the state water quality standards intended to restore and maintain the highest possible quality of waters of the state. Generally, Water Quality Improvement Projects or Total Maximum Daily Load Studies based on eutrophication models of the system of interest are developed to evaluate the current and future influence of nutrient inputs from point and/or nonpoint sources on dissolved oxygen (e.g., Roberts et al. 2012).

[17] Ecology Water Quality Improvement process: http://www.ecy.wa.gov/programs/wq/tmdl/index.html

5.2 Physical Characteristics

Tides in Puget Sound, including Quartermaster Harbor, are of the mixed semi-diurnal type with two high and two low tides each day. The tidal range is about 3.7 m (12 ft) between mean higher high water (MHHW) and mean lower low water (MLLW) (Mofield et al. 2002).[18]

Turnbeaugh (1976) conducted a circulation study of the harbor which indicated that weakest currents were found in the inner harbor. Surface current speeds during maximum flood and ebb tide were greatest in the outer harbor with maximum current speeds of 0.27 m/s (0.9 ft/s). Turnbeaugh (1976) also noted that although salinity and temperature varied vertically at various locations throughout the harbor, consistent with two layer partially-mixed estuarine circulation, longitudinal salinity differences were relatively small. This pattern in salinity is typical of inner bays of larger estuaries with relatively low freshwater input at the head of the bay (MacCready and Banas 2011). This pattern in longitudinal salinity (and density) was also observed during cruises conducted by UWT as part of this study (Figure 27).

Of primary interest to this study is the flushing time of the harbor, which as noted previously is an important factor in creating favorable conditions for phytoplankton blooms and low oxygen conditions (Rensel Associates and PTI 1991). The hydrodynamic model developed for this study (Albertson 2013) confirmed that the inner harbor is relatively poorly flushed in late summer (Figure 28). Albertson (2013) also presented spatially varying flushing rates for October, which highlighted the poor flushing time of the inner harbor – averaging about 86 days in 2009 based on the model results (Figure 29).

5.3 Water Quality

As noted above, dissolved oxygen data collected by King County since 2006 have indicated low dissolved oxygen conditions in Quartermaster Harbor, particularly in September and October (see Figure 2). Also noted above, and illustrated again here is that coincident with summer algal blooms, nitrate concentrations fall below laboratory detection limits (Figure 30). Figure 30 also illustrates that nitrate concentrations in the main basin of Puget Sound (here represented by the King County ambient monitoring station in East Passage) rarely fall below laboratory detection limits – and then typically only during the spring algal blooms. Bottom water concentrations in East Passage also fall below the applicable state standard of 7 mg/L in late summer (to about 5 mg/L), but not nearly as low as in Quartermaster Harbor (Figure 31).

The first observations of low oxygen concentrations in the harbor were likely made by Turnbeaugh (1976) who reported a dissolved oxygen concentration of 3.8 mg/L in bottom waters of the inner harbor in October 1974. Turnbeaugh's map indicates that the sampling location where the lowest oxygen concentration was observed in October 1974 is similar to King County's Station MSWH01 at the Yacht Club in the inner harbor (Figure 31).

[18] The elevation of the NAVD 88 datum relative to MLLW at the Burton tide station in Quartermaster Harbor is 0.89 m (2.92 ft).

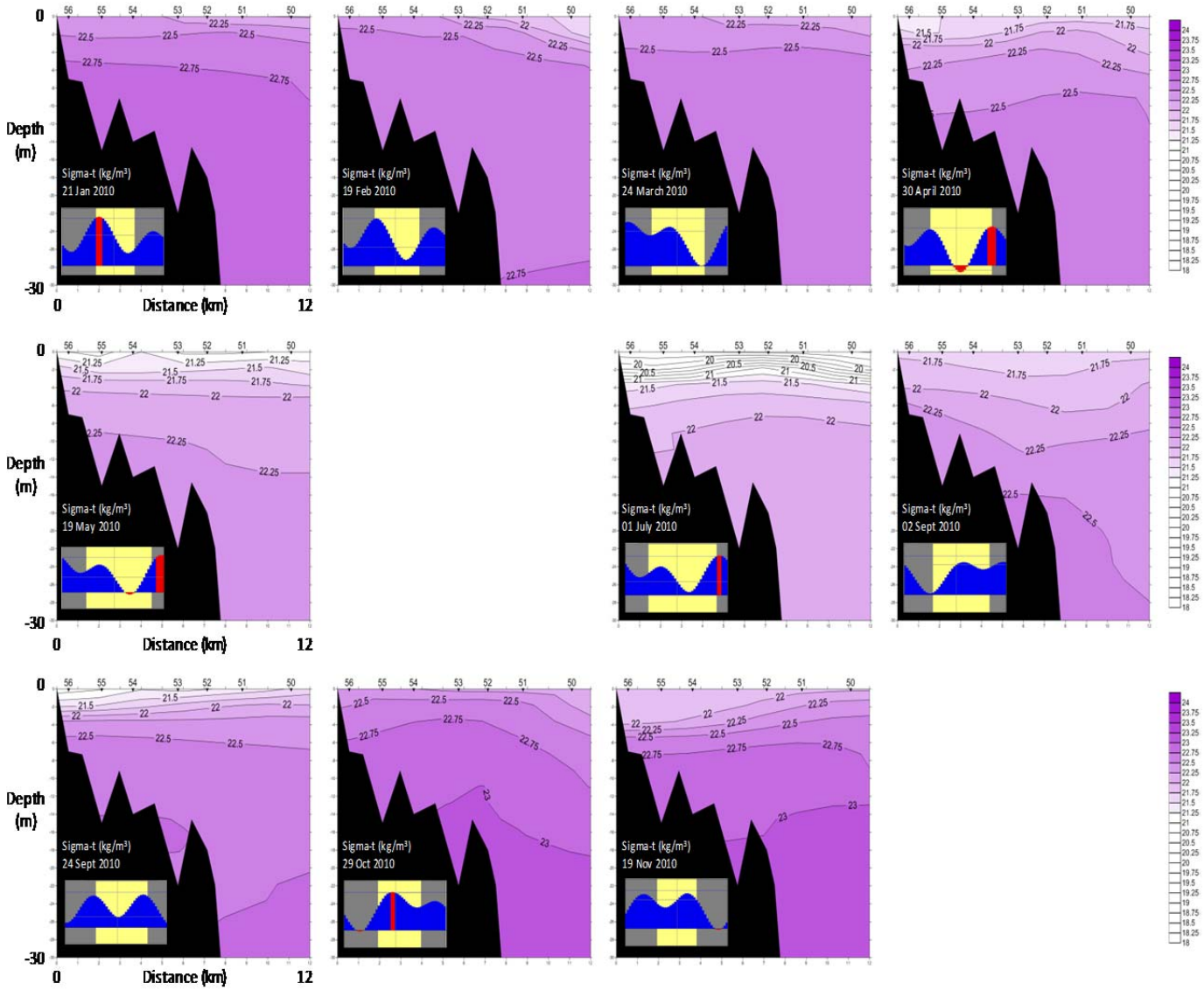

Figure 27. Color contour maps showing the longitudinal distribution of density (sigma-t) in Quartermaster Harbor based on monthly cruises conducted by UW Tacoma in 2011 (King County 2014).

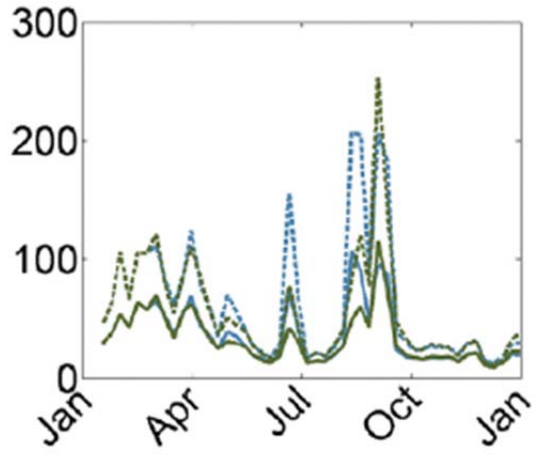

Figure 28. Graph showing Quartermaster Harbor flushing times (days) determined for 2009 conditions from the fine resolution hydrodynamic model developed for this study.

Source: Albertson (2013)

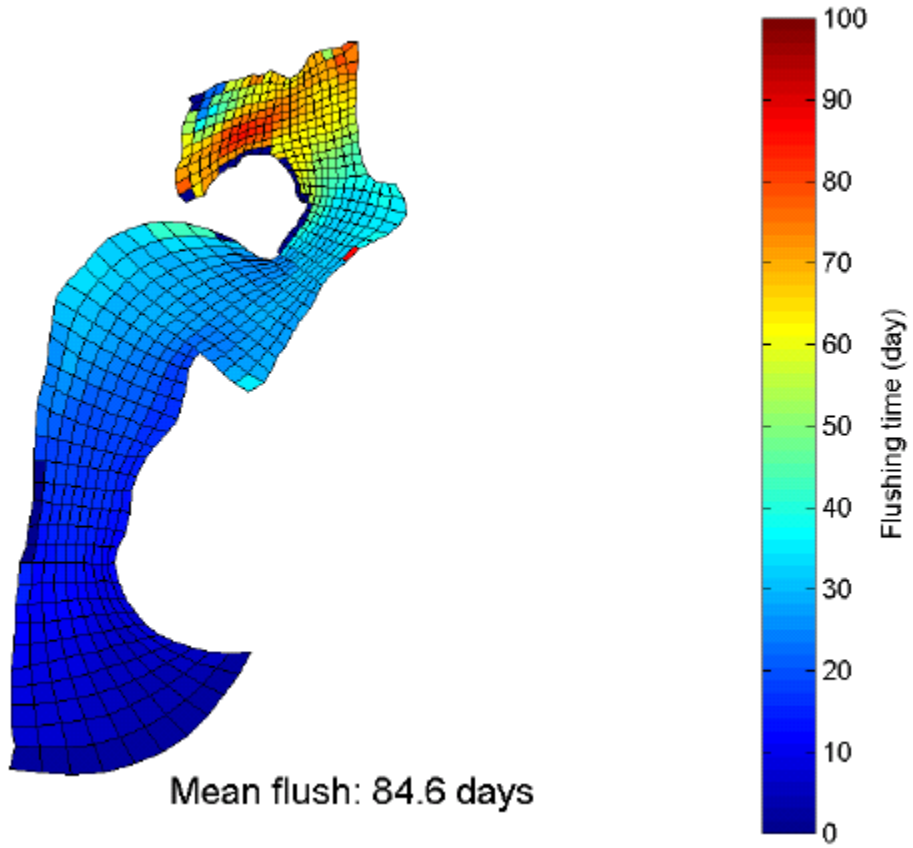

Figure 29. Map of the fine resolution hydrodynamic model grid of Quartermaster Harbor illustrating the predicted October 2009 flushing time (Albertson 2013).

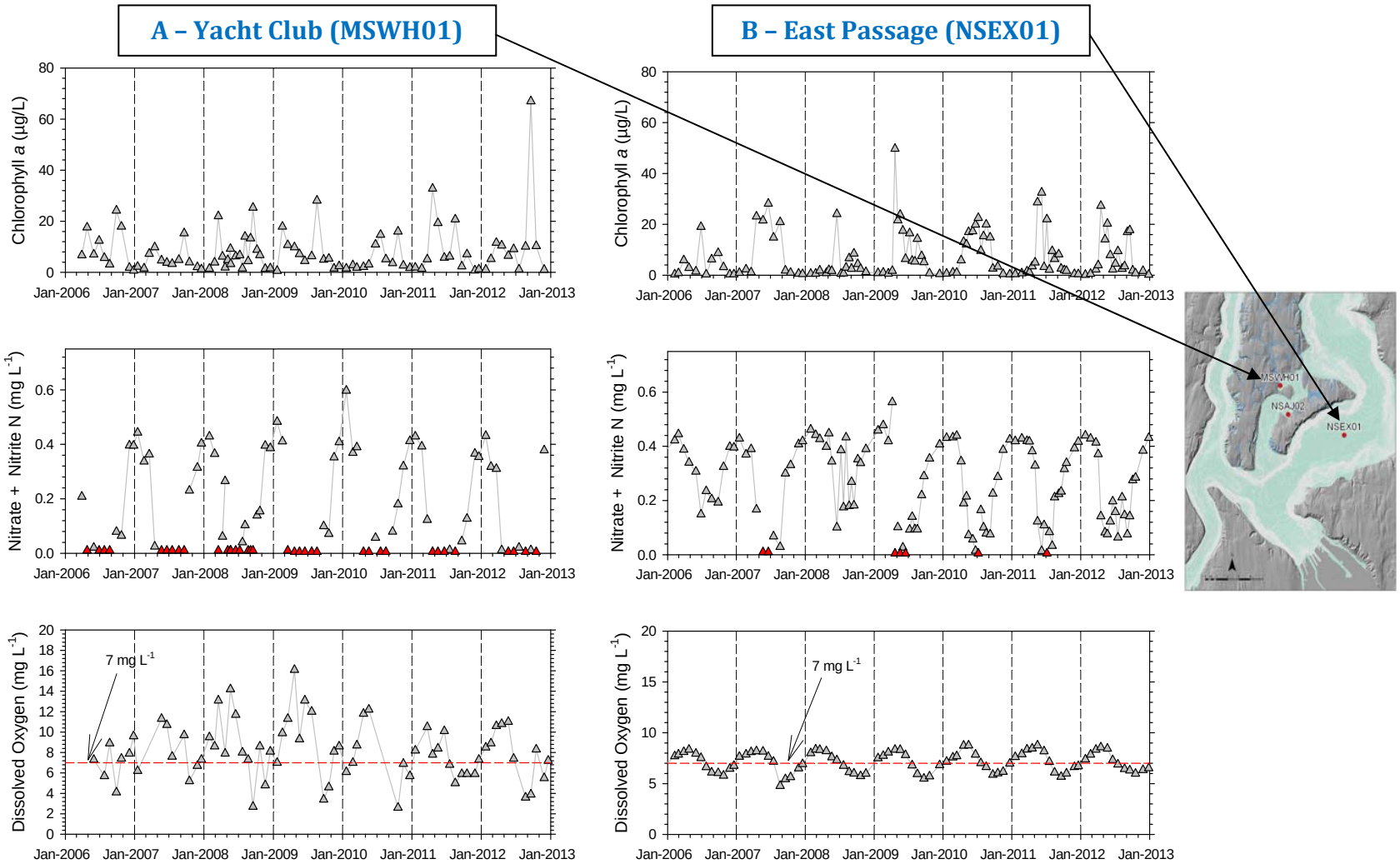

Figure 30. Time series plots comparing surface water concentrations of chlorophyll *a* and nitrate nitrogen and bottom water concentrations of dissolved oxygen at A) the Yacht Club and at B) East Passage from 2006 through 2012.

Note: Red triangles in the center panel represent nitrate concentrations that were below the laboratory detection limit of 0.02 mg/L. The state standard for dissolved oxygen is shown as a dashed red line in the bottom panel.

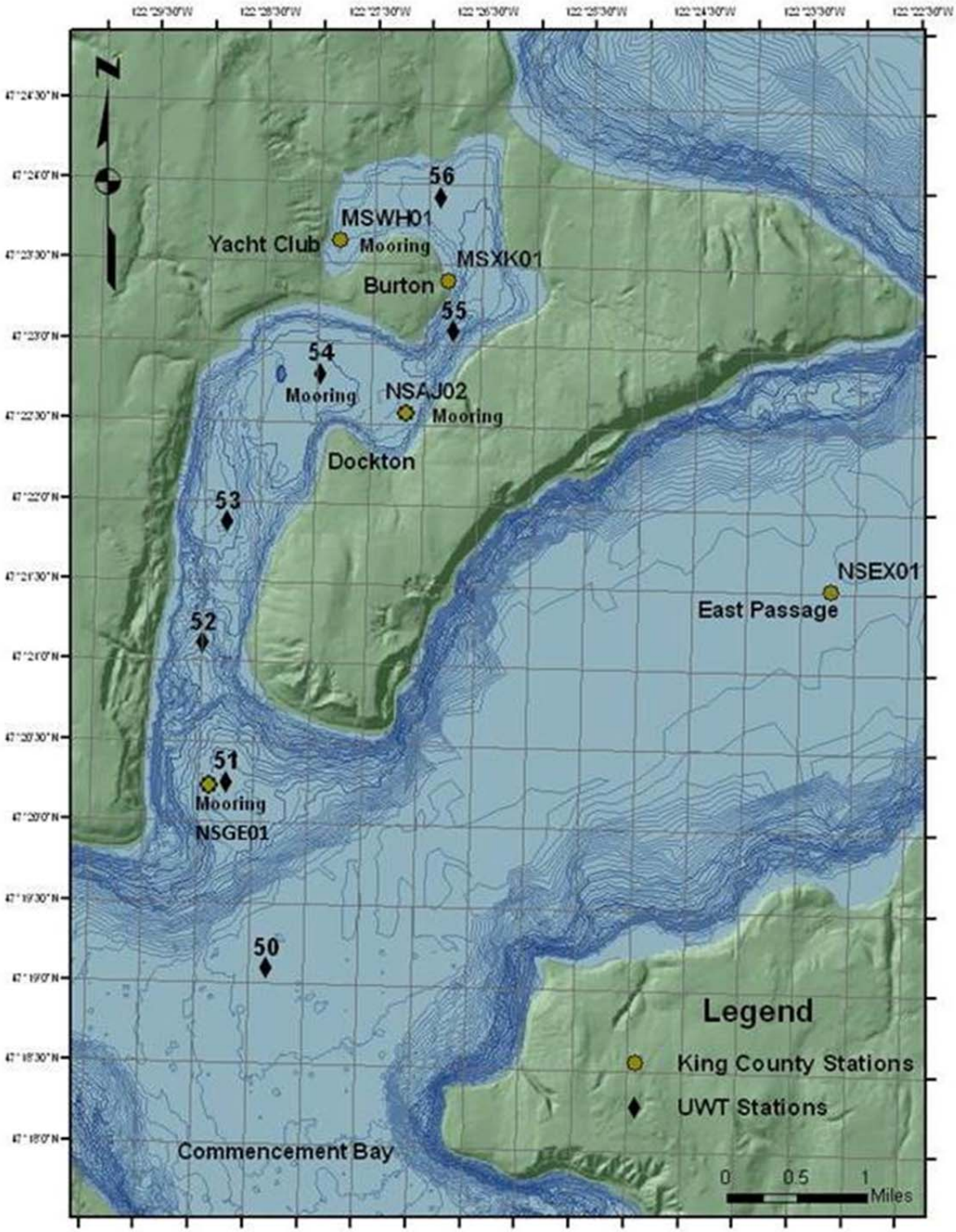

Figure 31. Map showing marine monitoring stations sampled by King County and UWT as part of this study.

Figure 31 illustrates the locations of King County and UWT mooring and monthly monitor stations sampled as part of this study. The reader is referred to the marine monitoring report for a detailed overview of water quality conditions in Quartermaster Harbor (King County 2014).

In this report, the King County mooring data collected at Dockton (NSAJ02) and the Yacht Club (MSWH01) (at 15 minute recording intervals) are used to further highlight the patterns in low dissolved oxygen in the inner harbor (Figure 32). A moored multi-sensor probe was deployed initially at the Quartermaster Harbor Yacht Club along with a weather station during September 2008. The mooring was suspended from a float on the water surface. The dissolved oxygen data from this relatively short deployment indicated that dissolved oxygen levels in the inner harbor would decline precipitously near midnight and remain low (1 to 2 mg/L) until morning. These relatively extreme dissolved oxygen excursions were missed by the routine monthly sampling at the same location, which only takes place during the day.

The mooring and weather station were moved to Dockton in 2009. The Dockton mooring was fixed to a marina piling and therefore sampled different depths of water over the tidal cycles, but because the sensor recorded depth, it also recorded changes in tidal elevation (and the occasional tsunami wave). Although minimum dissolved oxygen concentrations were observed in September and October at Dockton (typically about 4 mg/L), extremely low oxygen levels were not recorded (Figure 32). In 2011, the mooring at the Yacht Club was re-established and the more extreme excursions in late summer/fall dissolved oxygen levels were observed again (Figure 32).

To get a better sense of the conditions preceding these events, the available data were examined more closely. Time series plots showing two to three weeks of data suggest that these events are typified by periods with diurnal winds changing from relatively strong northerly winds during the day to light southerly winds during the night with many, but not all, episodes occurring during lower low tides (Figure 33 and Figure 34). Salinity also increases at the Yacht Club during these low dissolved oxygen events, which is most apparent in Figure 34. This suggests that the episodes of extremely low dissolved oxygen are associated with events related to winds from the north during this late summer period. Sustained periods of winds from the south are not associated with low dissolved oxygen episodes in the inner harbor during this same period (see Figure 33). It should be noted that diurnal winds are also associated with clear sunny weather at this time of year and sustained southerly winds are associated with storms. Late summer low dissolved oxygen at the heads of fjords with little freshwater inflow have been observed in Dabob Bay (in Puget Sound) and in British Columbia mainland fjords (Pickard 1961, Kollmeyer 1965, Ebbesmeyer 1973).

What is still unclear is where the water with such low dissolved oxygen concentrations originates from. The subsurface dissolved oxygen levels measured at Dockton have also indicated excursions in the mooring and grab data to concentrations near 2 mg/L. It is possible that water with very low dissolved oxygen occurs near the bottom in the outer harbor that is upwelled into the inner during these episodes, it is also possible that there is

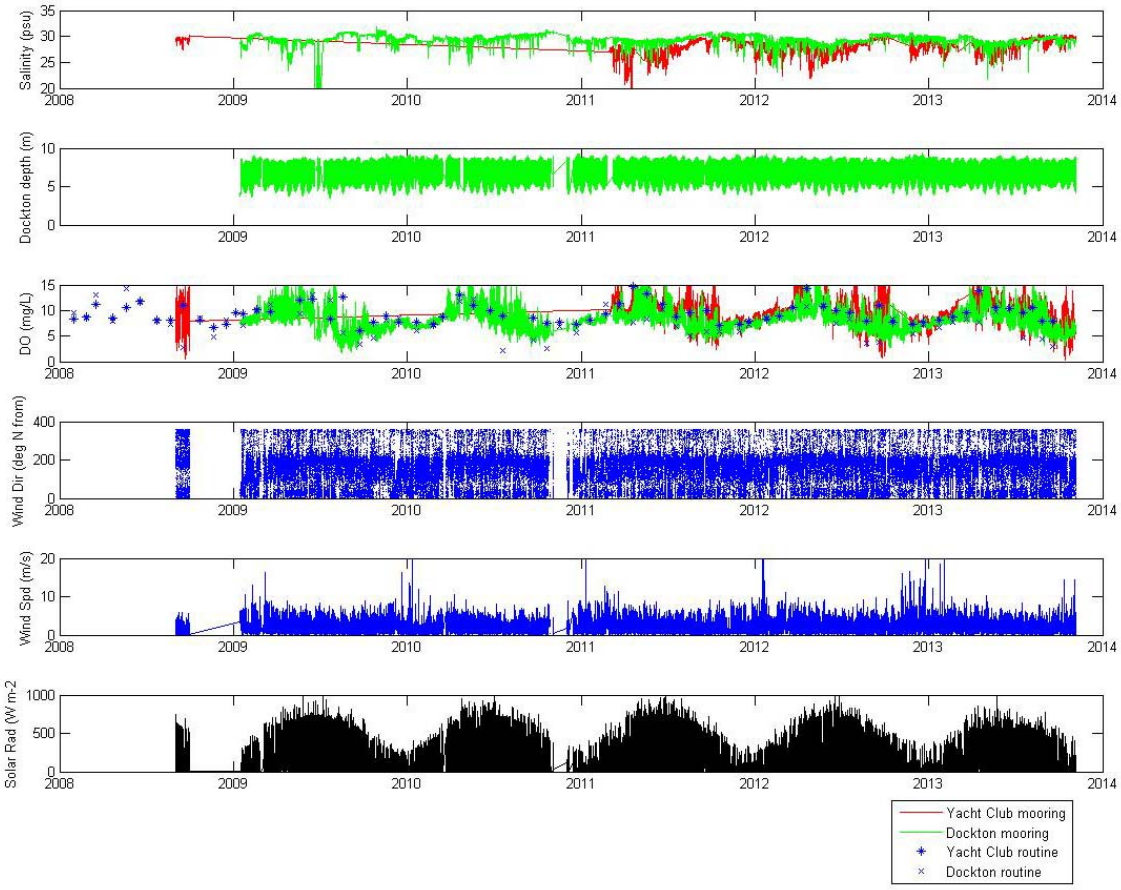

Figure 32. Time series plots of King County continuous mooring (Dockton and Yacht Club) and weather (Dockton) data collected by King County in Quartermaster Harbor since late 2008.

Note: Wind speed/direction and solar radiation data were collected at Dockton. The Dockton mooring is fixed to a pier piling so the depth of the sensors varies over the tidal cycle. The second panel from the top plots the depth over time of the mooring at Dockton. The mooring at the Yacht Club is suspended from a float approximately 1 m below the water surface.

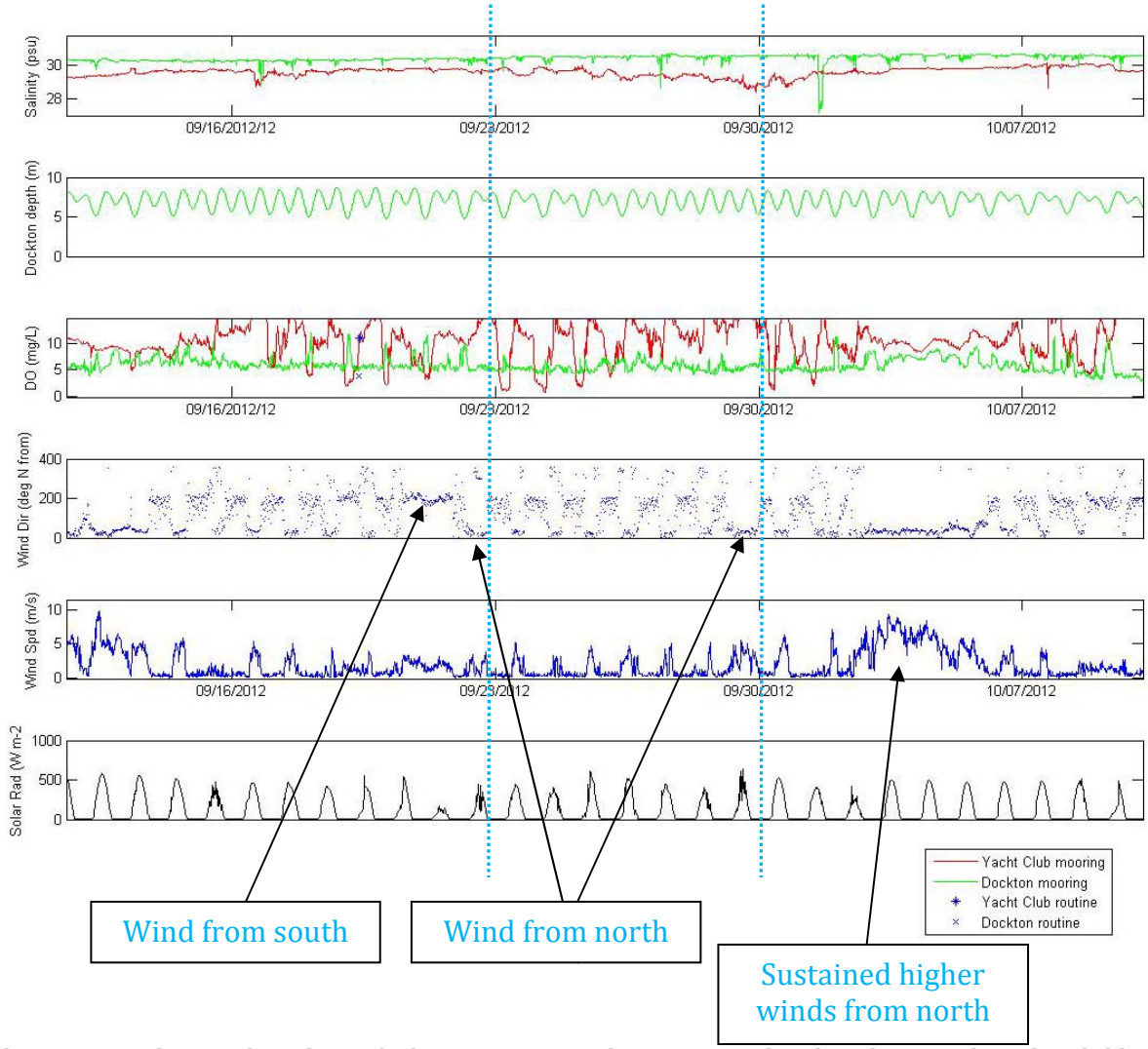

Figure 33. Time series plots of King County continuous mooring (Dockton and Yacht Club) and weather (Dockton) data collected by King County in Quartermaster Harbor during periods of low dissolved oxygen at the Yacht Club in September 2012.

Note: Vertical blue-dotted lines provided as a visual orientation to the conditions proceeding and following selected low dissolved oxygen events observed in the inner harbor.

Wind speed/direction and solar radiation data were collected at Dockton. The Dockton mooring is fixed to a pier piling so the depth of the sensors varies over the tidal cycle. The second panel from the top plots the depth over time of the mooring at Dockton. The mooring at the Yacht Club is suspended from a float approximately 1 m below the water surface.

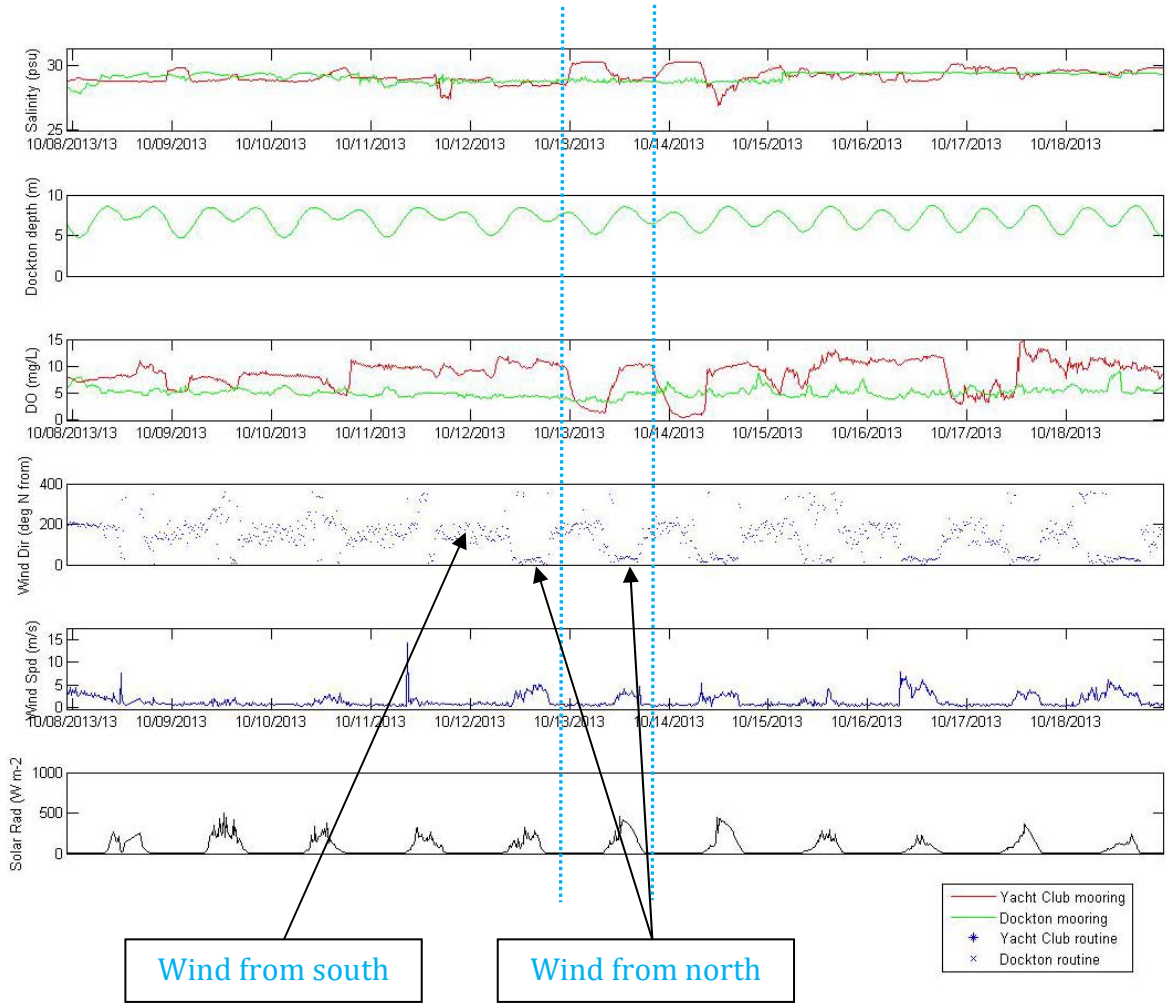

Figure 34. Time series plots of King County continuous mooring (Dockton and Yacht Club) and weather (Dockton) data collected by King County in Quartermaster Harbor during periods of low dissolved oxygen at the Yacht Club in October 2013.

Note: Vertical blue-dotted lines provided as a visual orientation to the conditions proceeding and following selected low dissolved oxygen events observed in the inner harbor.

Wind speed/direction and solar radiation data were collected at Dockton. The Dockton mooring is fixed to a pier piling so the depth of the sensors varies over the tidal cycle. The second panel from the top plots the depth over time of the mooring at Dockton. The mooring at the Yacht Club is suspended from a float approximately 1 m below the water surface.

a layer of low dissolved oxygen near the bottom of the inner harbor, or a portion of the inner harbor, that remains distinct under conditions of low tidal amplitude typical of this time of year and/or minimal mixing by weak winds from the south.

5.4 Harmful Algal Blooms

As noted previously, the toxin producing dinoflagellate *Alexandrium catenella* has been observed in inner Quartermaster Harbor (Nishitani et al. 1988). Phytoplankton analyses conducted by King County and UWT also noted the frequent occurrence of *Alexandrium* in Quartermaster Harbor, typically between August and November (King County 2014). In fact, Quartermaster Harbor has the distinction of having the highest concentration of *Alexandrium* cysts in sediments sampled throughout Puget Sound in 2005 (Horner et al. 2011). Cysts are a resting stage and are thought to provide the seed for initial blooms under favorable environmental conditions (Cox et al. 2008). Washington State Department of Health monitors toxin levels in shellfish throughout Puget Sound and closes shellfish beds to harvesting when toxin levels exceed safe limits for human consumption. Quartermaster Harbor is an initiation site for these toxic blooms and is frequently closed due to PSP (Horner et al. 2011).

Nishitani et al. (1988) also noted that *Alexandrium* in Quartermaster Harbor exhibited a diurnal migration pattern, migrating downward in the evening and then returning to the upper water column by morning. Perhaps it is possible that motile phytoplankton in the inner harbor during late summer/fall may be involved in the development of a low oxygen layer along the bottom of the inner harbor.

Alexandrium is not the only harmful algal species in Quartermaster Harbor. Phytoplankton monitoring indicates that a large bloom of *Heterosigma akashiwo*, a motile rhaphidophyte that can be toxic to fish and possibly other wildlife (Rensel 2007) was observed in Quartermaster Harbor in September 2011 (King County 2014). Another bloom was observed in July of 2013 that was attributed as the cause of a fish kill observed at the same time by Frank Jackson, an island resident.

Another potentially harmful phytoplankton species observed in Quartermaster Harbor is the dinoflagellate *Noctiluca scintillans*, which often results in a strong pinkish red or orange discoloration which makes the water look like tomato-soup. In the Pacific Northwest, this species does not appear to produce toxins and isn't associated with harmful effects, although when large blooms start to decay they can deplete water column oxygen concentrations (Puget Sound Action Team 2007). A large bloom was noted throughout the inner and outer harbor in September 2010. What is particularly interesting about this species is that it is not photosynthetic, but rather heterotrophic, feeding on other phytoplankton, protozoans, detritus, and fish eggs.

5.5 Sediment Nutrient and Dissolved Oxygen Flux

A study conducted by Ecology to support the development of the water quality model of South Puget Sound found that nutrient fluxes from marine sediments of shallow embayments may be a significant source of nitrogen to marine waters during the critical

period of low dissolved oxygen (Roberts et al. 2008). Based on the data provided in Roberts et al. (2008), the marine sediments of Quartermaster Harbor may also be a relatively significant source of nutrients to Quartermaster Harbor during the critical period of low dissolved oxygen (King County 2010e). King County (2010e) recommended conducting a benthic nutrient flux study in Quartermaster Harbor to confirm the rates measured in other shallow embayments of Puget Sound and provide site-specific data for use in the development of more accurate sediment nutrient loading estimates for the harbor.

The details of the Quartermaster Harbor sediment nutrient release study are provided in King County (2012c). Five stations were occupied for an approximate 24-hr period in September 2010 (Figure 35). The results were similar to the range of results reported by the recent study conducted in four South Puget Sound embayments that used the same equipment and methods (Roberts et al. 2008). There was a distinct gradient in the results with the greatest sediment oxygen demand and nutrient flux observed at the shallowest location in the inner harbor (Table 3). Lowest nutrient release (and lowest sediment oxygen demand) was estimated for the deepest station in the outer harbor. This station also had very little fine sediment and the lowest amount of sediment total organic carbon. Highest nutrient release (and highest sediment oxygen demand) was observed at the station located in the innermost portion of the inner harbor. Sediment characteristics at this station, and at the other three stations with moderate nutrient release rates and sediment oxygen demand, were dominated by fines and had similar levels of sediment organic carbon, total nitrogen and sulfide (Table 3).

Because sediments may provide a long-term reservoir (i.e., internal source) of nitrogen for phytoplankton growth that could delay the response of the harbor to nitrogen loading reduction from human sources, additional studies of sediment nutrient flux may be warranted.

5.6 Synthesis

Similar to the difficulty of determining the concentrations of nitrate in streams and groundwater prior to human disturbance, there are no historical observations available for determining the natural nutrient-phytoplankton-oxygen dynamics of Quartermaster Harbor. It appears that low oxygen concentrations have occurred in the inner harbor at least since the mid-1970s.

In order to address the question of how the trophic state of the harbor has changed since its discovery by the Wilkes expedition, there appear to be at least two independent approaches. One approach would be to collect and analyze sediment cores from the harbor and conduct analyses similar to those used by Brandenberger et al. (2008) to reconstruct the history of hypoxia in the main basin of Puget Sound and Hood Canal. The second approach would be to develop and calibrate a nutrient-phytoplankton-oxygen model of the harbor and evaluate nitrogen reduction scenarios to estimate the relative human influence on harbor dissolved oxygen resources and perhaps the effects of human activity on the frequency and severity of harmful algal blooms in the harbor.

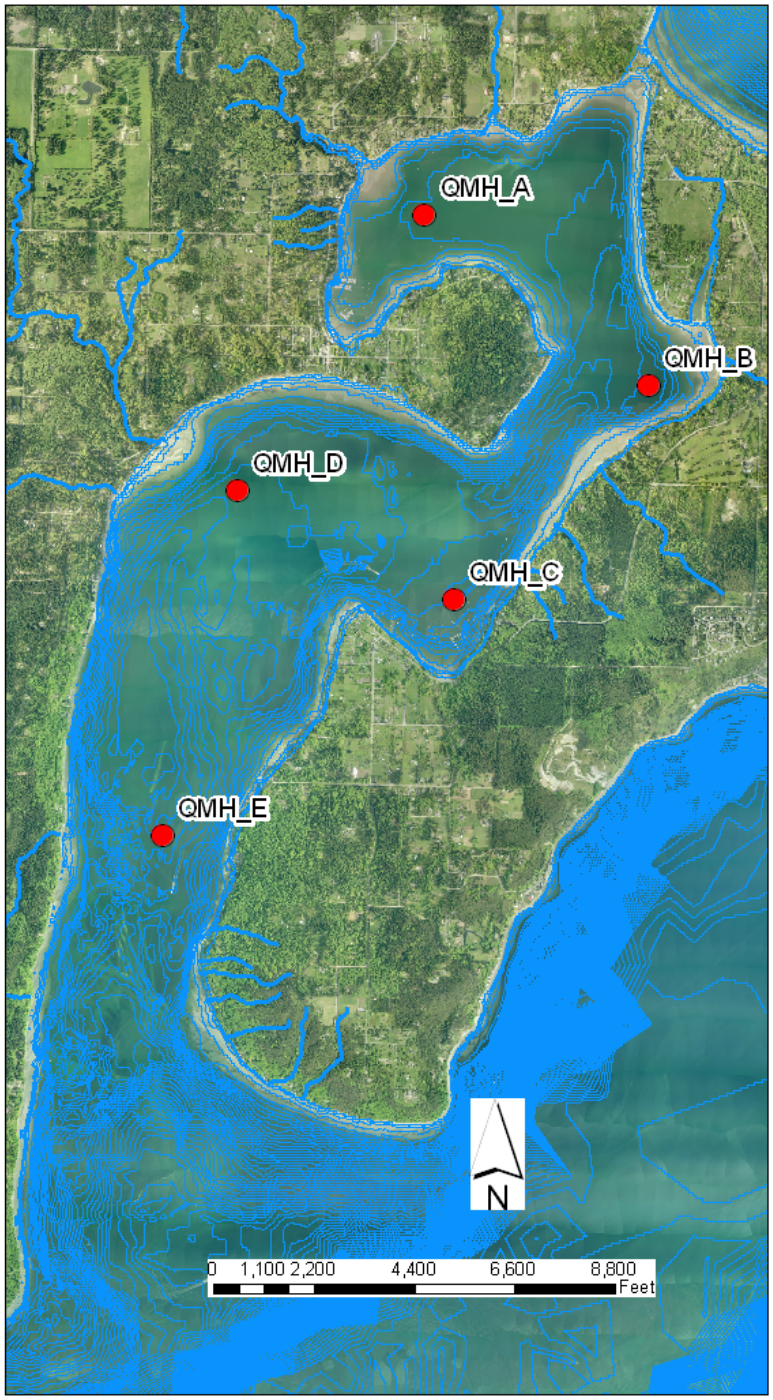

Figure 35. Map showing locations of benthic nutrient flux chambers.

Note: Bathymetric contours (5-ft intervals; NAVD 1988) based on data from Finlayson (2005) are shown to illustrate expected bottom topography at each sampling station.

Table 3. Comparison of dissolved oxygen and nutrient flux estimates to surface sediment (0-2 cm) chemistry measured in the vicinity of each benthic flux chamber.

	Sediment Data					Flux Data			
Station	**%Fines**	**%TOC**	**TN**	**NH3-N**	**TS**	**DO**	**DIN**	**Ortho-P**	**DSi**
	%		**mg kg^{-1} dry sediment**			**g m^{-2} d^{-1}**			
MSVK01 QMH-A	76	2.8	2,460	14.3	404	1.72	0.15	0.04	0.996
MSXM01 QMH-B	68	2.0	1,970	17.9	717	0.72	0.06	0.01	0.219
NSAJ03 QMH-C	75	2.5	2,280	9.2	935	0.64	0.05	0.0	0.079
MSZF01 QMH-D	75	2.1	2,030	11.5	1,010	0.95	0.01	0.0	0.019
NSCE01 QMH-E	19	0.5	458	5.2	21.7	0.16	-0.01	0.0	0.014

Sediment data from King County (unpublished)
TOC = Total Organic Carbon, TN = Total Nitrogen, NH-3 = Ammonia Nitrogen, TS = Total Sulfide, DO = Dissolved Oxygen, Ortho-P = Orthophosphate Phosphorus, DSi = Dissolved Silica

The first approach may be considered somewhat limited, because it does not directly address the anti-degradation standard of no more than a 0.2 mg/L effect on oxygen levels due to human activity. In other word, the sediment reconstruction approach would not resolve small changes in the trophic state of the harbor, but it might provide some insight as to whether the changes were large or small.

The second approach based on the development and calibration of eutrophication models has provided an estimate of the potential human influence on dissolved oxygen in Puget Sound (Ahmed et al. 2013, Roberts et al. 2013) and in Budd Inlet (Roberts et al. 2012). However, the mechanisms that result in the extremely low oxygen concentrations in Quartermaster Harbor appear to be more complicated than assumed in these modeling efforts due to the presence of harmful algal species. The complications associated with modeling harmful algae have been highlighted in a number of publications (Horner et al. 1997, Smayda and Reynolds 2001, Anderson et al. 2002, Gilbert et al. 2005). In general, there appear to be a multitude of factors that potentially contribute to the response of a particular strain of a harmful species to human disturbance, including increased nutrient loading.

Perhaps of even more relevance is the lack of association of episodes of low dissolved oxygen levels with fish kills. Fish kills have been observed in Quartermaster Harbor, but these fish kills appear to be associated with the occurrence of harmful types of algae. The suggestion is that the focus with respect to beneficial uses of the harbor might better be directed primarily toward understanding the factors influencing harmful algal blooms and

secondarily at concerns regarding dissolved oxygen, although some research has actually suggested that anoxic sediments may be a prerequisite for initiation of some harmful algal blooms (Smayda and Packard 1979).

6.0 NITROGEN LOADING

Initial estimates of nutrient loading from tributary streams, groundwater, nearshore septic systems, atmospheric deposition and sediments to Quartermaster Harbor were reported by King County (2010e). Since that time, additional stream and groundwater quality data were collected (King County 2013a) and a study of sediment nutrient flux in Quartermaster Harbor was conducted (King County 2012c). Furthermore, no initial estimate was developed for the input of nutrients via tidal and estuarine exchange flow through the harbor entrance. Also, as a result of presentations and public meetings, interest in quantifying the importance of inputs from boats moored in the harbor was also expressed.

The sub-sections below summarize the current best estimates of dissolved inorganic nitrogen (DIN) loading to the harbor focusing on the critical season (defined here as October) loading to the harbor as a whole and specifically to the inner harbor. Dissolved inorganic nitrogen refers to the sum of nitrate and ammonia nitrogen. In general, nitrate is the dominant form of inorganic nitrogen in fresh and marine water and ammonia nitrogen is the form of nitrogen released from marine sediments. For more detailed information on the sources of data and methods used to estimate nutrient loading to the harbor, other than those described below, the reader is referred to King County (2010e).

6.1 Groundwater

The initial estimate of groundwater flow to the harbor was revised based on incorporation of additional years of water balance data for the drainage basin (based on stream flow and precipitation data collected through 2010). Details of the approach used are outlines in King County (2012c) and are based on a relatively simple water balance approach similar to that used by Paulson et al (2007) to estimate groundwater input to Hood Canal. The updated groundwater recharge estimate is 16 cfs (Table 4). This estimate is fairly consistent with an independent estimate provided by the USGS regional aquifer-system analysis (RASA) model of 18.6 cfs (Vaccaro et al. 1998).

Table 4. Water balance-based estimate of recharge in the Quartermaster Harbor drainage basin.

A: Precipitation	49.3 in
B:ET	20 in
C: Runoff	14.9 in
D: Consumptive Use	0.4 in
E = A – B – C – D	
E: Recharge	14.0 in
Recharge =	16 cfs

ET = Evapotranspiration

Recharge initially enters the Shallow Aquifer, which appears to intersect primarily with the inner harbor (see Figure 19). It is assumed here that all of the recharge is discharged to Quartermaster and that half is delivered to the inner harbor and the other half to the outer harbor. It is unlikely that all of the recharge is discharged from the Shallow Aquifer to Quartermaster Harbor as a portion likely recharges the Deep Aquifer system. In other words, the estimate of recharge in the Quartermaster Harbor drainage basin may be fairly accurate, but the estimate of the amount of groundwater recharge that discharges to Quartermaster Harbor (and how the discharge is distributed) is highly uncertain at this time. Pending further refinements that include recharge of the Deep Aquifer and the amount and distribution of groundwater input to the inner and outer harbor, the current estimate of 16 cfs is considered to be an approximate upper bound for the submarine groundwater input to Quartermaster Harbor.

Although the initial harbor nitrogen loading estimate included an estimate of nitrogen loading from groundwater input to the harbor (King County 2010e), other research has highlighted the difficulty (and uncertainty) in extrapolating groundwater loading estimates from nutrient measurements made in water supply and groundwater monitoring wells (Pitz 2009). Although the estimated annual recharge and mean Shallow Aquifer nitrate concentration based on well data described above could be used to estimate groundwater nitrate loading to the harbor (16 cfs x 0.7 mg/L x 2.45 conversion factor ~= 27 kg N per day), this is assumed to be a worst-case upper bound estimate rather than an approximate best estimate of groundwater nitrogen loading (Pitz 2011). With the exception of inputs from visible nearshore seeps that are assumed to capture inputs from nearshore septic systems that are accounted for below, submarine groundwater input is assumed to travel through marine sediments where denitrification of groundwater nitrate would reduce or eliminate nitrate delivered to the harbor via groundwater.

6.2 Marine Boundary

Because upwelling waters off the Washington coast are rich in inorganic nitrogen and have been found to be a significant source of nitrogen to Puget Sound and Hood Canal (Cope and Roberts 2013, Roberts et al. 2013), a similar estimate for the contribution of nitrogen from Puget Sound through the entrance of Quartermaster Harbor is developed below.

Two independent approaches were used focusing on 2009, the year upon which the Quartermaster Harbor hydrodynamic model was developed and tested (Albertson 2013).

The first method relied on the development of a two-layer salinity mass balance of the harbor using the monthly salinity profiling data collected by UWT, similar to that used by Steinberg et al. (2010) for Hood Canal. Following Steinberg et al. (2010), the salinity mass balance was calculated as follows:

$Q_{SF} = Q_{UP} + Q_{FW}$, and

$Q_{SF} * S_{SF} = Q_{UP} * S_{UP} + Q_{FW} * S_{FW}$

Where Q is flow, S is salinity, and the subscripts SF, UP and FW represent the surface layer, upwelling water and freshwater inputs, respectively. These equations are solved for the upwelling flow (Q_{UP}):

$$Q_{UP} = Q_{FW} / (S_{UP}/S_{SF} - 1)$$

Upwelling DIN load can then be calculated from the upwelling DIN concentration (DIN_{UP}) and the upwelling flow (Q_{UP}).

Both methods relied on the surface and bottom inorganic nitrogen data collected by UWT. The salinity profiles from the CTD casts for stations 51 through 56 were averaged into surface (0-3 m) and bottom (>3 m) (3 m is an approximate average depth of the pycnocline in the harbor) for each station and then these values were used to calculate a volume-weighted average of surface and bottom salinity in the harbor for each month. The surface and bottom inorganic nitrogen data were also used to calculate a volume-weighted harbor mean surface and bottom inorganic nitrogen concentration.

Total freshwater inflow for 2009 was based on the sum of monthly mean Judd and Fisher creek flows (Mileta Creek flow was not measured in 2009) plus flow from the ungauged drainage area, which was based on scaling from the gauged to the ungauged drainage area. In addition to an estimate of surface water input to the harbor, an estimate of groundwater input based on the water balance approach presented in King County (2010e), but updated with data through 2010.

The marine boundary nitrogen loading estimates for the harbor as a whole and for the inner harbor are presented in Table 5 and Table 6, respectively. Unfortunately, UWT did not conduct sampling in October 2009, so the marine boundary loading estimate was based on the average loading calculated for September and November. In general, the estimated upwelling flow and nitrate flux varied over the year in response to variations in freshwater inflow, differences in surface and bottom water salinity and bottom water nitrate concentrations. Estimated upwelling nitrate flux was lowest during April to June when the difference between surface and bottom salinity was greatest. The marine boundary DIN loading estimates for the harbor as a whole and for the inner harbor in October are 1,305 and 1,416 kg/d, respectively.

The second method relied on the observed and modeled residual flow estimates presented by Albertson (2013). These residual flow estimates included an estimate based on current meter deployments conducted in October 2009 (King County 2009c) and model estimates based on a fine and coarse resolution hydrodynamic model grid (Albertson 2013). These estimates were made for a transect across the outer harbor (Figure 36). The estimated marine boundary DIN input to the harbor in October 2009 based on the residual flow estimates ranged from 1,320 to 2,000 kg/d (Table 7), which are in reasonably good agreement with the estimates derived from the first approach, particularly the estimates based on current meter data and the results from the fine resolution grid hydrodynamic model.

Table 5. Salinity box model results for monthly marine boundary inorganic nitrogen inputs to Quartermaster Harbor.

	S_{SF}	S_{UP}	Q sw	Q gw	Q_{FW}	Q_{UP}	DIN_{UP}	DIN_{UP}
	psu				cfs		mg/L	kg/d
Jan	-	-	39.9	16	55.9	-	-	-
Feb	29.1	29.5	10.6	"	26.6	1,935	0.216	1,024
Mar	28.9	29.4	17.2	"	33.2	1,919	0.447	2,102
Apr	27.2	29.4	15.7	"	31.7	392	0.527	506
May	27.5	29.4	16.2	"	32.2	466	0.421	481
Jun	28.2	29.2	5.6	"	21.6	609	0.323	482
Jul	29.3	29.7	4.1	"	20.1	1,472	0.324	1,168
Aug	29.7	30.1	3.9	"	19.9	1,478	0.700	2,535
Sep	30.2	30.5	4.6	"	20.6	2,074	0.328	1,667
Oct	-	-	8.1	"	24.1	-	-	(1,300)
Nov	29.9	30.4	27.0	"	43.0	2,571	0.148	932
Dec	-	-	16.5	"	32.5	-	-	-

[a] Value in parentheses is an average of the estimated loading in September and November.

Table 6. Salinity box model results for monthly marine boundary inorganic nitrogen inputs to inner Quartermaster Harbor.

	S_{SF}	S_{UP}	Q sw	Q gw	Q_{FW}	Q_{UP}	DIN_{UP}	$DINN_{UP}$
	psu				cfs		mg/L	kg/d
Jan	-	-	19.2	8	27.2	-	-	-
Feb	29.3	29.4	4.8	"	12.8	3,750	0.346	3,179
Mar	28.2	28.6	8.2	"	16.2	1,142	0.005	14
Apr	28.2	29.5	7.5	"	15.5	336	0.000	0
May	26.6	29.4	7.7	"	15.7	149	0.000	0
Jun	28.1	28.9	2.4	"	10.4	365	0.000	0
Jul	29.3	29.5	1.8	"	9.8	1,436	0.080	281
Aug	29.6	29.9	1.7	"	9.7	957	0.060	141
Sep	30.2	30.4	2.1	"	10.1	1,525	0.440	1,644
Oct	-	-	3.6	"	11.6	-	-	(1,416)[a]
Nov	29.3	30.1	13.0	"	21.0	769	0.630	1,187
Dec	-	-	7.8	"	15.8	-	-	-

[a] Value in parentheses is an average of the estimated loading in September and November.

Table 7. Marine boundary inorganic nitrogen input to Quartermaster Harbor in October 2009 based on residual flow estimates provided by Albertson (2013).

	Landward flux		DIN_{UP}	DIN_{UP}
	m^3/s	cfs	mg/L	kg/d
Current meter data	65	2,295	0.238	1,338
Modeled				
Fine grid	64	2,260	0.238	1,318
Coarse grid	97	3,426	0.238	1,998

Although the estimate of late summer DIN flux to the harbor as a whole appears reasonable based on the consistency between the two relatively independent calculation methods, the estimate for the inner harbor should be viewed with caution for a number of reasons. For one, the relatively high exchange flow estimated for the inner harbor in October seems to be at odds with the very low flushing rate predicted by the model (see Figure 29), which indicated a mean flushing time of over 80 days for the inner harbor. The inner harbor also

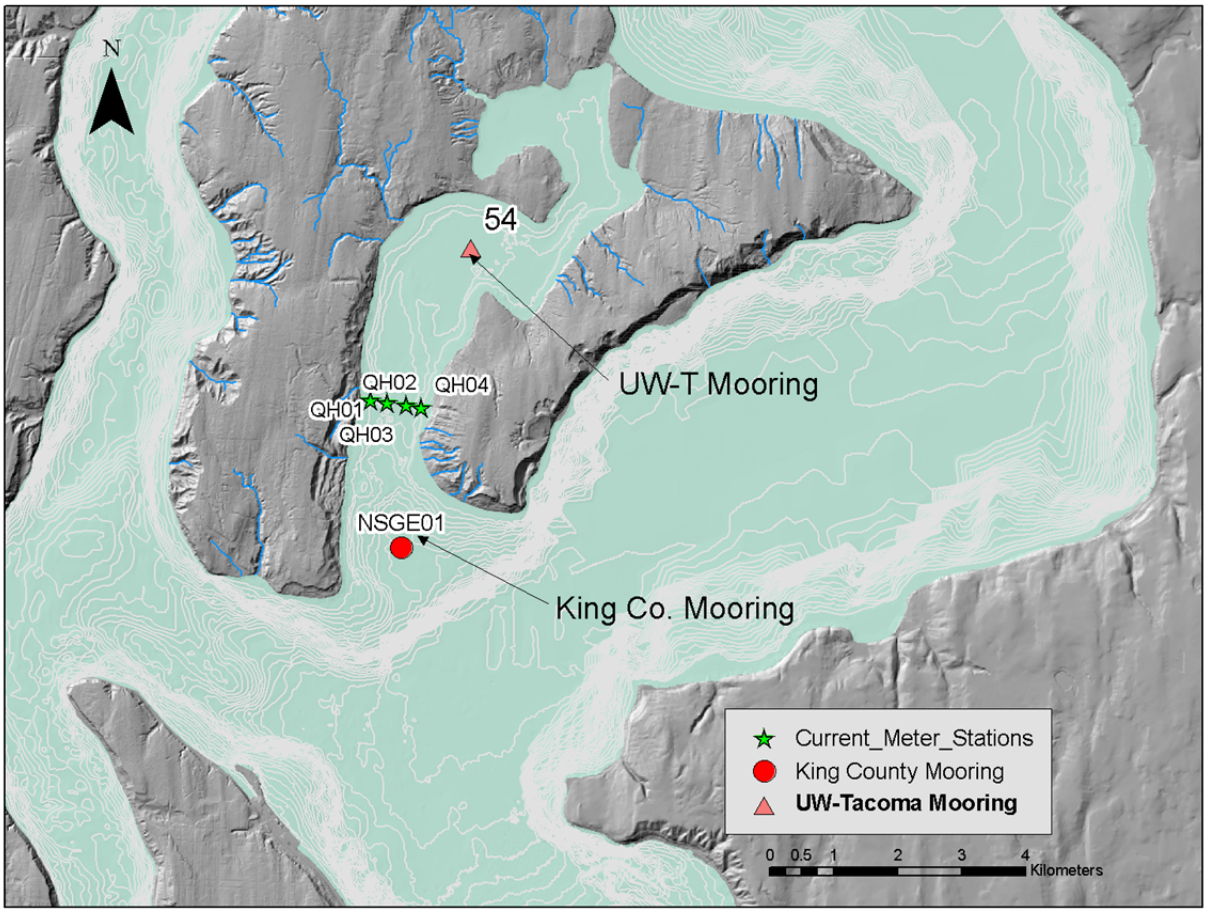

Figure 36. Map showing locations of bottom-mounted acoustic doppler current profilers.

does not appear to be strongly stratified in October (nor is the rest of the harbor). At this time of year, the salinity in Puget Sound, and by extension in Quartermaster Harbor, is uniformly high due to low freshwater input not only in Quartermaster Harbor, but

throughout Puget Sound. In addition, the groundwater estimate included in the calculation of Q_{FW} is highly uncertain and the flux estimate is sensitive to the freshwater flow estimate. Using half or 1.5 times the assumed groundwater inflow of 8 cfs changed the estimated inner harbor DIN boundary flux from 980 to 1,855 kg/d.

6.3 Marine Vessels

Since the University of Washington (1976) study of Quartermaster Harbor was initiated because "…a concern by local residents was, and still is, that overnight boat use has been creating detrimental effects on the quality of Quartermaster Harbor by the dumping of sewage into harbor waters," it is no surprise that nitrogen inputs from harbor vessels was expressed as a concern during public meetings and presentations for this project. Ideally, to estimate inorganic nitrogen inputs from boats, one would not only have daily counting of all occupied vessels in the harbor, but also the number of people on board and whether or not they discharge sanitary waste to the harbor. Information as complete as this is not currently available, but information is available for the number of boat slips in the inner and outer harbor (Toy 2010).

Based on the assumption that there are 160 boats in the inner harbor and 50 boats in the outer harbor (Toy 2010), that there are two people on each boat and that each person releases 6.4 kg DIN each year (Whiley 2010), and that 20 vessels on any particular day are occupied results in an estimated DIN load of 1.6 kg/d to the harbor from untreated vessel discharges. If all 210 of the boats were occupied on any given day, and wastes were discharged untreated, the estimated DIN load would be 8.4 kg/d.

6.4 Nearshore Septic Systems

The initial estimate of DIN loading from nearshore septic systems was updated with improved information and similar assumptions as follows. It was assumed that there were 539 septic systems (identified as occupied parcels adjacent to the shoreline) serving an average household size of 2.4 people releasing 6.4 kg DIN per year. It was assumed that these systems provided minimal treatment based on studies of nearshore septic systems along Hood Canal (Atieh 2008, Atieh et al. 2008). The DIN loading estimate from nearshore septic systems was reduced by 10 percent to estimate ultimate loading to the harbor. This amount of attenuation is assumed to be rather conservative based on additional evaluation of nearshore nitrogen inputs to Hood Canal (Cope and Roberts 2013). These assumptions result in an estimated DIN loading of 19.1 kg/d from nearshore septic systems – considered an upper bound estimate.

Based on an estimate of 185 systems releasing DIN to the inner harbor and the same assumptions regarding loading to the system and attenuation, the estimated DIN loading to the inner harbor from nearshore septic systems is 6.7 kg/d – also considered to be an upper bound estimate.

6.5 Surface Water

Based on the methods and data presented in King County (2010e), but using update flow and water quality data for Judd, Fisher and Mileta Creek through 2010, the current estimate of DIN loading to the harbor from surface drainage to the harbor as a whole is 15.9 kg/d and 9.0 kg/d to the inner harbor in October.

Although DIN loading from groundwater was estimated in the initial loadings report (King County 2010e), it is currently considered to be so highly uncertain and likely captured already in the surface water and nearshore septic loading estimates. The estimate of groundwater recharge is used in the estimate of total freshwater flow to the harbor to estimate the marine boundary DIN input.

6.6 Atmospheric Deposition

The data and methods used to estimate atmospheric deposition are documented in King County (2010e). The estimated DIN input from atmospheric deposition to the harbor was updated using data through 2010. The estimated deposition of DIN to the surface of Quartermaster Harbor in October is 4.1 kg/d. The estimated deposition to the inner harbor is 1.1 kg/d.

6.7 Benthic 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).

Based on measurements made in Quartermaster Harbor as part of this study (see Table 3) it is assumed that that inner and outer harbor DIN flux from the sediments is 0.10 and 0.02 g m^{-2} d^{-1}, which results in a harbor-wide DIN sediment flux of 400 kg/d and a flux in the inner harbor of 360 kg/d.

6.8 Synthesis

As noted in the initial loading estimates that included sediment nutrient fluxes based on data collected from other shallow embayments in Puget Sound (Roberts et al. 2008), sediment nutrient release in late summer during the critical oxygen period appears to be much larger than all other quantified sources, with the possible exception of inorganic nitrogen delivered from Puget Sound through the marine boundary (Table 8 and Figure 37).

In general, there remains a great deal of uncertainty in the estimates of nitrogen loading to the harbor, with the possible exception of the estimate of loading from surface runoff. Although there is uncertainty associated with the estimated input of nitrogen from atmospheric deposition and marine vessels, their relative contribution to the harbor appears to be small.

Table 8. Summary of estimated DIN inputs to Quartermaster Harbor in October.

	Quartermaster Harbor (Total)	Outer Harbor	Inner Harbor
		kg DIN d^{-1}	
Marine boundary [a]	2,700 [a]	1,300	1,400
Sediment flux	400	40	360
Surface flow	15.9	6.9	9
Nearshore septics	19.1	12.4	6.7
Atmospheric deposition	4.1	3.0	1.1
Marine vessels [b]	1.6	0.8	0.8

[a] It is assumed here that the marine boundary flux estimates for the outer and inner harbor are independent and that the sum equals the total marine flux to the harbor. This is assumed to be an upper bound estimate.
[b] Assumes all 10 vessels discharging sanitary waste are located in the inner harbor and 10 vessels are located in the outer harbor.

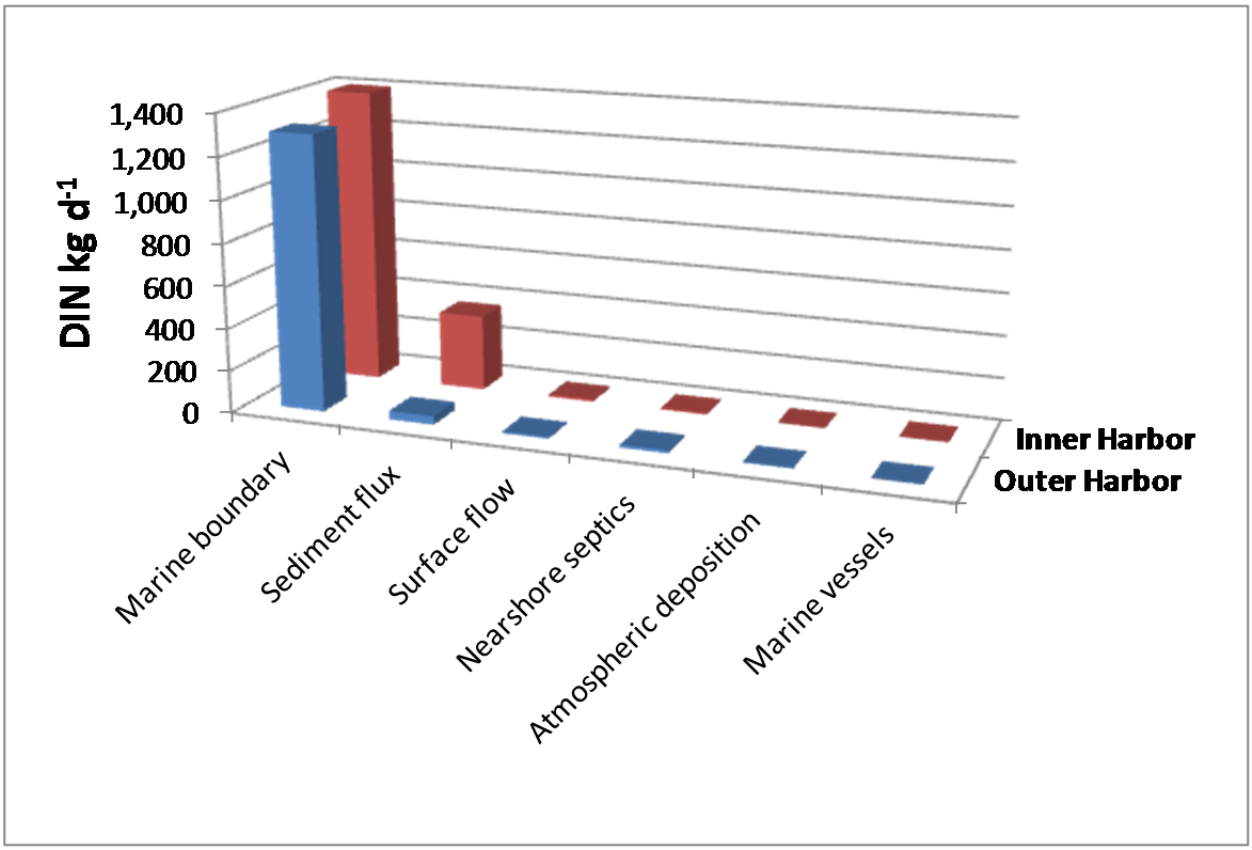

Figure 37. Bar chart illustrating the relative contribution of DIN to Quartermaster Harbor in October, the critical period when dissolved oxygen concentrations are typically lowest.

Note: The total height of the bar indicates the loading rate to the entire harbor.

Inputs from nearshore septic systems are particularly difficult to measure directly and effectiveness of any particular system to remove nitrogen is dependent on local soil and groundwater conditions. More sophisticated and intensive field studies similar to those used to evaluate nearshore inputs to Hood Canal may be needed to better estimate inputs from groundwater and nearshore septic systems (e.g., Swarzenski et al. 2007, Simmonds et al. 2008).

Although site specific measurements of benthic nutrient flux were made as part of this study, measurements were made at a single point in time using a relatively simple sampling approach. Sheibley and Paulson (2013) have reviewed the available data and techniques used to measure benthic nutrient fluxes in Puget Sound, which may lead to further improvements in methods and data in the future.

The estimated input of nitrogen to Quartermaster Harbor via the marine entrance boundary with Puget Sound appears to be the largest source of nitrogen to the harbor during the critical late summer period for dissolved oxygen. This is consistent with estimates for Puget Sound as a whole and for other embayments with restricted circulation during this time of year (e.g., Hood Canal/Lynch Cove) (Cope and Roberts 2013, Roberts et al. 2013). The estimate for the harbor as a whole is somewhat uncertain, but seems to be reasonable based on the similarity of estimates derived from current meter data, hydrodynamic model output and a simple model based on a salinity balance. The estimated marine input to the inner harbor is somewhat less certain – it has only been estimated using the salinity box model.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Based on historical data and information collected as part of this study, it appears that human activity on Vashon-Maury Island has resulted in elevated surface and groundwater concentrations of nitrogen, particularly as nitrate. Increases observed in the Shallow Aquifer have not exceeded the drinking water MCL of 10 mg/L and concentrations appear to vary to some degree in relation to susceptibility to contamination based on the CARA designations. Stream base flow nitrate concentrations in late summer appear to integrate the patchiness in observed Shallow Aquifer nitrate concentrations and would provide a basis for making a first approximation estimate of the relative human contribution from upland sources to nitrogen inputs to Quartermaster Harbor.

It is uncertain to what extent any particular source contributes to elevated nitrate concentrations in island freshwater systems, but sources include onsite septic systems, application of nitrogen containing fertilizer or manure, uncovered manure storage, animal manure/urine (urine is the primary source of nitrogen from animals, including humans) and red alder. However, of these sources, onsite septic systems are clearly a contributor to nitrate in groundwater because they are designed to deliver soluble nitrogen below the soil surface to be diluted into the local groundwater system before reaching a stream or the marine shoreline. An onsite septic system does not need to fail in order to discharge inorganic nitrogen to groundwater and ultimately to receiving waters. Upgrading conventional septic systems, particularly systems along the shoreline limited by area and soil quality, would be costly. Development of local decentralized systems or connection to the existing centralized wastewater treatment system on the island is not a new idea and was evaluated as recently as 2008 (King County 2008).

There remains a great deal of uncertainty regarding the human contribution, particularly human activity on Vashon-Maury Island, to nitrogen and other factors that may cause low dissolved oxygen concentrations and harmful algal blooms in Quartermaster Harbor. The current best estimates of the relative contribution of nitrogen sources to the harbor developed as part of this study and information generated in other related studies of Puget Sound suggest that only a portion of the observed low dissolved oxygen in late summer is due to human influence. This is consistent with other studies in Puget Sound.

However, the state anti-degradation standard for dissolved oxygen is based on a determination of an explicit effect of no more than 0.2 mg/L decline in oxygen due to human influence. Determination of whether or not this threshold has been exceeded has been a challenge throughout Puget Sound, particularly for work conducted on this issue in Hood Canal (Cope and Roberts 2013).

The approach that is typically taken to determine the human contribution to the observed low oxygen levels, and one that was originally intended for this project, is to develop and calibrate a numerical eutrophication model and compare current condition and natural

condition model scenarios to assess compliance with the anti-degradation standard for dissolved oxygen (no more than 0.2 mg/L decline due to human influence). This approach is challenging for a number of reasons, especially considering the occurrence of species of motile, potentially harmful algae and complicated interactions with sediment and weather conditions. Managing water quality under this level of uncertainty presents challenges that should be acknowledged and addressed (Cloern 2001, Harrison 2007, Allen et al. 2011).

Additional scientific information that could help address some of these challenges in Quartermaster Harbor includes the following:

- Review current fresh and marine monitoring programs and recommend changes to ensure that sampling designs are robust to detecting change, particularly with respect to separating natural variability from anthropogenic effects
- Investigate the causes of fish kills, including analyses of key water quality and planktonic variables and analysis of fish tissues by pathologists
- Standardize and perform trend analysis of paralytic shellfish poison (PSP) monitoring data collected by the Washington State Department of Health
- Estimate flushing and nutrient flux rates in potentially nutrient sensitive areas
- Use the existing Ecology Puget Sound/Georgia Basin model to supply boundary conditions to the current Quartermaster Harbor hydrodynamic/water quality model or increase the resolution of the Puget Sound/Georgia Basin model within Quartermaster Harbor
- Collect and analyze sediment cores to attempt to better identify the history of carbon, nutrients and phytoplankton (and levels of anoxia) since before extensive inhabitation and development
- Conduct a study that attempts to separate the relative contribution of alder, OSS, fertilizer and domestic animal waste to harbor nitrogen loading
- Develop groundwater susceptibility/vulnerability maps based on available nitrate data and land characteristics specific to Vashon-Maury Island

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Appendix A

Outreach Activity Summary and Change Incorporated into the 2012 King County Comprehensive Plan

Outreach Activity Summary - Phase 1 January 2009 to December 2009

A webpage describing the project's goals, objectives and approach was created and posted on King County's website in 2009[19]. Notice of the website availability was communicated to the community via press release[20] and emails to interested parties.

Letters of introduction were sent to the Puyallup Tribal Council Shellfish Section, the Northwest Indian Fisheries Commission, Puget Sound Partnership and Puget Sound Restoration Fund. The letter sent via email briefly described the project and included an offer to present the project's goals, objectives and approach at appropriate meetings[21]. Project staff did not receive inquiries to the initial communications sent in 2009.

The project's goals, objectives and approach were communicated to King County's Inter-departmental Policy Group and to the county's Puget Sound Team[22]. These groups consist of representative of Department Directors and Division Managers, whose operations are affected by, or influence, environmental regulations and practices and/or the recovery of Puget Sound. The departments include: Natural Resources and Parks, Development and Environmental Services, Transportation, and Seattle King County Public Health (SKCPH). Staff from the King County Executive's office participates on both groups and staff from the King County Council sat on the Puget Sound Team. The King County Executive is a member of the Puget Sound Ecosystem Coordination Board.

A public presentation of the project's goals, objectives and approach was made to Vashon community[23] with notice of the presentation provided to the Vashon-Maury Island Community Council, its Septic Solutions subcommittee, and Vashon-Maury Island Groundwater Protection Committee and press release to notify for residents of the study area. A press release describing the project's goals, objectives and approach and schedule for the public meeting on Vashon was made to the Vashon Beachcomber, Vashon Loop, Seattle Times and Seattle Post Intelligencer newspapers[24]. The web site developed for the project supported the outreach by providing expanded information.

Outreach to residents in the study area was provided via the following activities:

- The annual Vashon Low Tide Festival on May 25, 2009 - Project overview poster and with staff to interpret[25];
- The Public Health Seattle-King County Marine Recovery Area (MRA) - Project overview poster[26] and staff to interpret at Sludge Fest event in April 2009, MRA

[19] Web site address http://www.kingcounty.gov/qmhnitrogenstudy
[20] See press release issued 09_10_28
[21] See project introduction emails sent between 09_11_20 and 09_12_22
[22] See communication to King County's Inter-departmental Policy Group 09_10_14 and 09_12_22 and Puget Sound Team 09_10_14
[23] See presentation of the project's goals, objectives and approach 09_11_19
[24] See press release issued 09_10_28
[25] Vashon Low Tide Festival 09_05_25 participation request

public meetings in June 2009 and door to communications with MRA residents in the fall of 2009;

- The Vashon Island Backbone Campaign- Project overview poster and staff to interpret at the 2009 Green Jobs forum[27];
- Newspaper article and editorial on project in the Vashon Beachcomber newspaper[28];
- Presentation of a project poster at the South Sound Symposium on May 6, 2009[29];
- Presentation(s) at the King County Water and Land Resources Science Fair in 2009[30]; and,
- Regular meetings of the Septic Solutions subcommittee of the Vashon-Maury Island Community Council and Vashon-Maury Island Groundwater Protection Committee - Project introduction overview and routine progress updates.

The Nitrogen Loading Study plan was shared with each group including the proposal to monitor the performance of individual On-Site Sewage (OSS) systems in the Quartermaster Harbor portion of the Marine Recovery Area. Note: After evaluating the available literature and assessing the potential scope to monitor individual OSS the study team determined that monitoring the performance of individual On-Site Sewage systems was not necessary as data on system performance collected in studies of Hood Canal nitrogen loading could be used to inform the Quartermaster Harbor study so it was unnecessary to solicit monitoring site volunteers.

Outputs

Initiation of public outreach and communication effort including:

- Emails to tribal community via NWIFC and Puyallup Tribe
- Information to King County policy managers via Interdepartmental and PSP teams
- Presentation to community, press release issued and responded to inquiries
- Input secured on OSS monitoring plan from contacted groups
- Web page created, updated and notice of update provided to all groups contacted (http://www.kingcounty.gov/environment/watersheds/central-puget-sound/vashon-maury-island/quartermaster-nitrogen-study.aspx)

[26] QHN Project overview poster for Public Health Seattle-King County Marine Recovery Area (MRA) Sludge Fest event on April 18, 2009 and project overview poster (link to most recent update on project web page)
[27] Vashon Backbone Campaign Green Jobs forum notes 09_10_22
[28] Scientists to study nitrogen levels in Quartermaster Harbor http://www.pnwlocalnews.com/vashon/vib/news/67795062.html and We must be good stewards of our harbor http://www.pnwlocalnews.com/vashon/vib/opinion/70298537.html
[29] Poster presented at South Sound Symposium on May 6, 2009
[30] Presentation(s) at the King County Water and Land Resources Science Fair on October 28, 2009

Outreach Activity Summary - Phase 2 January 2010 to December 2011

Study progress was conveyed to partners and interested parties through ongoing education and outreach program on Vashon-Maury Island as follows:

Project updates were sent to the Puyallup Tribal Council Shellfish Section, the Northwest Indian Fisheries Commission and King County's Inter-departmental Policy Group[31]. The update included an offer to present the project's goals, objectives and approach at appropriate meetings and a presentation was made to the Puyallup Tribe Shellfish Biologist along with the Puget Sound Restoration Team on February 8, 2011[32]. The county's Puget Sound Team was dissolved in 2010 so no team update was provided however the King County Executive who serves on the Puget Sound Partnership Ecosystem Coordination Board representing the South Central Puget Sound was provided with a summary of the project in preparation for his visit to the Vashon community in April 2010 an update on the project presentation made to the Vashon community in October 2010[33].

Press releases were prepared and provided to the Vashon Beachcomber newspaper in 2010 and 2011.[34] The webpage was updated to incorporate Phase 2 work (see footnote 1).

The initial nutrient loading report findings along with successive water quality monitoring results and nitrogen management policy options were presented to the community in public meetings with sponsorship by a Vashon High School Science teacher in 2010 and 2011.[35]

The initial nutrient loading report findings along with successive water quality monitoring results and nitrogen management policy options were presented to the community in other public meetings including:

- The Vashon Low Tide Festival on May 5, 2010 and 2011;[36]
- A meeting concerning Shellfish Harvest and the Vashon-Maury Island Marine Recovery Area held on August 25, 2010;[37]
- A talk with the Vashon Kiwanis held on November 16, 2010;[38]

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[31] Project updates were sent to the Puyallup Tribal Council Shellfish Section, the Northwest Indian Fisheries Commission and King County's Inter-departmental Policy Group on December 22, 2010.
[32]Presentation to the Puyallup Tribe Shellfish Biologist and Puget Sound Restoration Fund team on February 8, 2011.
[33] Project summary in April 2010 and update on the project presentation made to the Vashon community in October 2010 provided to King County Executive who serves on the Puget Sound Partnership Ecosystem Coordination Board representing the South Central Puget Sound.
[34] Press releases provided to the Vashon Beachcomber newspaper in 2010 and 2011.
[35] Presentations to the Vashon community in public meetings held in October 2010 and 2011. http://www.kingcounty.gov/environment/watersheds/central-puget-sound/vashon-maury-island/quartermaster-nitrogen-study/QMH-documents.aspx
[36] Presentation materials for Vashon Low Tide Festival on May 5, 2010 and 2011
[37] Public meeting concerning Shellfish Harvest and the Vashon-Maury Island Marine Recovery Area held on August 25, 2010

- A display in the Vashon Public Library regarding the Quartermaster Harbor Nitrogen Loading Study from November 16, 2010 thru February 23, 2011;[39]
- A Vashon Beachcomber news story regarding the Quartermaster Harbor Nitrogen Loading Study published September 27, 2010;[40]
- An outreach letter sent to property owners in the Mileta Creek drainage advising them of the high nitrogen levels found in the creek as part of the study Quartermaster Harbor Nitrogen Loading Study and seeking permission to access their property to further sample the stream;[41] and,
- A related Vashon Beachcomber news story regarding the University of Washington-Tacoma work to study the Quartermaster Harbor's paralytic shellfish poisoning problem.[42]

Outputs

Ongoing public outreach and communication effort as follows:

- Project update presentation and provided to all groups contacted in Phase 1 as requested
- Project update press release issued to all newspapers contacted in Phase 1
- Webpage updated to incorporate Phase 2 work

[38] Talk with the Vashon Kiwanis held on November 16, 2010

[39] Display in the Vashon Public Library regarding the Quartermaster Harbor Nitrogen Loading Study beginning November 16, 2010

[40] **Streams appear to be the largest source of nitrogen in Quartermaster Harbor, study shows** http://www.pnwlocalnews.com/vashon/vib/news/103885399.html

[41] Outreach letter to property owners in the Mileta Creek drainage advising them of the high nitrogen levels found in the creek and seeking permission to access their property to further sample the stream sent in 2010.

[42] **Oceanographer studies Quartermaster Harbor's paralytic shellfish poisoning problem** http://www.pnwlocalnews.com/vashon/vib/news/82717117.html

Outreach Activity Summary - Phase 3 January 2011 to December 2013

An audience survey was conducted at the community workshop meeting held on October 12, 2011 to help inform the agencies performing Quartermaster Nitrogen Loading Study and other stakeholders. The survey asked meeting participants a series of questions to determine their interest in and knowledge about Quartermaster Harbor. Twenty five surveys were returned and showed the following:

- The majority of respondents (23) were residents of VMI and half resided in the QH watershed.
- Meeting or exceeding water quality standards in Quartermaster Harbor was very important for most respondents.
- Most respondents participated in activities in or around Quartermaster Harbor that they rated as very import although many activities were pursued with a relatively low annual frequency.
- Survey participants felt the greatest risk to Quartermaster Harbor water quality came from on-site sewage followed by fertilizer then boater waste, animal waste, other nitrogen sources and wastewater treatment plants.
- Most respondents were not familiar with the range of programs being conducted to monitor or mange the environment in or around Quartermaster Harbor.
- A majority of respondents agreed it was important to address low dissolved oxygen levels and work to open shellfish harvest and in Quartermaster Harbor.
- A majority of respondents advised they would be willing to make changes to the ways they use or manage their property if it would improve water quality in Quartermaster Harbor.
- There were fewer respondents in agreement about paying for new or different goods or services if they would improve water quality in Quartermaster Harbor.
- Survey participants felt King County could act to improve water quality in the following priority: controlling boater sewage, reducing fertilizer use, inspecting on-site sewage systems, controlling animal waste, requiring nitrogen reduction technology for new on-site sewage systems and promoting planting of coniferous trees.
- A few respondents expressed areas of particular water quality concern including the Jensen Point neighborhood, boats and two marinas (Dockton and Yacht Club), and two creeks (Judd and Mileta).
- Respondents advised they wanted to receive additional information via newspapers, email or the web and meetings.
- Other things respondents wanted to know included trends in the Quartermaster Harbor water quality over time (one stated the water has warmed) and would the water quality improve if the portage land bridge were removed.

- Suggestions included emphasis monitoring around inner harbor around the holidays when the boats congregate and Quartermaster Harbor is a "jewel" – people if excited might be galvanized to clean it up.
- Seven respondents provided their contact information to receive additional information.

The Vashon-Maury Island Groundwater Protection Committee[43] and the King County department of Public Health[44] were worked with to develop nutrient management policies for Quartermaster Harbor. Nitrogen management policies were drafted and docketed for adoption in the 2012 update to the King County Comprehensive Plan.[45]

The study findings were written and presented to partners and interested parties on Vashon Maury Island.
Convey study results to partners and interested parties through ongoing education and outreach program on Vashon-Maury Island.

- Prepare project finding presentation and provide to all groups contacted in Phase 1 as requested
- Issue project finding press release to all newspapers contacted in Phase 1
- Update webpage to incorporate Phase 3 work Plan elements and send notice of availability to all groups contacted.
- Prepare a summary of study findings plus proposed policy, regulation and BMP's for nutrient management on VMI. Distribute to public residing in the study area, post to website and review in public agency meeting on VMI.

Outputs

- Recommendations for changes to policy and regulation for nutrient management of nitrogen sources
- Ongoing public outreach and communication efforts

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[43] Presentation on Quartermaster Harbor Nitrogen Loading Study made to the Vashon-Maury Island Groundwater Protection Committee on July 27, 2012 along with subcommittee report on nitrogen management policy recommendations to be included in the 2012 amendment to the King County Comprehensive Plan. Vashon-Maury Island Groundwater Protection Committee home page for access to meeting notes and agendas http://www.kingcounty.gov/environment/waterandland/groundwater/management-areas/vashon-maury-island-gwma/committee.aspx

[44] Meeting with Larry Fay from Seattle and King County Public Health to review proposed 2012 Comp Plan update policies for Vashon-Maury Island.

[45] Excerpt containing nitrogen management policy recommendations for Vashon-Maury Island included in the Executives Recommended 2012 amendment to the King County Comprehensive Plan at request of the Vashon-Maury Island Groundwater Protection Committee and King County Department of Natural Resources and Parks, Water and Land Resources Division. Full draft of the King County Executives recommended 2012 amendment to the King County Comprehensive Plan available at http://www.kingcounty.gov/property/permits/codes/growth/CompPlan/2012_ExecRec.aspx

- Project finding presentation provided to all groups contacted in Phase 1 as requested
- Project finding press release issued to all newspapers contacted in Phase 1
- Webpage updated to incorporate Phase 3 work Plan elements and notice of availability sent to all groups contacted
- Summary of study findings, recommended nitrogen loading targets for Quartermaster Harbor plus proposed policy, regulation and BMP's for nutrient management on VMI prepared, distributed to public residing in the study area, posted to website and reviewed in public agency meetings on VMI.

Partnering

The Work Plan included partnering with several agencies and stakeholders. The following is a list of partners and short summary of activity:

- The Vashon-Maury Island Groundwater Protection Committee (VMI GWPC). Estimated in-kind match approximately $2,900.[46] The VMI GWPC facilitated public outreach on VMI and assisted in developing nitrogen management policy recommendations for inclusion in the 2012 update to the King County Comprehensive Plan.
- The non-profit Vashon-Maury Island Community Council (VMICC)[47]. This organization monitored progress on the study and provided input to shape policy recommendations related to management of on-site sewage systems thru their Septic Solutions Subcommittee up until their mass resignation in July 2010 and subsequently by the reconstituted Land-Use and Natural Resources committee beginning in July 2011.
- The non-profit Preserve Our Islands organization on Vashon-Maury Island[48] was consulted and resolved they will also be providing oversight and advocacy to both the low-dissolved oxygen issues in Quartermaster Harbor as well as the work being done to address potentially failing septic systems along the harbors shoreline.
- The Vashon Beach Watchers, [49]a group of private citizens who monitor the water quality in Quartermaster Harbor in coordination with the Sound Toxins organization were contacted routinely to participate in community meetings and workshops.
- The Vashon Low Tide Festival[50] (and see footnotes 7 and 18) organizers were contacted and coordinated with to communicate the nitrogen management study to

[46] The ten member Vashon-Maury Island Groundwater Protection Committee received written and or verbal quarterly updates on the Quartermaster Harbor Nitrogen Loading study for the duration of the project over the course of sixteen regular meetings from 2009 thru 2012 in addition to their policy work documented in Phase 3.
[47] Vashon-Maury Island Community Council http://www.vmicc.org/
[48] Preserve Our Islands organization on Vashon-Maury Island http://www.preserveourislands.org/our-work/
[49] The Vashon Beach Watchers http://www.soundtoxins.org/partners-beachwatchers.html
[50] **Low Tide Celebration 2012 at Point Robinson Park** Article June 20, 2012 By Erin Durrett http://www.vashonloop.com/article/low-tide-celebration-2012-point-robinson-park

the public participating in their annual public outreach event focusing on marine flora and fauna on Vashon-Maury Island.

- The Puyallup Tribe Shellfish Section who were contacted and provided comments on the study during a presentation on the study made to them in 2011 (see footnote 14).
- The Puget Sound Restoration Fund Organization[51] were contacted in relation to their nutrient mitigation mussel raft water quality improvement experiment conducted in Quartermaster Harbor in 2011[52] and provided comments on the study during presentations made on the study (also see footnote 14).
- Public Health Seattle and King County, Environmental Health Section[53] were contacted in relation to development of nitrogen management policies for the 2012 update to the King County Comprehensive Plan (see footnotes 25-27) and coordination with the implantation of the Vashon-Maury Island Marine Recovery Area for correction of failing on-site sewage systems located in part on the shore of Quartermaster Harbor.[54]

Outputs:

The partnering efforts increased understanding of the marine receiving water environment, yielded assistance with development of policy and management recommendations, and public outreach activities.

Project Outcomes

Overall environmental outcomes from this project include reduction in the vulnerability of Vashon-Maury Island groundwater resources to contamination, maintenance/improvement of receiving water conditions and protection of local aquatic resources.

Additional short, interim, and long term science, policy, and public awareness outcomes include:

Short Term: Residents educated on sources of nitrogen entering Quartermaster Harbor, the sensitivity of marine water quality and habitat to nitrogen loading impacts of land use. Public Health Seattle and King County, Environmental Health Section engaged to develop and implement policies to reduce nutrient and bacterial loading to improve water quality in Quartermaster Harbor.

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[51] The Puget Sound Restoration Fund Organization http://www.restorationfund.org/
[52] The Puget Sound Restoration Fund Organization nutrient mitigation mussel raft water quality improvement experiment conducted in Quartermaster Harbor in 2011 http://www.restorationfund.org/projects/mitigation
[53] Public Health Seattle and King County, Environmental Health Section http://www.kingcounty.gov/healthservices/health/ehs.aspx
[54] Public Health Seattle and King County Vashon-Maury Island Marine Recovery Area http://www.kingcounty.gov/healthservices/health/ehs/wastewater/mra.aspx

Interim: Increased environmental awareness within community and scientific understanding of the nitrogen cycle in Quartermaster Harbor. Changing property owner's behavior concerning the acquisition, operation and maintenance of their on-site sewage systems.

Long term: Reduced nitrogen loading and increase dissolved oxygen levels in Quartermaster Harbor through, ongoing education, outreach and participation in planning and regulatory efforts.

What we learned from the outreach

Residents and community leaders are concerned about the water quality in Quartermaster Harbor. There is a general interest in taking action to protect the water quality but less agreement on the nature of the problem and best course(s) of action to correct the problem(s) including the best method(s) to pay for solutions. Conclusion of the study should help to bring clarity to the causes and potential strategies to correct the problem. Identifying the best way to pay for nitrogen reduction will become clearer as the exact nature of the problem is determined.

Connection of Quartermaster Harbor to Tramp Harbor to flush the harbor was routinely raised as a potential solution to the water quality problems. This viability of this suggestion needs to be addressed in the process of determining a final course of action to manage water quality in Quartermaster Harbor.

Recommendations for future outreach work

Future outreach opportunities should be centered on implementing nutrient reduction strategies focused on the Quartermaster Harbor drainage in coordination with the pathogen reduction and island-wide groundwater protection/stewardship efforts already underway. Timing for future outreach work should be coordinated with the conclusion of the Quartermaster Harbor study, adoption of the 2012 King County Comprehensive Plan amendments and implementation of the Pollution Identification and Correction grant work program beginning in 2012. The nitrogen management strategies developed for Quartermaster Harbor and should be coordinated with nitrogen management efforts for the South Puget Sound and Hood Canal.

Outreach should be conducted on a stewardship basis when possible to give people high level of personalized attention and support. A helpful tool to compliment stewardship activities would be to develop a nitrogen impact calculator and management strategy recommendations website similar to the King County Local Hazardous Waste Program website[55].

[55] King County Local Hazardous Waste Program website

Funding for future outreach work can come from a variety of sources. Policies proposed in the 2012 King County comprehensive plan call for county agencies (Water and Land Resources along with Public Health) to focus their program resources on implementing measure to reduce nutrient and pathogen loading in the watershed. Staff in the water quality section of the northwest regional office of Ecology have monitored the progress of the Quartermaster Harbor nitrogen loading study and expressed interest in working with the county to develop an Ecology grant funding application for a project to reduce nutrient and pathogen loading to avert the need for developing a Total Maximum Daily Loading plan in the future. Staff in the Puyallup Tribe shellfish section expressed interest in working with Quartermaster Harbor property owners to assist them if they want to cultivate shellfish on their tidelands. Preserve Our Islands, a local nonprofit organization has expressed their interest in supporting efforts to improve water quality in Quartermaster Harbor to further their broader goal of protecting/restoring the Maury Island Aquatic Reserve[56] area designated by the Department of Natural Resources. The Vashon-Maury Island Groundwater Protection Committee along with the Land Use and Natural Resources subcommittee of the Vashon-Maury Island Community Council have also been actively involved in activities related to Quartermaster Harbor to date and could provide guidance in the future.

Related Activities:

Groundwater Protection

King County has been working with island residents, state and federal agencies as applicable to protect the ground water on Vashon Maury since 1982. Beginning with the preparation of the Carr Report on island groundwater resources in1983[57] the county subsequently down-zoned large areas of the island to protect groundwater recharge areas in 1986. In 1989 the county started a 10 year groundwater protection planning process that supported designation of the island as an EPA sole source aquifer in 1994[58], completion of Ecology approved Groundwater Protection Plan in 1998[59] and formation of a Groundwater Protection Committee in 2001[60]. The Groundwater Protection Committee working with King County support undertook a Water Resources Evaluation project starting in 2004[61], prepared a Watershed Plan in 2005[62] and developed a set of watershed sustainability indicators in 2012[63]

[56] DNR Maury Island Aquatic Reserve
[57] Carr Report on Vashon-Maury island groundwater resources completed in1983
[58] Vashon-Maury Island EPA sole source aquifer designation in 1994
[59] Ecology approved Groundwater Protection Plan for Vashon-Maury Island completed in 1998
[60] Formation of the Vashon-Maury Island Groundwater Protection Committee in 2001
[61] Vashon-Maury Island Water Resources Evaluation project starting in 2004
[62] Vashon-Maury Island Watershed Plan prepared in 2005
[63] Vashon-Maury Island watershed sustainability indicators prepared in 2012

Pathogen Reduction

Public Health Seattle-King County has been closely involved in the ongoing work to protect groundwater and watershed resources on Vashon-Maury Island. The agency led the initial effort to prepare the 1998 Groundwater Protection Plan and in 2008 adopted an On-Site Septic System Management Plan[64] outlining a comprehensive strategy to identify and maintain on-site septic systems in King County. The plan also designated a Marine Recovery Area on portions of Vashon-Maury Island including the west side outer Quartermaster Harbor[65] where on-Site septic systems must be inspected annually and repaired or replaced if necessary by July 2012. Beginning in July 2012 Public Health Seattle-King County working with King County Water and Land Resource have received a two year grant to develop a Pollution Identification and Correction (PIC) Program to reduce pathogen and nutrient loading to the watershed draining into the west side outer Quartermaster Harbor. The PIC program will also develop recommendations to implement a sustainable funding source to maintain the water quality improvements accomplished under the program.

Nutrient Management Policy Recommendations – King County Comprehensive Plan

The Vashon-Maury Island Groundwater Protection Committee[66] and the King County department of Public Health[67] were worked with to develop nutrient management policies for Quartermaster Harbor. Nitrogen management policies were drafted and docketed for adoption in the 2012 update to the King County Comprehensive Plan.[68]

The policy recommendations pertaining directly to Quartermaster Harbor water quality and management of on-site septic systems are located in the Community Plan section for Vashon found in Chapter 10 and listed in underline below.

In June 2011 the Vashon Maury Island Groundwater Protection Planning Committee recommended new policies to be incorporated into the Comprehensive Plan to further the objectives of the Vashon-Maury

[64] Public Health Seattle-King County On-Site Septic System Management Plan adopted in 2008
[65] Marine Recovery Area on portions of Vashon-Maury Island including outer Quartermaster Harbor
[66] Presentation on Quartermaster Harbor Nitrogen Loading Study made to the Vashon-Maury Island Groundwater Protection Committee on July 27, 2012 along with subcommittee report on nitrogen management policy recommendations to be included in the 2012 amendment to the King County Comprehensive Plan. Vashon-Maury Island Groundwater Protection Committee home page for access to meeting notes and agendas http://www.kingcounty.gov/environment/waterandland/groundwater/management-areas/vashon-maury-island-gwma/committee.aspx
[67] Meeting with Larry Fay from Seattle and King County Public Health to review proposed 2012 Comp Plan update policies for Vashon-Maury Island.
[68] Excerpt containing nitrogen management policy recommendations for Vashon-Maury Island included in the Executives Recommended 2012 amendment to the King County Comprehensive Plan at request of the Vashon-Maury Island Groundwater Protection Committee and King County Department of Natural Resources and Parks, Water and Land Resources Division. Full draft of the King County Executives recommended 2012 amendment to the King County Comprehensive Plan available at http://www.kingcounty.gov/property/permits/codes/growth/CompPlan/2012_ExecRec.aspx

Island Watershed Plan and Vashon-Maury Island Groundwater Protection Plan concerning sustainability of the islands groundwater, streams and marine waters.

CP-1228b **The Vashon-Maury Island Groundwater Protection Committee, along with King County support:,**

a. should complete and implement measures for the sustainability of water quality, water quantity and ecosystem health on Vashon-Maury Island;

b: report the findings to the community; and

c. evaluate the results to help guide ongoing watershed management activities.

Seasonal dissolved oxygen levels within inner Quartermaster Harbor have fallen well below the Washington State marine water quality standard of seven mg per liter over the last four years of monthly monitoring by King County. Quartermaster Harbor is a regionally significant natural resource area that provides rearing and spawning habitat for herring, surf smelt, sand lance, salmon (i.e., Chinook, Coho, chum, and cutthroat) plus shellfish resources, including geoduck clams. Based on the value of the harbor's natural resources and to protect and restore shellfish harvest opportunities, Quatermaster Harbor was included in the Maury Island Marine Reserve designated by the Department of Natural Resources and the Marine Recovery Area designated by Public Health Seattle King County.

Excess nutrients, nitrogen compounds in particular, can lead to excessive phytoplankton and algae growth that can then deplete oxygen concentrations when the algae die. Nitrogen and phosphorus are essential nutrients for marine plants and phytoplankton, particularly nitrate as phytoplankton preferentially take up nitrate and other nitrogen compounds. Potential sources of nitrogen loading include on-site sewage systems, animal manure, fertilizer and other less direct sources like nitrogen-fixing vegetation including alder trees and atmospheric deposition.

In 2009, King County in cooperation with the Washington State Department of Ecology and University of Washington-Tacoma, started a four year study to identify and quantify the sources of nitrogen loading in Quartermaster Harbor. The draft 2010 Washington Water Quality Assessment under review by Ecology proposes to upgrade the Quartermaster Harbor dissolved oxygen listing to "Category 5" based on Ecology ambient monitoring station QMH002 (#10178). Designation as a Category 5 polluted water body means that Ecology has data showing that the water quality standards have been violated for one or more pollutants and there is no Total Maximum Daily Load (TMDL) pollution control plan. TMDLs are required for the water bodies in category 5 to bring water quality up to standards.

Education and incentives to implement best management practices to reduce nutrient and bacteria loading can improve water quality. Routine on-site sewage system inspection and maintenance can help to control nutrient loading from existing on-site sewage systems. When new on-site sewage systems are installed, using a system rated to provide nitrogen reduction could limit total nitrogen loading on average ~ 50% or more depending on system loading and site conditions.

CP- 1228c **King County should focus outreach education and incentives to implement best management practices designed to reduce excessive nutrient and bacterial contaminate loading within the Quartermaster Harbor drainage area. The Vashon-Maury Island Groundwater Protection Committee, together with King County support, should seek grants to enhance existing outreach education and incentives when funding opportunities occur.**

CP- 1228d **King County should revise regulations to require new on-site sewage systems within the Quartermaster Harbor drainage area to meet the nitrogen reduction treatment standard established by the Washington State Department of Health, where feasible, If the final Quartermaster Harbor Nitrogen loading study demonstrates it would significantly reduce future nitrogen loading in the harbor.**

CP- 1228e **King County should request Ecology assistance to develop a Total Maximum Daily Load water quality improvement plan to reduce point and nonpoint pollution sources to Quartermaster Harbor if the harbor water quality is listed as a Category 5 polluted water body on the 2010 Washington State Water Quality Assessment.**

Island wide there are approximately 5,000 on-site sewage systems used to treat the wastewater for residences, businesses and public facilities not served by the Vashon Sewer District. Failing on-site sewage systems can contaminate surface, ground and marine waters with hazardous bacteria and excessive nutrient loading (nitrogen and phosphorus). Regular inspection and maintenance of on-site sewage systems can ensure system performance, extend system life and identify failing systems so they can be repaired when needed.

CP- 1228f **The Vashon-Maury Island Groundwater Protection Committee, with King County support, should evaluate need and potential sources of funding for an enhanced management program for existing on-site sewage systems on**

Vashon-Maury Island to ensure they receive routine inspection, maintenance and repair if necessary to protect water quality.