Prepared in cooperation with U.S. Department of the Navy

Tidal Flushing of Mercury from the Bremerton Naval Complex through the PSNS015 Stormwater Drain System to Sinclair Inlet, Kitsap County, Washington, 2011–12

Scientific Investigations Report 2018–5087

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2018

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Contents

Figures

Tables

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)

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

$$°F = (1.8 \times °C) + 32.$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). The vertical datum mean lower low water (MLLW) is defined as -0.769 m relative to NAVD 88.

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

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given either in microsiemens per centimeter at 25 degrees Celsius (µS/cm) or millisiemens per centimeter at 25 degrees Celsius (mS/cm).

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

Concentrations of chemical constituents on solids are given in either percentage of dry weight, milligrams per kilogram (mg/kg) or nanograms per milligram (ng/mg), which are equivalent.

Abbreviations

BNC	Bremerton Naval Complex
CFU	colony forming unit
FTHg	filtered (dissolved) total mercury
MLLW	mean lower low water
MPN	most probable number
MRL	Mercury Research Laboratory
NWQL	National Water Quality Laboratory
PETG	polyethylene terephthalate copolyester
PFA	perfluoroalkoxy
PTHg	particulate total mercury
QFF	quartz fiber filter
RPD	relative percent difference
THg	total mercury
TSS	total suspended solids
USGS	U.S. Geological Survey
WAWSC	Washington Water Science Center
WTHg	whole total mercury (FTHg + PTHg)

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Abstract

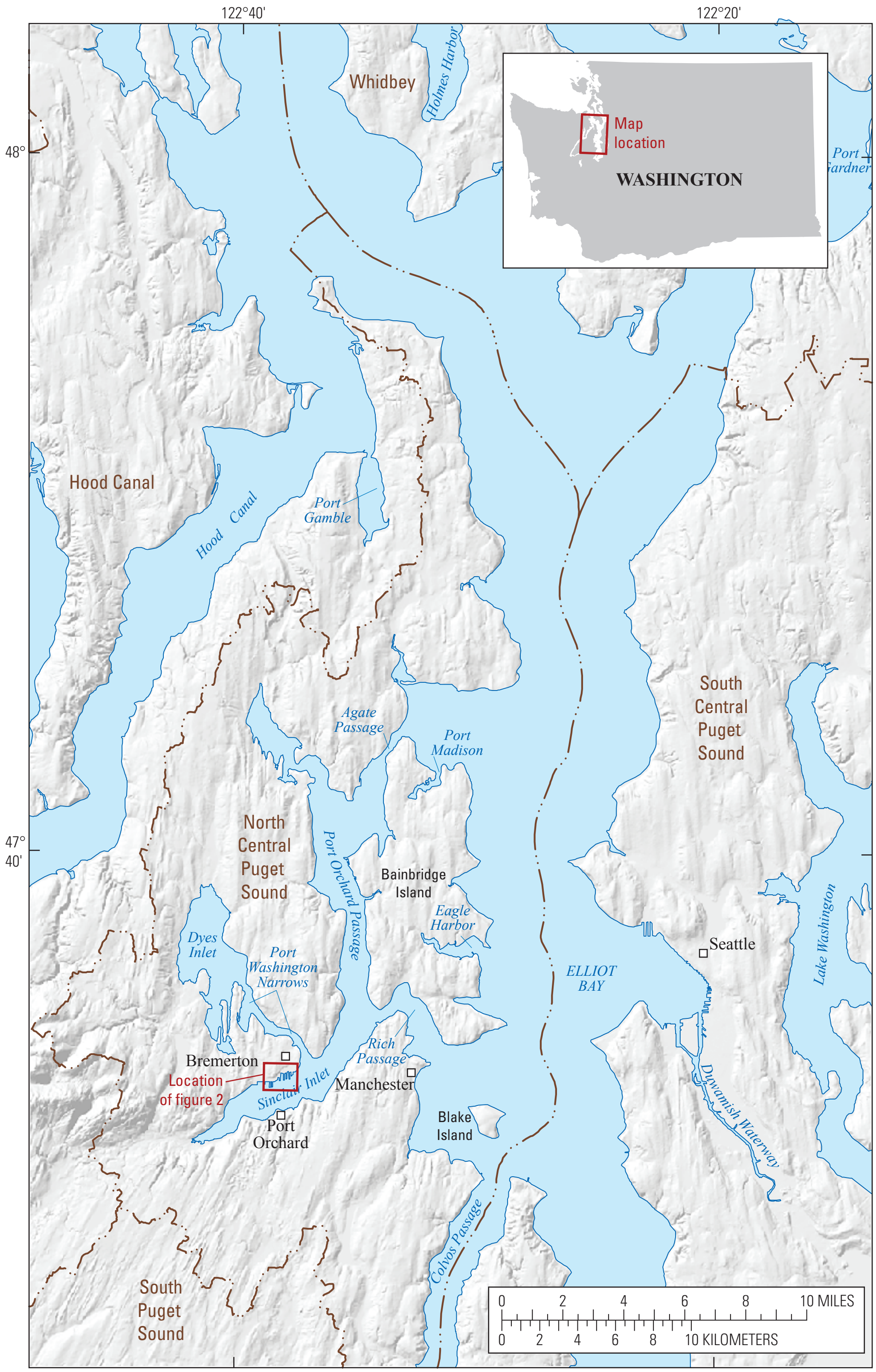
The sediments of Sinclair Inlet, in Puget Sound, Washington, have elevated levels of contaminants including mercury. The Bremerton Naval Complex is adjacent to Sinclair Inlet, and has known areas of historical soil mercury contamination. The U.S. Geological Survey, in cooperation with the U.S. Navy, has been investigating the potential for mercury sources on the Bremerton Naval Complex to recontaminate recently remediated marine sediment. In 2011–12, the U.S. Geological Survey conducted three tidal-related sampling campaigns to characterize mercury dynamics in the largest stormwater drain system on the Bremerton Naval Complex, which passes through the soils of an area known as Site 2 that has elevated soil mercury concentrations. The sampling campaigns confirmed that the stormwater drain system, PSNS015, serves as a conduit for seawater transport more than 250 m landward of the contaminated soils that subsequently facilitates mercury transport to Sinclair Inlet.

During the December 2011 reconnaissance sampling campaign, no freshwater source of mercury to PSNS015 was identified. There was heavy precipitation preceding and stormwater runoff generated during the reconnaissance survey, which suggests that the primary source of mercury in PSNS015 is not precipitation-induced. During the May 2012 spring-tide sampling campaign, the water in PSNS015 drained to Sinclair Inlet during a negative low tide, and the highest filtered total mercury concentration in the stormwater drain system (60 ng/L) was measured during the lower-low tide in the freshwater flowing into the seaward-most stormwater drain vault from either up-pipe or local groundwater intrusion. Similar conditions were not observed during the June 2012 companion neap-tide sampling campaign, when the water-level elevation of the positive low tide in Sinclair Inlet dropped only slightly below the stormwater drain vault elevation, the water in the seaward-most stormwater vault was brackish rather than fresh, and the filtered total mercury concentration never exceeded 24 ng/L. Particulate total mercury concentrations and dynamics during the spring- and neap-tide sampling campaigns were variable, with higher concentrations (as much as 133 ng/L) measured throughout the neap-tide study compared to those measured during the spring-tide study (as much as 4.34 ng/L). The highest filtered total mercury concentration of all sampling campaigns (1,140 ng/L) was measured during ebb tide in a nearshore monitoring well that represents groundwater discharging from the contaminated soils directly to Sinclair Inlet along an unwalled part of the shoreline.

The results suggest that mercury extracted from Site 2 soils can be carried to Sinclair Inlet during ebb tides by at least two mechanisms: (1) through groundwater directly to Sinclair Inlet along an unwalled part of the shoreline or (2) through the stormwater drain system when the water level in Sinclair Inlet drops below the water level in the stormwater drain system. The data can be used to guide future modifications to the seawall and stormwater drain system that aim to hydraulically disconnect the stormwater drain system from the surrounding contaminated soils.

Introduction

The sediments in Sinclair Inlet within Puget Sound, Washington (fig. 1) have elevated concentrations of many organic compounds and elements including mercury (Malins and others, 1982). Mercury, particularly methylmercury, is toxic to aquatic biota and humans when consumed. A remedial investigation of the marine waters off the Bremerton Naval Complex (BNC), Bremerton, Washington (fig. 2), was completed under the Comprehensive Environmental Response, Compensation, and Liability Act in 1996 (U.S. Navy, 2002) and the final Record of Decision was issued in 2000 (U.S. Environmental Protection Agency, 2000). The remediation actions included isolating a considerable volume of contaminated marine sediment from interactions with the benthic food web by placing dredge spoils from navigational and cleanup dredging in a covered confined aquatic disposal pit created in 2001. Three pathways were identified as having the capability to transport chemicals from the terrestrial landscape of the BNC to the marine environment, thus having the potential to recontaminate recently remediated marine sediment. The pathways included discharges from the dry dock systems, from groundwater, and from stormwater systems (U.S. Environmental Protection Agency, 2000).



USGS National Elevation Data (NED) 2000, 30 meter resolution
UTM zone 10, datum NAD83

Figure 1. Location of Sinclair Inlet within Puget Sound, Kitsap County, Washington.

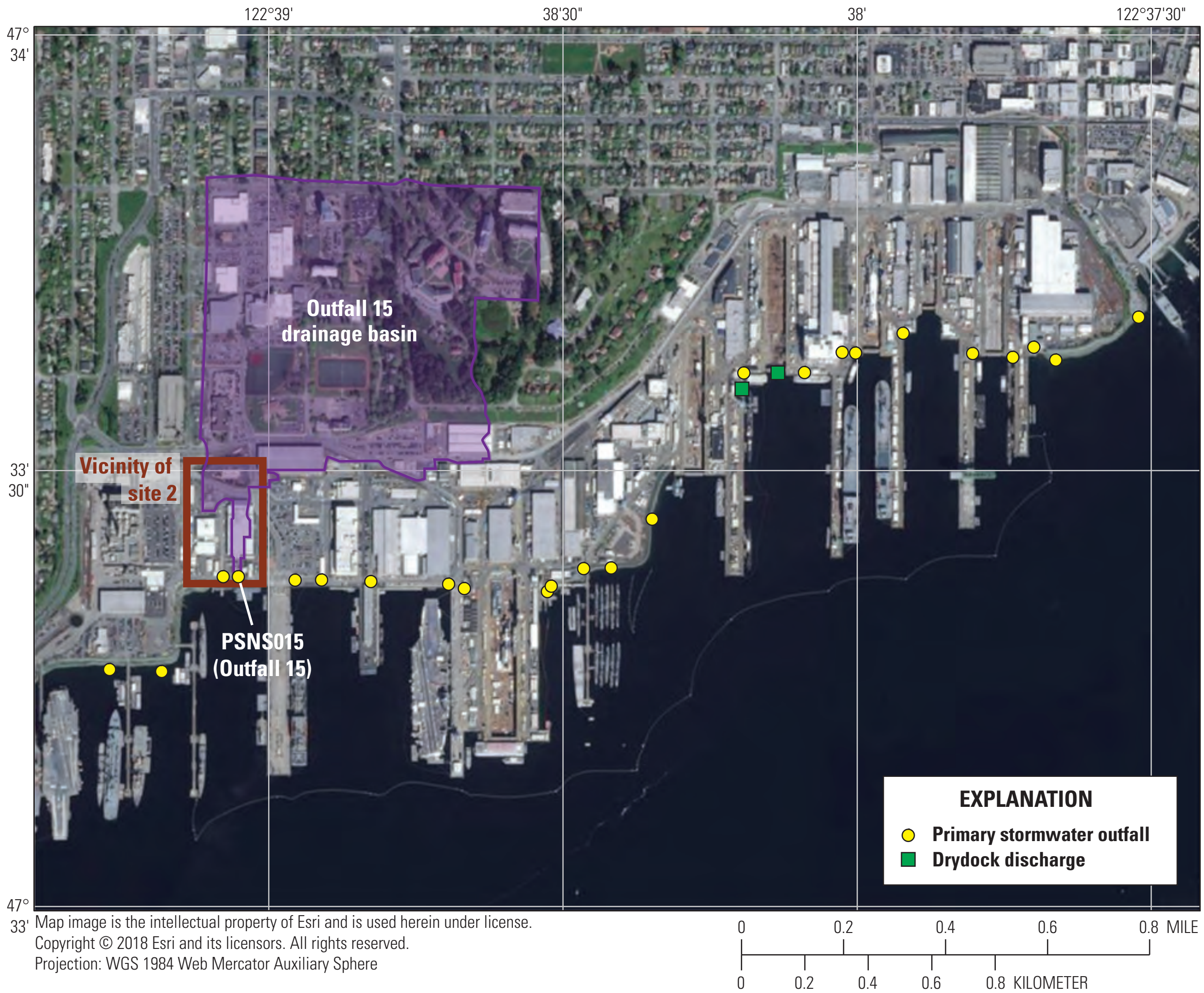


Figure 2. Location of the PSNS015 stormwater drain system drainage basin relative to the vicinity of Site 2 on the Bremerton Naval Complex, Kitsap County, Washington. Recreated from figure ES-8 in the Final Supplemental Mercury Investigation Report PSNS Superfund Site, Bremerton Naval Complex (U.S. Navy, 2017a). Outfall and drydock discharge locations are where the pipes intersect the water's edge/seawall, but are not the actual discharge locations into Sinclair Inlet (which are further out in the water).

A previous investigation by the U.S. Geological Survey (USGS), in cooperation with the U.S. Navy, identified contaminated soils in Site 2 in the BNC (figs. 2 and 3) as the largest anthropogenic source of filtered (dissolved) total mercury (FTHg) to Sinclair Inlet (Paulson and others 2012, Huffman and others 2012, Paulson and others 2013). FTHg (reported as nanograms per liter, ng/L) is defined as all chemical forms of mercury in the filtrate passing through a quartz fiber filter (QFF) with a 0.7 micrometer (μm) nominal pore size. Particulate total mercury (PTHg, reported as ng/L) is defined as all chemical forms of mercury captured on the QFF. Total mercury in an unfiltered water sample (WTHg, reported as ng/L) is the sum of the filtered and particulate fractions:

$$WTHg = FTHg + PTHg \quad (1)$$

Total mercury on suspended solids (reported as mg/kg) is the particulate fraction divided by total suspended solids (TSS, reported as milligram per liter, mg/L):

$$\text{THg on solids (ng/mg or mg/kg)} = \text{PTHg (ng/L)/ TSS (mg/L)}. \quad (2)$$

Site 2 historically contained an electrical shop, cleaning facilities and storage facilities, and a time-critical removal action occurred in the 1980s because of toxic chemicals leaking from containers. During a site investigation (U.S. Navy, 1992), total mercury concentrations in Site 2 soils ranged from 6.6 to 31 mg/kg for 42 samples collected at depths as deep as 12 m below ground. A 75-m long seawall along the shoreline south of Site 2 (fig. 3) limits tidal intrusion into the contaminated soils. However, the stretch

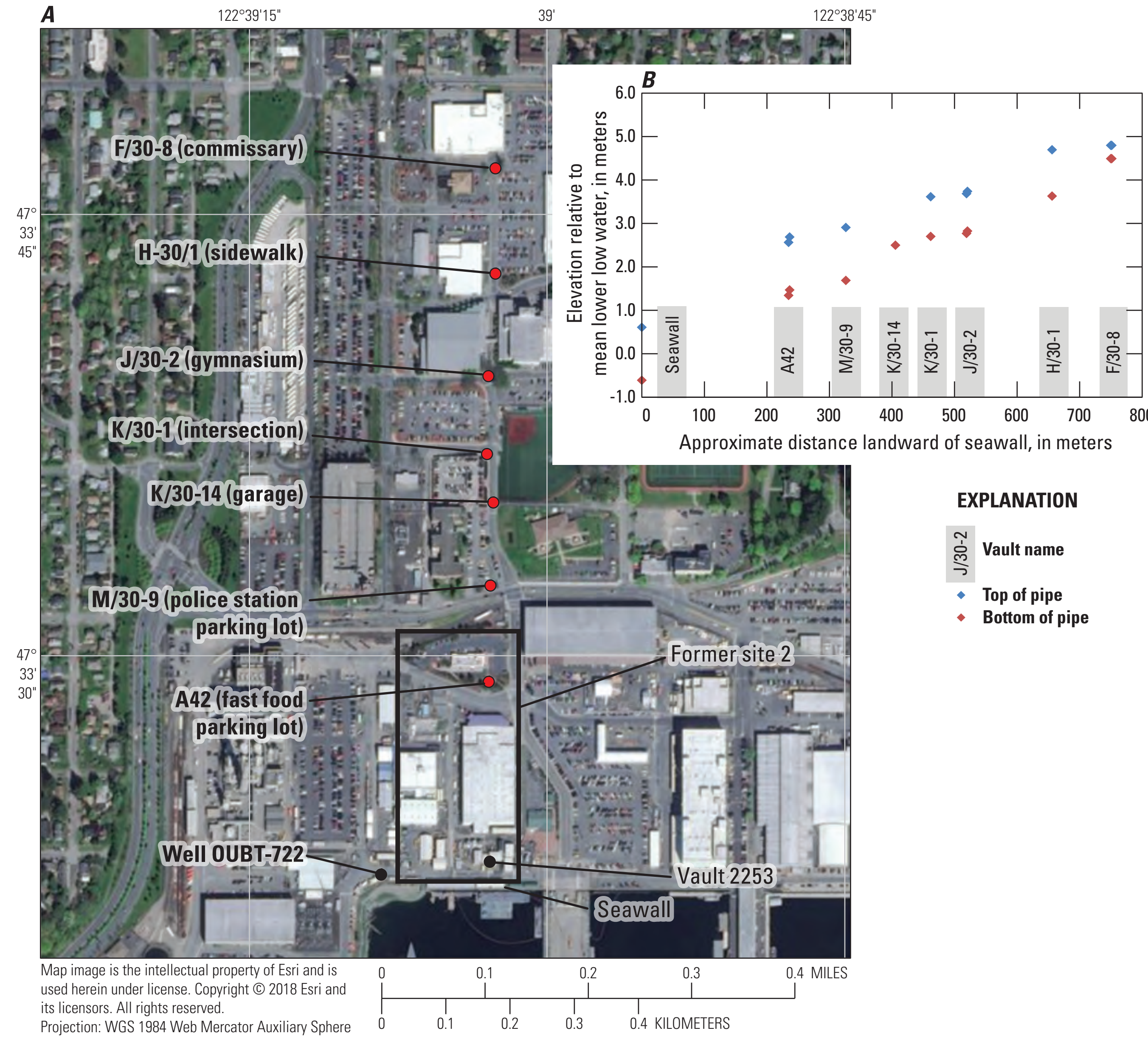


Figure 3. PSNS015 stormwater drain (*A*) vault monitoring locations (approximate) and graph showing (*B*) elevations along the main line of stormwater drain, Bremerton Naval Complex, Kitsap County, Washington.

of shoreline immediately west of Site 2 is unwalled, and the groundwater flow direction in this vicinity is not influenced by dry dock pumping (Jones and others, 2016), so there is a direct groundwater discharge pathway from Site 2 to Sinclair Inlet. Additionally, the largest stormwater drain system on the BNC, PSNS015, passes through the soils of Site 2 (figs. 2 and 3). The main line of stormwater drain PSNS015 runs perpendicular to the shoreline, with a complex network of side arms that drains a 0.41 km^2 area containing industrial facilities and facilities for parking, housing, shopping, recreation, and dining for military personnel and their families (Paulson and others, 2012). The 1.2-m diameter PSNS015 main line pipe passes through the seawall, then drops vertically and extends about 30-m horizontally into Sinclair Inlet. At the seawall, the pipe is situated between +0.61 m and -0.61 m relative to mean lower low water (MLLW).

The PSNS015 stormwater drain system (hereinafter PSNS015) has been the focus of multiple Navy studies to map the stormwater drain system, including locations and elevations of vaults and drain pipes in support of identifying areas for repair owing to cross-connections with the sewer system, cracks and breaks in the pipes, and dead-end lines (EMCON, 1992). Elevated mercury concentrations have been measured in water samples collected from vaults along the PSNS015 main line (Paulson and others, 2012), including FTHg of 144 ng/L in the A42 vault (in the fast food parking lot) in January 2009 and FTHg of 89.4 ng/L in vault 2253 near the seawall in March 2010 (fig. 3). Elevated FTHg concentrations as much as 2,300 ng/L were measured in a groundwater monitoring well (well OUBT-722, also known as LTMP-3) near the shoreline west of the seawall during a June 2008 tidal study (Paulson and others, 2012). The highest concentrations were measured near the water table in the well during ebb tides when the water level in Sinclair Inlet dropped below the water level in the well. These data, in combination with elevated FTHg concentrations (702 ng/L) in one nearshore piezometer located just west of the seawall, suggest that Site 2 soils continue to be a source of mercury to Sinclair Inlet through direct groundwater discharge and through PSNS015.

As the lead agency for the environmental cleanup, the U.S. Navy does 5-year reviews to ensure that the remedial actions selected in the Records of Decision at BNC remain protective of human health and the environment. In the U.S. Navy's fourth 5-year review (U.S. Navy, 2017b), a protectiveness determination could not be made for the area containing PSNS015 (OU B Terrestrial) or the receiving waters in Sinclair Inlet (OU B Marine) because:

> "The magnitude and effects of the mercury source in the Outfall 15 drainage basin… [is] not sufficiently understood… Source control evaluations are incomplete and a remedy has not been selected for mercury in the marine environment (U.S. Navy, 2017b, page 9-1)."

The working hypothesis at Site 2 is that seawater intrudes relatively short distances landward around the seawall, and much longer distances through the stormwater drain system during flood tides. The seawater can infiltrate contaminated Site 2 soils through cracks and breaks in the stormwater drain pipe network and preferentially extract mercury from the soils. During ebb tides, the mercury-containing water then drains back to Sinclair Inlet both around the western end of the seawall, and through the stormwater drain main line pipe. The drainage back to Sinclair Inlet is likely most significant during spring tides with large tidal differentials. That is when +3 m or higher high tides allow seawater to infiltrate infrequently saturated near-surface soils, followed by negative low tides when the Sinclair Inlet water-level elevation drops below the water level in the stormwater drain system, allowing a fast and near complete draining of both seawater and the overlying freshwater lens from the stormwater drain system to the inlet. In contrast, the drainage back to Sinclair Inlet is likely far less during neap tides when the tidal differentials are small. During those times the water-level elevation in Sinclair Inlet does not drop below the water level in the stormwater drain system, and minimal draining of the system is expected to occur.

To further test this hypothesis and provide data for the U.S. Navy to make a protectiveness determination regarding mercury (U.S. Navy, 2017b), the USGS completed three tidal sampling campaigns in 2011–12 to characterize mercury dynamics in PSNS015. The objectives were to: (1) identify potential freshwater sources of mercury to the A42 vault other than Site 2 soils; (2) determine the landward-most extent of seawater intrusion within PSNS015; and (3) characterize tidally influenced concentrations of mercury and ancillary parameters in the A42 vault and other nearby locations during a spring tide and a neap tide.

Methods

Field Sampling

To identify potential sources of mercury to the A42 vault other than Site 2 soils, such as a freshwater source, a reconnaissance survey was conducted on December 28, 2011, following a rainfall event. The reconnaissance survey also was timed to capture a higher high tide to determine the landward-most extent of seawater intrusion within PSNS015. Vertical profiles of water-quality parameters (temperature, pH, specific conductance, and depth) were collected near the time of the +4.0 m higher high tide in three vaults along the main line of PSNS015 (fig. 3): A42 (in the fast food parking lot), M/30-9 (in the police station parking lot), and J/30-2 (just south of the gymnasium). During the subsequent ebb to a +1.7 m higher low tide, 23 freshwater samples were collected from 18 locations within 6 vaults along the main line from F/30-8 (near the commissary) seaward to A42, excluding K/30-1 (fig. 3, table 1). Vault and pipe naming conventions were in accordance with EMCON (1992). Grab samples of water for mercury analysis were collected directly into new polyethylene terephthalate copolyester (PETG) bottles lowered on a pole to sample the inflow at the upstream end of the vault, the outflow at the downstream end of the vault, or the inflow from drain pipes draining to the vault. For the F/30-8 vault (commissary), the outflow of water is equal to the sum of the inflow from the pipes and groundwater infiltration directly into the vault. For downstream vaults, the outflow of water is equal to the sum of inflow from the main line and side pipes and groundwater infiltration directly into the vault. A second set of grab samples for TSS, alkalinity, and major ions were collected into acid-cleaned PETG bottles. Aliquots from the second set of samples were used for field determination of specific conductance. The sample bottles were stored in sealed bags on ice and transported to the USGS Washington Water Science Center (WAWSC) for processing and shipping.

Table 1. Sampling locations within vaults along the PSNS015 stormwater drain system and the nearby groundwater monitoring well and National Water Information System associated station ID, Bremerton Naval Complex, Kitsap County, Washington.

[See figure 3 for vault locations. **Abbreviations:** NWIS, U.S. Geological Survey National Water Information System; Y, a sample was collected from this location; –, a sample was not collected from this location]

NWIS station ID	Sampling location description	Sampling campaign		
		December 2011 reconnaissance	May 2012 Spring tide	June 2012 Neap tide
		F/30-8 (Commissary)		
473346122390308	Inflow	Y	–	–
473346122390302	Outflow	Y	–	–
473346122390303	Pipe 3 (southwest)	Y	–	–
473346122390304	Pipe 4 (west)	Y	–	–
473346122390305	Pipe 5 (west-northwest)	Y	–	–
473346122390306	Pipe 6 (northwest)	Y	–	–
		H/30-1 (Sidewalk)		
473343122390201	Pipe 1 (north-northwest)	Y	–	–
473343122390203	Pipe 3 (northeast)	Y	–	–
473343122390204	Pipe 4 (east)	Y	–	–
		J/30-2 (Gymnasium)		
473339122390300	Inflow	Y	Y	Y
473339122390303	Outflow	Y	Y	Y
473339122390302	Pipe 2 (east)	Y	–	–
		K/30-1 (Intersection)		
473337122390301	Inflow	Y	–	–
473337122390305	Outflow	Y	–	–
473337122390303	Pipe 3 (east)	Y	–	–
473337122390306	Pipe 6 (southwest)	Y	–	–
473337122390307	Pipe 7 (northwest)	Y	–	–
		K/30-14 (Garage)		
473335122390300	Inflow	–	Y	Y
473335122390302	Outflow	–	Y	Y
		M/30-9 (Police station parking lot)		
473332122390303	Outflow	Y	–	–
		A42 (Fast food parking lot)		
473329122390301	Inflow	Y	–	–
473329122390304	Outflow / Bottom	Y	Y	Y
473329122390300	Surface	Y	Y	Y
473329122390302	Pipe 2 (east)	Y	Y	–
473329122390306	Pipe 6 (west-southwest)	Y	Y	–
473329122390307	Pipe 7 (west)	–	–	Y
473329122390309	Pipe 9 (southeast)	Y	–	–
		OUBT-722 Groundwater monitoring well		
473322122390703	Mid-level	–	Y	–

Two 13-hour tidal sampling campaigns were conducted at the A42 vault in May and June 2012 to compare mercury dynamics within PSNS015 during a spring tide and a neap tide, both of which had higher high tides of approximately +4 m. During the May 7, 2012, spring tide, samples were collected over a 4.9 m tidal differential from a lower high tide (+3.7 m around 06:00) to a lower low tide (-1.0 m around 12:30) to a higher high tide (+3.9 m around 20:00). All reported times are local time. During the June 26–27, 2012, neap tide, samples were collected over a 3.2 m tidal differential from a higher high tide (+3.8 m around 23:00 on June 26) to a lower low tide (+0.7 m around 06:00 on June 27) to a lower high tide (+2.5 m around 12:00 on June 27). During both sampling campaigns, rainfall was less than 0.25 cm in the previous 24 hours, so the stormwater drain system was not conveying stormwater runoff.

During the tidal sampling campaigns, the water level in the A42 vault was measured every 30 minutes per USGS methods (Cunningham and Schalk, 2011; Kozar and Kahle, 2013). Water temperature, pH and specific conductance were continuously monitored at an elevation 0.2 m above the bottom of the vault for the entire 13-hour study. Vertical profiles of temperature, pH, and specific conductance were recorded every 30 minutes when a seawater/freshwater interface was present. Hourly samples of water were collected near the bottom of the vault using a peristaltic pump and Teflon™ tubing (after purging the sample line) in new 2-L PETG bottles for FTHg and PTHg analyses, and in acid-cleaned 1-L PETG bottles for TSS, alkalinity, and major ions determination. When a seawater/freshwater interface was present, a sample from immediately below the water surface also was collected in the same manner. Opportunistic samples from upstream vaults, well OUBT-722, and drain pipes flowing into the A42 vault also were collected. At select times, samples of water from vaults and flowing drain pipes were pumped into autoclaved bottles for bacteria analysis. Specific conductance was measured in the field on subsamples from the 1-L PETG bottles. In total, 28 environmental water samples during the May spring tidal study and 44 samples during the June neap tidal study were collected from within the A42 vault (bottom, surface, or drain pipes), other vaults (J/30-2 and K/30-14) and well OUBT-722 (table 1). The samples were stored in sealed bags on ice and transported to the USGS WAWSC for processing and shipping.

Laboratory Processing and Analysis

At the WAWSC, samples collected in PETG bottles for mercury were processed in a laminar-flow hood as described by Lewis and Brigham (2004). Briefly, the samples were filtered through a QFF held in a Savillex® perfluoroalkoxy (PFA) filtering tower assembly into a 500-mL PFA bottle for FTHg analysis. The filtrate was acidified with 10 mL of 6 molar hydrochloric acid per liter of water within 6 hours of sample collection. The filters were transferred to PFA petri dishes for PTHg analysis. Bottles and petri dishes were bagged and shipped to the USGS Mercury Research Laboratory (MRL) in Middleton, Wisconsin, for analysis. The FTHg was determined using U.S. Environmental Protection Agency method 1631, revision E (U.S. Environmental Protection Agency, 2002a) that includes oxidation, purge and trap, desorption, and cold vapor atomic fluorescence spectrometry. The method detection limit for FTHg was approximately 0.05 ng/L. Filters for PTHg analysis were prepared by room-temperature acid digestion and oxidation with aqua regia followed by overnight heating (50 °C) in a 5-percent (weight/volume percentage) bromine monochloride solution to ensure complete oxidation (Olund and others, 2004). The solution was analyzed by cold vapor atomic fluorescence spectrometry. The method reporting limit for PTHg was approximately 0.05 ng of mercury per filter.

At the WAWSC, an aliquot from the second PETG bottle was filtered through a 0.45 µm glass-fiber filter for alkalinity, major ions, and total iron and manganese. Alkalinity was performed at the WAWSC using the inflection-point method (Wilde, variously dated). Bottles for major ions and total iron and manganese were shipped on ice to the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado, for analysis by ion chromatography and inductively-coupled plasma-optical emission spectrometry methods (Fishman and Friedman, 1989; Fishman, 1993). The TSS was measured at the WAWSC from the remaining sample in the second PETG bottle. The aliquot was filtered gravimetrically through a 0.4 µm pore-size, 47-mm diameter, Nuclepore® polycarbonate filter and determined to a precision of 0.001 mg, as previously described in Huffman and others (2012).

During the May 2012 study, bacteria samples were analyzed at the WAWSC for *E. coli* and total coliforms using an enzyme substrate method (Colilert-18, IDEXX, Westbrook, Maine) and reported as Most Probable Number (MPN) per 100 mL. During the June 2012 study, in cooperation with the Environmental Investment project (Washington State Department of Ecology, 2012), bacteria samples were submitted to Twiss Analytical (Poulsbo, Washington) for fecal coliform analysis by membrane filtration (U.S. Environmental Protection Agency, 2002b) and reported as Colony Forming Units (CFU) per 100 mL.

Quality Assurance and Control

Sampling and processing procedures were in accordance with USGS and WAWSC protocols (U.S. Geological Survey, variously dated; Conn and others, 2017), including those for low-level mercury (Lewis and Brigham, 2004). Sampling, processing, and analytical procedures followed those described in detail in Huffman and others (2012). The field water-quality parameters (temperature, pH, and specific conductance) were measured with a 6920V2 multi-parameter sonde (YSI Inc., Yellow Springs, Ohio) that had been calibrated per USGS protocols (Wilde, variously dated) at the WAWSC laboratory just prior to each tidal study. All mercury sampling equipment and PFA bottles were hot acid-cleaned at the MRL using procedures described by Lewis and Brigham (2004). The QFF were pre-combusted at the MRL. Field notes, field parameters, and laboratory results were reviewed by WAWSC personnel. All data are publicly available in the USGS National Water Information System (https://nwis.waterdata.usgs.gov/usa/nwis/qwdata) under the project code D6M1200 by Station ID (table 1).

Two field equipment blank samples (one each collected during the May and June sampling campaigns) had non-detectable concentrations of PTHg (<0.083 and <0.116 ng/L, respectively) and trace concentrations of FTHg (0.17 and 0.07 ng/L, respectively), indicating that the equipment cleaning procedures were appropriate for low-level mercury analysis. A sample of mercury-free blank water was pumped through the field pump tubing in between two hourly samples from the A42 vault during the June study to assess carryover contamination from using the same tubing throughout each 13-hour study. A trace concentration of FTHg (0.11 ng/L) was detected at a level like that measured in the equipment blank and much lower than (approximately 1 percent of) the FTHg concentration measured in the preceding stormwater sample collected with that tubing (8.66 ng/L). The concentration of PTHg in the field carryover sample was 2.27 ng/L, which was approximately 15 percent of the PTHg concentration in the preceding stormwater sample (15.6 ng/L) and lower than the range of measured environmental concentrations during the June study (4.16–133 ng/L). Environmental results were not corrected for potential carryover contamination.

Two field replicates for mercury analysis were collected during each 13-hour tidal study by filling a second bottle immediately after the first bottle. Relative percent difference (RPD) ranged from 11 to 41 percent for FTHg (<1 to 6 ng/L difference) and 4 to 36 percent for THg on solids (0.02 to 3 mg/kg difference). The RPD of specific conductance in these same samples was 3–15 percent. A single alkalinity field replicate analyzed at the WAWSC had an RPD of 13 percent. The RPD of major ions, iron, and manganese ranged from 1.2 percent for calcium to 32 percent for manganese. These RPDs indicate both analytical variations as well as short-term temporal variation at the sampling location.

Results for *E. coli* and total coliforms were less than 1 MPN/100 mL in a field replicate and the associated environmental sample during the May study. All May 2012 bacteria samples were analyzed outside of the 24-hour hold time, and results are considered qualitative. During the June study, two field replicates had a RPD of 0.4 and 11.3 percent as compared to the associated environmental sample.

The USGS NWQL and MRL performed laboratory quality assurance and control measures per their protocols, which included instrument calibration, laboratory blank samples, replicate samples, matrix spike samples, and analysis of reference materials, if available (Stevenson, 2013; Stevenson and Barnard, 2013; U.S. Geological Survey Mercury Research Laboratory, 2017). Laboratory quality-control samples at the MRL included 58 FTHg laboratory control samples (FTHg approximately 5 ng/L) and 36 FTHg matrix spike samples. Percentage recoveries ranged from 91 to 122 percent (average = 104 percent) and from 84 to 116 percent (average = 100 percent), respectively. PTHg laboratory quality-control samples included 51 high and low standards, 29 analyses of a certified reference material (IAWA-SL-1, International Atomic Energy Agency, with 0.13 mg mercury/kg dry lake sediment), 35 matrix spike samples, and 35 sample replicates. Percentage recoveries ranged from 92 to 115 percent (average = 101 percent), 91 to 112 percent (average = 101 percent), 91 to 137 percent (average = 102 percent), and 83 to 116 percent (average = 101 percent), respectively. The percent difference between the 35 environmental samples and laboratory replicates ranged from -16 to 9 percent (average = -2 percent). Many of the environmental PTHg results were not reported by MRL because laboratory quantification criteria were not met owing to matrix interference and low spike recovery. This included 20 of 23 reconnaissance survey samples and three neap study samples.

From October 2011 through September 2012, reported concentrations of major ions in blind samples submitted to the NWQL was generally within two F-pseudo sigma (a non-parametric statistical measure of variance, similar to standard deviation) of the MPN. The median percent recovery of spiked samples ranged from 95 percent for bromide to 105 percent for fluoride. Complete results of NWQL performance are available through the Inorganic Blind Sample Project (https://bqs.usgs.gov/ibsp/charts.php) and the Standard Reference Sample Project (https://bqs.usgs.gov/srs/) at the USGS Quality Systems Branch. Two laboratory replicates of stormwater samples at Twiss Analytical for fecal coliforms had a RPD of 3.3 and 16 percent. A laboratory blank sample of deionized water for TSS was 0.33 mg/L. All 38 field replicates of TSS had a RPD of less than 40 percent or less than 2 mg/L difference. Five laboratory replicates of TSS had a RPD of 6.5–18 percent. Other than the May 2012 qualified bacteria data, the results from the various field and laboratory quality-assurance samples were satisfactory, and no other qualifications to the data were made.

Sources of Filtered Total Mercury Other Than Site 2 Soils

The December 2011 reconnaissance survey was timed with a precipitation event for detecting potential freshwater sources of mercury to PSNS015. No freshwater source of mercury to the A42 vault was identified during the reconnaissance survey. All 23 samples collected during ebb tide on December 28 from six PSNS015 main line vaults and flowing drain pipes (fig. 3, table 2) were freshwater (specific conductance <300 µS/cm) and had low concentrations of major ions and mercury (FTHg < 10 ng/L, PTHg < 5 ng/L). In the three samples with reported PTHg results, one was less than, one was similar to, and one was greater than the corresponding FTHg concentration (table 2). In all cases during the reconnaissance survey, the FTHg concentration in the inflow and outflow was less than 5 ng/L.

Table 2. Summary of field parameters and concentrations of major ions and mercury in freshwater samples in main line vaults in the PSNS015 stormwater drain system during an ebb tide reconnaissance survey sampling campaign, Bremerton Naval Complex, Kitsap County, Washington, December 28, 2011.

[See figure 3 for vault locations. Results are for filtered water samples, with the exception of pH, specific conductance, total suspended solids, and particulate total mercury. **Description of sample location within vault:** E, east; N, north; NE, northeast; NNW, north-northwest; SE, southeast; SW, southwest; W, west; WNW, west-northwest; WSW, west-southwest. **FTHg:** Filtered total mercury. **PTHg:** Particulate total mercury. **WTHg:** Whole total mercury. **Abbreviations:** µS/cm, microsiemen per centimeter at 25 degrees Celsius; mg/L, milligram per liter; µg/L, microgram per liter; ng/L, nanogram per liter; mg/kg, milligram per kilogram; <, less than; –, not measured; n, below the reporting level but at or above the detection level; nr, not reported, did not meet laboratory quantification criteria owing to matrix interference and low spike recovery]

Description of sample location within vault	pH	Specific conductance (µS/cm)	Alkalinity (mg/L as calcium carbonate)	Dissolved solids (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Chloride (mg/L)	Fluoride (mg/L)
F/30-8 (Commissary)										
Inflow	6.8	104	33	58	10.1	2.37	0.58	3.45	2.61	0.04 n
Outflow	6.9	94	33	68	9.49	2.98	0.67	3.52	2.47	<0.04
Pipe 3 (SW)	6.5	19	4	<20	2.06	0.412	0.24	0.94	0.88	<0.04
Pipe 4 (W)	7.0	255	73	148	18.0	14.7	1.77	7.45	5.85	<0.04
Pipe 5 (WNW)	7.0	144	33	97	9.23	6.6	1.31	4.09	3.54	<0.04
Pipe 6 (NW)	6.6	24	4	<20	2.5	0.354	0.47	1.17	0.88	<0.04
H/30-1 (Sidewalk)										
Pipe 1 (NNW)	7.2	177	56	92	16.8	8.5	1.09	6.00	4.83	0.05 n
Pipe 3 (NE)	7.6	164	47	107	18.2	5.51	1.46	6.16	9.43	0.07 n
Pipe 4 (E)	7.2	178	53	110	17.5	7.47	1.23	6.12	6.56	0.04 n
J/30-2 (Gymnasium)										
Inflow	7.2	141	31	79	11.5	4.03	1.09	8.60	11.8	<0.04
Outflow	7.0	134	37	90	11.3	4.03	1.16	8.78	11.7	0.06 n
Pipe 2 (E)	7.8	120	17	74	5.4	1.49	1.12	12.4	17.5	<0.04
K/30-1 (Intersection)										
Inflow	7.1	194	47	114	12.5	5.3	1.54	15.6	21.3	0.04
Outflow	7.1	191	43	106	12.3	5.21	1.62	15.9	21.4	<0.04
Pipe 3 (E)	7.0	85	16	52	5.98	1.84	1.23	7.88	10.4	<0.04
Pipe 6 (SW)	7.1	61	22	–	8.39	0.678	1.15	2.94	2.72	0.05
Pipe 7 (NW)	6.7	37	14	<20	3.67	1.35	0.31	1.65	1.38	<0.04
M/30-9 (Police station parking lot)										
Outflow	7.3	254	30	109	10.6	4.55	1.6	18.4	29.1	<0.04
A42 (Fast food parking lot)										
Inflow	6.8	56	8	38	3.04	0.807	0.62	4.95	6.99	<0.04
Outflow	6.7	47	7	35	2.66	0.706	0.58	4.62	6.47	<0.04
Pipe 2 (E)	6.9	249	12	123	4.69	3.99	2.06	31.6	54.9	0.05 n
Pipe 6 (WSW)	7.2	75	17	41	6.26	1.02	1.37	5.04	6.69	0.1
Pipe 9 (SE)	7.0	35	10	<20	3.82	0.325	0.48	2.40	2.06	0.04 n

Table 2. Summary of field parameters and concentrations of major ions and mercury in freshwater samples in main line vaults in the PSNS015 stormwater drain system during an ebb tide reconnaissance survey sampling campaign, Bremerton Naval Complex, Kitsap County, Washington, December 28, 2011.—Continued

Description of sample location within vault	Silica (mg/L as silica dioxide)	Sulfate (mg/L)	Iron (mg/L)	Manganese (µg/L)	FTHg (ng/L)	PTHg (ng/L)	WTHg (ng/L)	PTHg, as a percent of whole total mercury	Total suspended solids (mg/L)	Total mercury on solids (mg/kg)
F/30-8 (Commissary)										
Inflow	5.99	2.42	43.0	20.2	1.60	nr	nr	nr	4.24	nr
Outflow	7.63	2.92	38.6	12.6	2.27	nr	nr	nr	5.03	nr
Pipe 3 (SW)	2.85	1.00	156	5.98	3.55	nr	nr	nr	11.2	nr
Pipe 4 (W)	32.3	12.3	6.4	1.30	0.59	nr	nr	nr	6.44	nr
Pipe 5 (WNW)	16.0	7.47	163	20.2	3.19	nr	nr	nr	33.0	nr
Pipe 6 (NW)	1.39	0.78	75.9	8.77	3.47	nr	nr	nr	10.3	nr
H/30-1 (Sidewalk)										
Pipe 1 (NNW)	18.0	6.68	146	25.5	1.12	0.599	1.72	35	2.19	0.27
Pipe 3 (NE)	17.0	3.43	590	65.3	2.30	4.82	7.12	68	20.8	0.23
Pipe 4 (E)	17.7	5.68	296	45.0	1.53	1.54	3.07	50	4.66	0.33
J/30-2 (Gymnasium)										
Inflow	9.48	5.04	142	14.1	2.76	nr	nr	nr	9.98	nr
Outflow	9.14	4.92	114	12.8	2.69	nr	nr	nr	18.9	nr
Pipe 2 (E)	3.75	4.74	72.6	4.37	2.78	nr	nr	nr	10.9	nr
K/30-1 (Intersection)										
Inflow	11.0	7.48	116	15.8	3.00	nr	nr	nr	9.87	nr
Outflow	10.5	7.13	118	14.2	4.29	nr	nr	nr	9.51	nr
Pipe 3 (E)	4.71	2.90	90.3	4.23	9.00	nr	nr	nr	12.8	nr
Pipe 6 (SW)	5.55	1.55	551	10.1	3.18	nr	nr	nr	70.5	nr
Pipe 7 (NW)	2.17	1.12	43.4	29.3	1.64	nr	nr	nr	2.75	nr
M/30-9 (Police station parking lot)										
Outflow	8.69	7.05	112	13.5	3.53	nr	nr	nr	13.0	nr
A42 (Fast food parking lot)										
Inflow	1.65	1.68	45.2	2.94	2.82	nr	nr	nr	27.8	nr
Outflow	1.31	1.60	32.1	2.96	3.11	nr	nr	nr	29.7	nr
Pipe 2 (E)	2.63	8.69	68.3	3.48	3.63	nr	nr	nr	19.4	nr
Pipe 6 (WSW)	4.54	2.01	182	13.4	2.89	nr	nr	nr	47.4	nr
Pipe 9 (SE)	1.46	0.91	76.8	3.89	2.39	nr	nr	nr	20.7	nr

The December 2011 results contrast with those from a single sample collected in the A42 vault in January 2009 with a FTHg concentration of 144 ng/L (Paulson and others, 2012). Both sampling periods occurred during heavy precipitation; the 2-day rainfall totals on the previous day and day of sampling were 7.1 cm in December 2011 and 4.5 cm in January 2009. Both sampling periods followed an approximate +4 m high tide. The 2009 sample was collected at a -0.5 m low tide as compared to the 2011 samples that were collected during a tide ebbing to a +2 m low. These very different mercury results in 2009 and 2011 suggest that mercury dynamics in PSNS015 may be affected by subtle tidal differences, particularly low tide elevation following a higher high tide.

Saltwater Intrusion in the PSNS015 Stormwater Drain System

Data collected during the December 2011 reconnaissance survey, May 2012 spring tide and June 2012 neap tide were used to determine the landward extent of saltwater intrusion within PSNS015. Saltwater is characterized in this report by specific conductance greater than about 40 millisiemens per centimeter (mS/cm). Brackish water, a mixture of saltwater and freshwater, is characterized in this report by specific conductance greater than about 1 mS/cm (1,000 µS/cm). As was hypothesized, data from the 2011–12 tidal sampling campaigns confirm that PSNS015 functions as a conduit for Sinclair Inlet seawater to move landward of Site 2 soils on the BNC and then drain back to Sinclair Inlet on the subsequent ebb tide. At the +4 m higher high tide on December 28, 2011, seawater from Sinclair Inlet intruded upstream in the PSNS015 stormwater drain main pipe landward of the Site 2 soils at least as far as the M/30-9 vault (police station parking lot) (appendix 1, table 1.1). During the approximate +4 m high tides of the 2012 spring and neap sampling campaigns, seawater from Sinclair Inlet intruded upstream (fig. 4*A*) in the PSNS015 main pipe landward of the Site 2 soils at least as far as the J/30-2 (gymnasium) sampling site, which is more than 500 m landward of the seawall (fig. 3). As the stormwater drain vault water level dropped during the subsequent ebb tide, saltwater moved out to Sinclair Inlet and a freshwater lens remained in the A42 vault (fig. 4*B*). During the neap ebb tide to a + 0.7 m low tide, the water level in the vault remained higher with more saltwater as compared to the spring ebb tide to a -1 m low tide in which all of the saltwater drained out of the vault (fig. 4*B*). During the subsequent flood tide, saltwater intruded back upstream in the PSNS015 system, increasing the water level within the A42 vault, and pushing freshwater up the stormwater drain system as a thin freshwater lens on the water surface (fig. 4*C*).

Water Level and Mercury Dynamics in the A42 Vault During a Spring and Neap Tide

Data collected during the May 2012 spring tide and June 2012 neap tide were used to characterize water levels and tidally influenced concentrations of mercury and ancillary parameters in the A42 vault and other nearby locations. The water level in Sinclair Inlet dropped approximately two meters below the A42 vault bottom elevation (1.34 m) during the May 2012 spring tide (fig. 5*A*). The Sinclair Inlet water level dropped approximately equal to the A42 vault bottom elevation during the June 2012 neap tide (fig. 5*B*). During both 1-day sampling campaigns, seawater drained out of the stormwater drain system to Sinclair Inlet during ebb tide, leaving a shallow freshwater seaward flow of water in the bottom of the A42 vault as indicated by the change in specific conductance from approximately 40 to less than 1 mS/cm (figs. 5*A* and 5*B*).

During the May 2012 spring tidal study, concentrations of FTHg in water samples collected in bottom water of the A42 vault were less than 10 ng/L during high tide and ebb tide (table 3). These samples were mostly or all seawater (specific conductance > 1,000 µS/cm). During the 6 hours surrounding low tide when the Sinclair Inlet water level dropped below the vault water level (about 10:00–16:00 on May 7, 2012), FTHg concentrations in the remaining shallow freshwater in the vault were 35–60 ng/L. During the subsequent flood tide as seawater intruded back into the vault, FTHg concentrations in bottom water again dropped below 10 ng/L. For the three-paired surface and bottom water samples collected when the vault water level was less than 2 m (table 3; approximately 7:30 local time during ebb, approximately 8:30 during ebb, and approximately 17:30 during flood), FTHg concentrations in the fresher surface sample were higher than those in the saltier bottom sample.

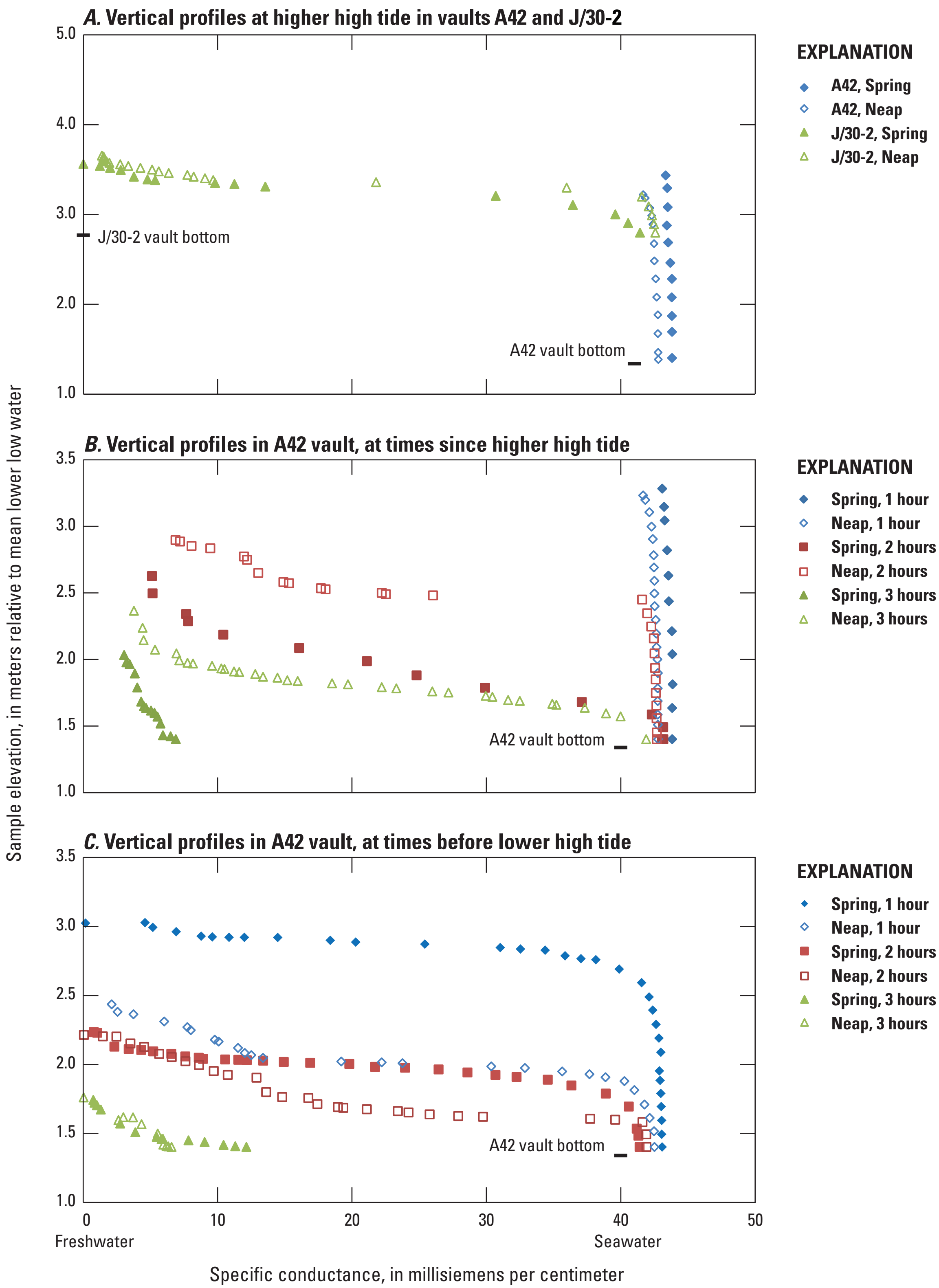


Figure 4. Saltwater dynamics in stormwater drain PSNS015 vaults during a May 2012 spring tide and a June 2012 neap tide, Bremerton Naval Complex, Kitsap County, Washington. Vertical profiles at (*A*) higher high tide in vaults A42 and J/30-2; (*B*) times since higher high tide in vault A42; (*C*) times before lower high tide in vault A42. See figure 3 for vault locations and elevations.

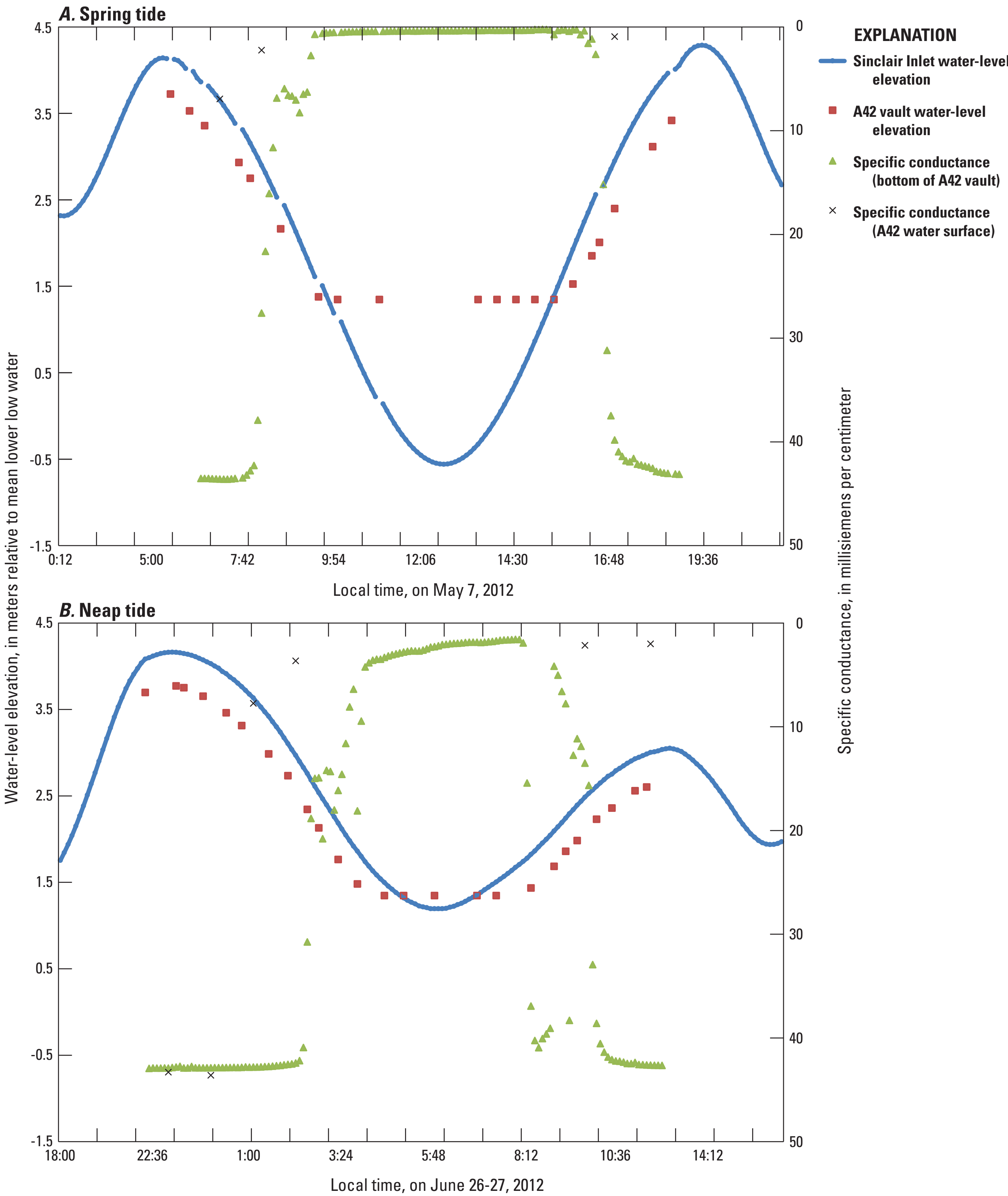


Figure 5. Water-level elevation and specific conductance in the A42 vault as compared to Sinclair Inlet water-level elevation during (*A*) a spring tide and (*B*) a neap tide, Bremerton Naval Complex, Kitsap County, Washington, 2012.

Table 3. Mercury concentrations measured in water samples collected from the A42 vault in the PSNS015 stormwater drain system during a spring tide in May 2012 and a neap tide in June 2012, Bremerton Naval Complex, Kitsap County, Washington.

[Depths are relative to mean lower low water. All times are local time. **FTHg:** Filtered total mercury. **PTHg:** Particulate total mercury. **WTHg:** Whole total mercury. **Abbreviations:** m, meter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; mg/kg, milligram per kilogram; mg/L, milligram per liter; ng/L, nanogram per liter; nr, not reported, did not meet laboratory quantification criteria owing to matrix interference and low spike recovery; –, not measured ; <, less than]

Date	Time	Tidal stage	Sinclair Inlet water-level elevation (m)	Water level in vault (m)	Sampler location in water column	Sampling depth (m)	Specific conductance (µS/cm)	FTHg (ng/L)	PTHg (ng/L)	WTHg (ng/L)	PTHg, as a percentage of whole total mercury	Total suspended solids (mg/L)	Total mercury on solids (mg/kg)
May 7, 2012 Spring tidal study													
05-07-12	0618	Lower high	4.05	3.53	Bottom	0.76	44,700	0.37	0.120	0.49	25	2.20	0.055
05-07-12	0724	Ebb	3.52	3.36	Surface	2.58	6,930	7.88	1.28	9.16	14	3.03	0.422
05-07-12	0736	Ebb	3.39	2.93	Bottom	0.76	44,300	0.61	1.79	2.40	75	2.52	0.708
05-07-12	0830	Ebb	2.63	2.75	Surface	1.98	2,240	21.1	0.381	21.5	1.8	44.9	0.008
05-07-12	0840	Ebb	2.46	2.16	Bottom	0.76	8,360	3.93	0.004	3.93	0.1	14.3	<0.001
05-07-12	0924	Slack	1.72	1.35	Bottom	0.76	6,500	11.5	4.34	15.8	27	4.70	0.923
05-07-12	1042	Slack	0.40	1.35	Bottom	0.15	511	52.5	2.67	55.2	4.8	11.3	0.236
05-07-12	1148	Lower low	-0.38	–	Bottom	0.15	419	54.7	1.57	56.3	2.8	15.1	0.104
05-07-12	1336	Slack	-0.28	1.35	Bottom	0.15	327	60.0	1.88	61.9	3.0	10.9	0.173
05-07-12	1454	Slack	0.77	1.35	Bottom	0.15	321	55.1	0.336	55.4	0.6	252	0.001
05-07-12	1618	Slack	2.25	1.53	Bottom	0.15	252	35.3	0.325	35.6	0.9	455	0.001
05-07-12	1712	Flood	3.13	–	Bottom	0.15	10,300	9.15	0.562	9.71	5.8	240	0.002
05-07-12	1742	Flood	3.54	2.40	Surface	1.98	926	23.3	0.545	23.8	2.3	215	0.003
05-07-12	1854	Flood	4.16	3.42	Bottom	0.15	42,500	0.70	0.804	1.50	53	8.43	0.095
05-07-12	1918	Higher high	4.25	–	Bottom	0.15	41,600	0.44	0.711	1.15	62	7.82	0.091
June 26–27, 2012 Neap tidal study													
06-26-12	2300	Higher high	4.16	3.77	Surface	1.670	43,300	0.99	4.16	5.15	81	2.01	2.07
06-27-12	0006	Ebb	4.03	3.46	Surface	1.670	43,600	0.98	5.44	6.42	85	2.05	2.65
06-27-12	0112	Ebb	3.63	3.31	Surface	2.432	7,740	23.0	5.79	28.8	20	1.44	4.03
06-27-12	0124	Ebb	3.53	2.99	Bottom	0.756	43,700	1.08	8.68	9.76	89	2.58	3.37
06-27-12	0218	Ebb	2.97	2.73	Surface	1.975	3,640	8.66	15.6	24.3	64	1.89	8.23
06-27-12	0242	Ebb	2.68	2.34	Bottom	0.756	31,700	4.84	nr	nr	nr	2.25	nr
06-27-12	0312	Slack	2.33	1.76	Bottom	0.756	18,600	3.96	18.7	22.7	83	2.24	8.35
06-27-12	0406	Slack	1.74	1.48	Bottom	0.604	4,390	17.7	133	151	88	6.64	20.0
06-27-12	0506	Slack	1.32	1.35	Bottom	0.604	2,880	6.82	nr	nr	nr	2.16	nr
06-27-12	0600	Lower low	1.19	1.35	Bottom	0.604	2,180	5.50	nr	nr	nr	1.86	nr
06-27-12	0700	Slack	1.36	1.35	Bottom	0.604	1,870	5.57	20.3	25.9	78	1.59	12.8
06-27-12	0730	Slack	1.50	1.35	Bottom	0.604	1,730	5.47	21.4	26.9	80	2.55	8.40
06-27-12	0842	Slack	1.95	1.69	Bottom	0.604	2,440	23.8	73.3	97.1	75	1.40	52.2
06-27-12	0930	Flood	2.34	1.98	Bottom	0.604	1,390	21.7	70.0	91.7	76	1.53	45.8
06-27-12	0948	Flood	2.49	2.23	Surface	1.609	2,140	5.20	12.1	17.3	70	2.62	4.62
06-27-12	1042	Flood	2.82	2.36	Bottom	0.604	41,900	3.49	20.2	23.7	85	2.30	8.79
06-27-12	1124	Flood	2.98	2.56	Bottom	0.604	42,600	2.48	11.2	13.7	82	2.48	4.51
06-27-12	1130	Lower high	3.00	2.60	Surface	2.158	2,000	4.98	8.83	13.8	64	2.73	3.24

PTHg concentrations in A42 vault water samples were low throughout the spring tidal study and contributed less than 30 percent to the WTHg concentration except in seawater samples (specific conductance >40,000 µS/cm) when FTHg were very low. The highest PTHg concentrations during the May 2012 spring tide (as much as 4.34 ng/L) were measured in the shallow freshwater at the bottom of the vault during ebb tide (9:24 local time, table 3). The low PTHg concentrations also resulted in low THg on solids concentrations of less than 1 mg/kg throughout the spring tidal study. The subsequent flood tide appeared to stir up vault bottom sediment as indicated by elevated TSS of 215–455 mg/L. These particulates had low mercury concentrations (THg on solids <0.1 mg/kg).

During the June 2012 neap tidal study, concentrations of FTHg were generally less than 10 ng/L, and never exceeded 25 ng/L (table 3). In contrast to the spring study when higher FTHg concentrations were measured in freshwater for multiple hours in a row during ebb and low tide, there was no consistent temporal pattern of FTHg concentrations. In general, FTHg concentrations were lower in seawater (specific conductance >40,000 µS/cm) than in brackish and freshwater samples. The PTHg concentrations in all June 2012 neap tide samples were higher than all but one May spring tide sample, ranging from 4.16 ng/L at high tide to 133 ng/L nearing low tide when the vault water-level elevation was shallow. A second PTHg spike (70.0–73.3 ng/L) occurred at the end of low tide as the vault water-level elevation was beginning to rise again during the flooding tide. In contrast to the reconnaissance survey and spring tidal study, PTHg concentrations during the neap tidal study accounted for more than 60 percent of WTHg concentrations in all but one sample. It is not clear why most of the mercury in water was bound to particles during the neap study as compared to the reconnaissance survey and spring tidal study. However, it is important new information that suggests that under certain conditions most of the mercury in water may be bound to particulates. Further, TSS concentrations were low throughout the neap tidal study, resulting in THg on solids concentrations as much as 52.2 mg/ kg during the flood tide. These particulate concentrations are much higher than sediment concentrations in Sinclair Inlet, which tend to be less than 1 mg/kg (U.S. Navy, 2017a).

Mercury Concentrations in Opportunistic Samples Collected During a Spring and Neap Tide

Opportunistic samples were collected for mercury analyses from selected vaults landward of the A42 vault, drain pipes flowing into the A42 vault, and well OUBT-722 during the spring and neap tidal sampling campaigns for characterizing tidally influenced mercury concentrations near Site 2 and PSNS015 (table 4). During the May 2012 spring tide, mercury concentrations were low (FTHg < 4 ng/L and PTHg <15 ng/L) at sampled vault locations landward of the A42 vault, including vaults K/30-14 (intersection) and J/30-2 (gymnasium) during ebb tide. There was one elevated FTHg concentration (33.4 ng/L), which was measured in a surface (freshwater) sample at J/30-2 on the flood tide. During the June 2012 neap tide, mercury concentrations were moderately low (FTHg < 15 ng/L and PTHg < 15 ng/L) at sampled locations landward of the A42 vault (table 4) except for one elevated PTHg concentration (30.2 ng/L) that was measured in a brackish water sample (10,700 µS/cm) during ebb tide at the vault K/30-14 (garage) site.

There were three discharges from exposed drain pipes in the A42 vault that were observed and sampled during the spring tidal study. Two discharges were from Pipe 6 from the west-southwestern side of the vault. The first was a freshwater discharge with moderate mercury concentrations (specific conductance = 775 µS/cm, FTHg = 14.5 ng/L, PTHg = 78.3 ng/L). The second was a warm water discharge (temperature = 25.8 degrees Celsius) with elevated specific conductance (9,160 µS/cm), dissolved solids (5,130 mg/L) and major ions similar to an effluent or backwash-type sample, and low mercury concentrations (FTHg = 1.25 ng/L, PTHg = 4.82 ng/L). The third discharge was from Pipe 2 on the east side of the vault. Temperature and major ions were not measured on this sample, and the sample had high specific conductance (22,300 µS/cm) and low mercury concentrations (FTHg = 2.41 ng/L, PTHg = 9.92 ng/L) (table 4).

During the neap tidal study, one discharge from a drain pipe in the A42 vault was observed and sampled; the discharge was from Pipe 7 that enters the vault from the west. The sample was slightly brackish (specific conductance = 1,030 µS/cm and elevated sodium and chloride concentrations) with moderate mercury concentrations (FTHg = 28.2 ng/L; no PTHg results; table 4). No other large drain pipe discharges were observed during neap tidal study.

Table 4. Mercury concentrations measured in water samples collected opportunistically from flowing side drain pipes into the A42 vault and vaults landward of the A42 vault in the PSNS015 stormwater drain system and the nearby groundwater well OUBT-722 during a spring tide in May 2012 and a neap tide in June 2012, Bremerton Naval Complex, Kitsap County, Washington.

[Depths are relative to mean lower low water. All times are local time. **FTHg:** Filtered total mercury. **PTHg:** Particulate total mercury. **WTHg:** Whole total mercury. **Abbreviations:** m, meter; µS/cm, microsiemen per centimeter at 25 degrees Celsius; mg/kg, milligram per kilogram; mg/L, milligram per liter; ng/L, nanogram per liter; nr, not reported, did not meet laboratory quantification criteria owing to matrix interference and low spike recovery; –, not measured]

Date	Time	Tidal stage	Sampling location	Sinclair Inlet water-level elevation (m)	Sampling depth (m)	Specific conductance (µS/cm)	FTHg (ng/L)	PTHg (ng/L)	WTHg (ng/L)	PTHg, as a percentage of whole total mercury	Total suspended solids (mg/L)	Total mercury on solids (mg/kg)
May 7, 2012 Spring tidal study												
05-07-12	0600	Lower high	J/30-2 Inflow	4.11	3.83	669	1.62	1.75	3.37	52	3.02	0.58
05-07-12	0615	Lower high	J/30-2 Outflow	4.07	2.92	40,400	3.83	13.8	17.6	78	4.57	3.02
05-07-12	0650	Ebb	K/30-14 Inflow	3.85	1.50	18,300	2.39	4.70	7.09	66	2.40	1.96
05-07-12	0735	Ebb	A42 Pipe 6 (west-southwest)	3.39	3.26	775	14.5	78.3	92.8	84	5.69	13.8
05-07-12	0925	Slack	A42 Pipe 6 (west-southwest)	1.72	3.26	9,160	1.25	4.82	6.07	79	4.84	0.99
05-07-12	0950	Slack	OUBT-722 well	1.26	–	36,800	1,140	–	–	–	–	–
05-07-12	1002	Slack	K/30-14 Outflow	1.00	2.50	598	1.73	2.09	3.82	55	1.52	1.37
05-07-12	1020	Slack	J/30-2 Outflow	0.77	2.92	369	1.42	1.17	2.59	45	1.14	1.03
05-07-12	1040	Slack	A42 Pipe 2 (east)	0.52	2.33	22,300	2.41	9.92	12.3	80	17.1	0.58
05-07-12	1323	Slack	J/30-2 Outflow	-0.38	2.92	328	1.14	0.794	1.93	41	0.63	1.27
05-07-12	1344	Slack	K/30-14 Outflow	-0.21	2.50	440	1.64	2.22	3.86	58	1.62	1.37
05-07-12	1947	Higher high	J/30-2 Inflow	4.29	4.02	393	33.4	13.9	47.3	29	8.89	1.56
05-07-12	1959	Higher high	J/30-2 Outflow	4.28	2.92	41,100	0.89	11.8	12.7	93	25.3	0.47
June 26–27, 2012 Neap tidal study												
06-26-12	2315	Higher high	J/30-2 In low	4.16	4.27	755	7.62	nr	nr	nr	4.77	nr
06-26-12	2320	Higher high	J/30-2 Out low	4.15	2.93	42,800	3.02	9.85	12.9	77	1.75	5.64
06-27-12	0005	Ebb	K/30-14 Inflow	4.03	1.00	2,650	6.88	10.4	17.3	60	2.35	4.42
06-27-12	0115	Ebb	A42 Pipe 7 (west)	3.99	4.66	1,030	28.2	nr	nr	nr	2.23	nr
06-27-12	0025	Ebb	K/30-14 Outflow	3.94	2.50	42,900	2.99	8.1	11.1	73	1.45	5.58
06-27-12	0300	Slack	K/30-14 Outflow	2.47	2.50	2,630	2.11	11.5	13.6	84	2.42	4.75
06-27-12	0345	Slack	J/30-2 Outflow	1.95	2.93	594	1.26	3.15	4.41	71	2.58	1.22
06-27-12	1250	Lower high	K/30-14 Outflow	3.00	2.50	10,700	12.6	30.2	42.8	71	2.41	12.6
06-27-12	1325	Lower high	J/30-2 Outflow	2.91	2.93	369	0.84	nr	nr	nr	1.50	nr

The groundwater well OUBT 722 was sampled once during the spring tidal study. A sample collected from the middle of the screened interval during ebb tide was largely seawater (specific conductance = 36,800 µS/cm) and had very elevated concentrations of mercury (FTHg = 1,140 ng/L, no PTHg results; table 4) that were 19 times higher than the highest concentration measured in PSNS015. This is consistent with previous studies documenting elevated mercury concentrations in the well water (as much as 2,300 ng/L) when the Sinclair Inlet water level drops below the groundwater water level (Paulson and others, 2012). The WTHg concentration in the groundwater well was, at a minimum, 1,140 ng/L (assuming PTHg = 0 ng/L) and may have been much higher if the ratio of FTHg to PTHg measured in PSNS015 was applicable to well OUBT-722 (PTHg contributing anywhere from <1 percent to >90 percent of the WTHg concentration). Measurements of PTHg in groundwater well OUBT-722 when FTHg >1,000 ng/L are a large remaining data gap.

Bacteria Concentrations in Samples Collected During a Spring and Neap Tide

During the spring tidal study, there was a white pulpy discharge to the J/30-2 vault (gymnasium). The samples collected from the vault during the discharge event and the subsequent ebb to low tide had elevated *E. coli* (as much as 387 MPN/100 mL) and total coliforms (>2,420 MPN/100 mL) (table 5). Samples collected from J/30-2 and the A42 vault during flood tide had low bacteria levels (table 5). During the neap tidal study, there were measurable fecal coliforms (as much as 6,200 CFU/100 mL) in all three monitored vaults: J/30-2 (gymnasium), K/30-14 (garage), and A42 (table 6).

Table 5. Qualitative total coliforms and *Escherichia coli* results from water samples collected within the PSNS015 stormwater drain system during a May 2012 spring tidal study, Bremerton Naval Complex, Kitsap County, Washington.

[All times are local time. **Abbreviations:** µS/cm, microsiemens per centimeter at 25 degrees Celsius; MPN/100 mL, Most Probable Number per 100 milliliters; <, less than; >, greater than; –, not applicable]

Sampler location in water column	Date	Time	Tidal stage	Specific conductance (µS/cm)	Total coliforms (MPN/100 mL)	*Escherichia coli* (MPN/100 mL)	Notes
J/30-2 (Gymnasium)							
Surface	05-07-12	0600	Lower high	669	345	36	White particles
Bottom	05-07-12	1020	Ebb	369	>2,420	115	–
Bottom	05-07-12	1323	Low	328	1,986	387	–
Surface	05-07-12	1947	Higher high	393	2	<1	–
A42 (Fast food parking lot)							
Pipe 6 (west-southwest)	05-07-12	0925	–	9,160	102	2	Discharge event
Bottom	05-07-12	1110	Low	419	<1	<1	–
Bottom	05-07-12	1418	Flood	321	<1	<1	Turbid
Bottom	05-07-12	1542	Flood	252	4	<1	Turbid
Surface	05-07-12	1658	Flood	926	<1	<1	Turbid
Laboratory control samples							
Negative control (*Pseudomonas aeruginosa*)				–	<1	<1	–
Total coliforms positive control (*Klebsiella pneumoniae*)				–	45	<1	–
Escherichia coli positive control (*Escherichia coli*)				–	31	31	–

Table 6. Fecal coliform results from water samples collected within the PSNS015 stormwater drain system during a June 2012 neap tidal study, Bremerton Naval Complex, Kitsap County, Washington.

[**Abbreviations:** µS/cm, microsiemens per centimeter at 25 degrees Celsius; CFU/100 mL, Colony Forming Units per 100 milliliters; <, less than; –, not applicable]

Sampler location in water column	Date	Time	Tidal stage	Specific conductance (µS/cm)	Fecal coliforms (CFU/100 mL)
J/30-2 (Gymnasium)					
Surface	06-26-12	2330	Higher high	2,330	2,900
Bottom	06-27-12	0335	Ebb	594	1,600
Surface	06-27-12	1330	Lower high	369	6,200
K/30-14 (Garage)					
Surface	06-27-12	0045	Higher high	2,650	1,800
Bottom	06-27-12	0320	Ebb	2,627	110
Surface	06-27-12	1302	Lower high	10,700	220
A42 (Fast food parking lot)					
Surface	06-26-12	2338	Higher high	43,300	190
Surface	06-27-12	0132	Ebb	7,740	<10
Pipe 7 (West)	06-27-12	0145	–	1,033	<10
Surface	06-27-12	0231	Ebb	3,640	3,100
Bottom	06-27-12	0409	Ebb	4,390	380
Bottom	06-27-12	0606	Lower low	2,185	90
Bottom	06-27-12	0706	Flood	1,873	190
Bottom	06-27-12	0845	Flood	2,440	120
Bottom	06-27-12	0930	Flood	1,393	2,450
Bottom	06-27-12	1042	Flood	41,900	2,150
Bottom	06-27-12	1133	Lower high	42,600	1,790

Discussion

During the December 2011 reconnaissance survey, no freshwater source of mercury to the A42 vault was identified. There was heavy precipitation preceding and stormwater runoff generated during the reconnaissance survey, which suggests that the primary source of mercury in PSNS015 is not precipitation-induced. The water-level elevation and specific conductance data from the reconnaissance, spring and neap tidal sampling campaigns confirms that PSNS015 functions as a conduit for Sinclair Inlet seawater to move landward of Site 2 soils on the BNC and then drain back to Sinclair Inlet on the subsequent ebb tide. The side arms of PSNS015 were not sampled during these sampling campaigns, but based on pipe and vault elevations it is likely that seawater also intrudes into the A42 vault side arms.

The results from the two contrasting tidal sampling campaigns suggest that mercury concentrations in PSNS015 are variable and tidally driven. Elevated FTHg concentrations occurred for a 6-hour period when the Sinclair Inlet water level elevation dropped below the A42 vault elevation during the spring tidal study. Similarly, elevated FTHg concentrations were not observed when the Sinclair Inlet water-level elevation did not drop below the vault elevation during the neap tidal study. This supports the hypothesis that PSNS015 functions as a conduit for water to move into Site 2 soils during high tide, and then facilitates transport of FTHg extracted from Site 2 soils back to Sinclair Inlet during low tides, especially negative tides that drop below the elevations of the stormwater drain vaults. Preferential extraction of mercury from Site 2 soils may occur through geochemical processes such as complexation with chloride in the seawater (Grassi and Netti, 2000). Because seawater is denser than freshwater, as the seawater floods the stormwater drain system, it intrudes along the bottom of the pipe with a freshwater lens on top. The freshwater lens may be pushed farther landward within the stormwater drain system, out the side arms, and into Site 2 soils. As the water drains back out of the system to Sinclair Inlet during ebb tide, contaminated freshwater/groundwater from Site 2 soils may drain into the PSNS015 system. High mercury concentrations were measured in freshwater at various locations and times during the spring and neap sampling campaigns. For example, during the May 2012 spring tide sampling campaign, elevated FTHg was measured in freshwater at the bottom of the A42 vault during slack tide at 16:18 local time (35.3 ng/L, table 3), at the water surface during flood tide at 17:42 (23.3 ng/L, table 3), and at the water surface during high tide at 19:47 in upland vault

J/30-2 (33.4 ng/L, table 4). This suggests that contaminated groundwater infiltration through cracks and breaks is pervasive throughout PSNS015. The elevated mercury concentration in some of the discharges from side arms on the western side of the A42 vault could also be explained by a hydraulic connection between the side-arm pipes and the adjacent Site 2 soils.

Less clear are the PTHg dynamics within the stormwater drain system. Concentrations were an order of magnitude higher during the neap tidal study than during the spring tidal study, with maximum concentrations (as much as 133 ng/L; table 3) measured in samples collected just prior to and after low tide. The neap bottom water samples were collected at an elevation in the vault approximately 0.5 m higher than the spring samples, and the neap low-tide samples were more saline (1,730–4,390 µS/cm) than the spring low tide samples (<1,000 µS/cm) (table 3). One process-based hypothesis to explain the data is that there is sufficient time for mercury to accumulate and partition to particulates in PSNS015 during consecutive tidal cycles when high tides are high enough to inundate and transport particles from contaminated Site 2 soils, but low tides are non-negative and not low enough to completely drain the stormwater drain system. The three lower low tides prior to the neap sampling campaign were greater than 0 MLLW, so the stormwater drain system had not completely drained for at least 3 days. In contrast, the spring tide sampling campaign was the fourth consecutive day of complete flushing owing to negative lower low tides in Sinclair Inlet below the stormwater drain outfall elevation. Another hypothesis to explain the higher PTHg concentrations during the neap tidal study as compared to the spring tidal study is that under neap conditions PSNS015 is already full of water from incomplete flushing and a higher high tide pushes water out the side arms and into infrequently contacted high-mercury soils. During the subsequent ebb tide, mercury-laden particulates are then transported from these soils to the stormwater drain system during the following low tide. THg concentrations in Site 2 soils to 12 m below ground ranged from 6.6 to 31 mg/kg (U.S. Navy, 1992; Paulson and others, 2012) and may be the source of high-mercury particles to PSNS015. Regardless of the underlying process, it seems that differences in PTHg concentrations and dynamics and the contribution of particulate mercury to total mercury concentrations in whole-water are tidally variable.

By far, the highest mercury concentrations were measured in saline water in well OUBT-722 during ebb tide (FTHg = 1,140 ng/L; table 4). PTHg was not measured in the well during this study or previous studies and remains a large, important data gap. Most of the mercury in water samples from PSNS015 often was in the particulate fraction, suggesting that the WTHg concentration in this well could have been much higher than 1,140 ng/L. This suggests that the direct hydraulic connection between Sinclair Inlet and Site 2 soils just west of the seawall is an important pathway for mercury to enter Sinclair Inlet. Previous studies have indicated that the contaminated groundwater plume is restricted to a narrow strip just along the seawall and that the highest concentrations are near the groundwater surface (Paulson and others, 2012). Bi-directional discharge was not quantified, so fluxes of mercury through PSNS015 and around the seawall cannot be calculated.

Finally, during the neap tidal study, there were measurable fecal coliforms (as much as 6,200 CFU/100 mL; table 6) in the three monitored vaults. Those elevated coliform levels and the anecdotal evidence of a white, pulpy discharge suggests there may be cross-connections between the stormwater drain system and the sewer system.

The results of these tidal sampling campaigns and other sampling provided added insight into mercury sources and transport to Sinclair Inlet. However, there are data gaps remaining that may need to be addressed depending on potential remediation strategies, including:

- An estimate of the frequency and extent of Site 2 inundation by intruding seawater over annual time scales. A first order estimate could be made using tidal predictions alone, although this is a more complex question affected by actual tidal elevations, wind speed and direction, and precipitation, all of which affect water level elevations in PSNS015 and in groundwater west of the seawall.

- An understanding of the low tide elevations and related factors that can trigger hydraulic drainage of PSNS015, and estimates of how frequently the drainage occurs over annual time scales. Some drainage occurred during the neap tidal study even when water levels in Sinclair Inlet were similar to those in the A42 vault. The factors controlling drainage include actual tidal elevations and freshwater flows driven by weather and other discharges in the stormwater drain system.

- A better quantified estimate of mercury fluxes to Sinclair Inlet through PSNS015 and direct discharge of groundwater. This would require continuous measurements of bi-directional flow within PSNS015 and west of the seawall, which is very complex owing to unbounded conditions west of the seawall and mixing of seawater, freshwater, and other miscellaneous discharges from drain pipes within the system.

These data gaps cannot be addressed easily owing to the complexity of the site. It is likely that Site 2 inundation by a combination of freshwater and seawater through PSNS015 and around the seawall occurs regularly, given that seawater extended upstream in the PSNS015 main pipe approximately 250 m landward of Site 2 during tides around +4 m. In 2017, more than 75 percent of Sinclair Inlet high tides were +3 m or greater magnitude. Negative tides occurred during every month, and were most negative during winter (November through January) and summer (May through July) spring tides.

The study results do provide focus for potential remediation efforts, for example extending the seawall farther west and repairing sections of the large and aging PSNS015 stormwater drain system, particularly those passing through Site 2 soils. Mercury monitoring after the repairs could provide information about effectiveness in reducing hydraulic connectivity with Site 2 soils, thus reducing the amount of mercury transported to Sinclair Inlet.

Summary

In 2011–12, the USGS conducted three tidal-related sampling campaigns to characterize mercury dynamics in the PSNS015 stormwater drain system, which passes through the soils of Site 2 and functions as a conduit for landward seawater movement during high tides. The sampling campaigns documented the extent of seawater intrusion and quantified mercury concentrations and other ancillary parameters during a range of tidal conditions. No sources of precipitation-derived mercury were identified. Saltwater extended upstream in the PSNS015 main pipe approximately 250 m landward of Site 2 soils during +4 m high tides, with a freshwater lens remaining on top of the saltwater wedge. Spring tide conditions drained the water in PSNS015 to Sinclair Inlet, and the highest filtered (dissolved) total mercury (FTHg) concentrations (60 ng/L) were measured during the lower-low tide in the freshwater flowing into the seaward-most stormwater drain vault from either up-pipe or local groundwater intrusion. Similar conditions were not observed during the companion neap-tide sampling campaign, when the water-level elevation of the positive low tide in Sinclair Inlet dropped only slightly below the stormwater drain vault elevation, the water in the seaward-most stormwater vault was brackish rather than fresh, and the filtered total mercury concentration never exceeded 24 ng/L. Particulate total mercury concentrations and dynamics during the spring- and neap-tide sampling campaigns were variable, with higher concentrations (as much as 133 ng/L) measured throughout the neap-tide study compared to those measured during the spring-tide study (as much as 4.34 ng/L). The highest filtered total mercury concentration of all sampling campaigns (1,140 ng/L) was measured during ebb tide in a nearshore monitoring well that represents groundwater discharging from the contaminated soils directly to Sinclair Inlet along an unwalled part of the shoreline.

The results suggest that mercury extracted from Site 2 soils can be carried to Sinclair Inlet during ebb tides by at least two mechanisms: (1) through groundwater around the seawall or (2) through PSNS015 when the water level in Sinclair Inlet drops below the water level in the stormwater drain system. The data can be used to guide future modifications to the seawall and PSNS015 that aim to hydraulically disconnect the stormwater drain system from the underlying contaminated soils.

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Appendix 1. Vertical profiles in PSNS015 Stormwater Drain System at Higher High Tide

Table 1.1. Vertical profiles of depth, temperature, pH, and specific conductance in vaults A42, M/30-9, and J/30-2 in the PSNS015 stormwater drain system at higher high tide, Bremerton Naval Complex, Washington, December 28, 2011.

[The data are publicly available in the USGS National Water Information System (https://nwis.waterdata.usgs.gov/usa/nwis/qwdata) under the project code D6M1200 by Station ID (table 1). **Abbreviations:** °C, degrees Celsius; m, meter; µS/cm, microsiemens per centimeter at 25 °C]

Sample time	Depth of sensor below water surface (m)	Temperature (°C)	pH	Specific conductance (µS/cm)
A42 (Fast food parking lot)				
9:00	2.32	8.8	7.5	45,000
9:01	1.69	8.8	7.5	45,000
9:02	1.40	8.8	7.5	44,900
9:03	1.07	9.0	7.5	44,800
9:04	0.79	9.1	7.5	44,700
9:05	0.52	9.3	7.5	44,600
9:06	0.33	9.6	7.5	44,200
9:07	0.30	10.4	7.5	43,200
9:08	0.25	10.7	7.5	42,900
9:09	0.20	10.8	7.5	42,700
9:10	0.10	10.7	7.5	42,600
9:11	0.09	10.7	7.5	42,500
9:12	0.01	10.2	7.4	42,100
9:13	0.00	10.1	7.4	41,900
M/30-9 (Police station parking lot)				
9:15	0.00	10.0	8.3	669
9:16	0.20	10.0	8.1	505
9:17	0.50	9.9	8.0	441
9:18	0.60	10.0	8.0	510
9:19	0.70	10.0	7.4	2,720
M/30-9 (Police station parking lot)—Continued				
9:20	0.73	10.0	7.0	3,940
9:21	0.75	10.0	7.0	10,900
9:22	0.77	9.9	7.0	28,100
9:23	0.80	9.7	6.9	35,800
9:24	0.82	9.6	6.9	37,300
J/30-2 (Gymnasium)				
10:42	1.78	10.5	7.2	630
10:43	1.78	10.5	7.2	555
10:44	1.74	10.5	7.2	521
10:45	1.65	10.5	7.3	417
10:46	1.51	10.6	7.3	307
10:47	1.30	10.6	7.3	282
10:48	1.11	10.8	7.4	255
10:49	1.00	10.9	7.4	231
10:50	0.74	11.1	7.4	222
10:51	0.34	11.6	7.4	229
10:52	0.13	12.2	7.3	233
10:53	0.04	12.3	7.3	234
10:54	0.02	12.3	7.3	155

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