Investigation of Bacteria Sources in the Thornton Creek Watershed Seattle, Washington

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Cover photo: South Fork of Thornton Creek downstream of the Lake City Way culvert

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Summary

Thornton Creek consistently has high bacteria counts based on long term sampling at the mouth of the creek. The approach to locate bacteria sources within this watershed relied on forty-five samples collected in the morning and afternoon at each site. Samples were collected during both dry weather and wet weather. Smaller sub basins were defined as the portion of the watershed that drained to each sampling sites. Bacteria data was used to identify sub basin where the bacteria entered Thornton Creek in order to differentiate local from upstream sources and facilitate location of the bacteria sources within the smaller sub basins for control. Several sub basins have been identified as priority areas to evaluate for bacteria sources and are identified in Table 6 of this document.

Multiple *E. coli* and fecal coliform samples were collected in Thornton Creek during this study exceeded criteria by one to two orders of magnitude. The mainstem of Thornton Creek above Lake City Way that bisects the watershed frequently met or slightly exceeded criteria. Below Lake City Way there is degradation in water quality that impacts the bacterial load, aesthetics and the stream benthic community. Even though *E.coli* and fecal coliform counts in the lower mainstem of Thornton Creek are consistently above criteria, it may be necessary to initially focus on locating and controlling the upstream and tributary bacteria sources and decrease the upstream bacteria counts to potentially make it easier to discern downstream sources from the background.

Based on *Bacteroides* sampling in Thornton Creek it is highly probable that human sources of bacteria are prevalent. The *Bacteroides* technique provides apparently reliable information that human sources are present, but the lack of epidemiological studies or a correlation between *Bacteroides*, *E.coli* or fecal coliform bacteria make any quantification of these results beyond the capability of the current study. This study provides a methodology and results for locating episodic bacteria sources in an urban watershed.

Introduction

Identifying the location of bacteria sources and the species contributing the bacteria is necessary for control or elimination of a bacteria source in a waterbody. This study was designed to facilitate the location of bacteria sources throughout the Thornton Creek watershed and identify if there is a potential human component to the bacteria counts. Prior to this study, the sources of fecal coliform resulting in exceedances of the *WAC 173-201A* criteria and responsible for the periodic closing of Matthews Beach on Lake Washington had not been located or controlled. This study focused on locating where unidentified bacteria sources enter the stream and is the necessary first step to correcting and eliminating these bacteria sources. This study is primarily sampled *E.coli* bacteria which are a better indicator of human health risk for primary contact recreation than fecal coliform (EPA 1986, 2007). Subsets of fecal coliform bacteria were collected to correlate with the *E.coli* and address the *WAC173-201A* bacteria criteria.

Thornton Creek (Figure 1) is in a fully urbanized basin and discharges into northeast Lake Washington adjacent to a popular public swimming beach. Over 90% of the creek's main channel, more than 15 miles, flows above ground, through more than 700 backyards and through 15 parks and natural areas to Lake Washington. A three and a half mile stretch of Interstate 5, the State's busiest highway, passes through the watershed (SPU 2000). The un-sewered areas in this watershed represent parks, open space and non-developable land – there are no homes served by septic systems (King County 2003).

Of the streams monitored in King County, Thornton Creek consistently ranks among the highest for fecal coliform bacteria counts and exceedances of *WAC 173-201A* bacteria (Figure 2). Existing ambient fecal coliform data was collected near the mouth of Thornton Creek. Sections of this stream are listed as category 5 on the current 303(d) list submitted to EPA (data from station 0434 shows that fecal coliform bacteria standards were not met each year in samples collected between 1998 and 2002, http://apps.ecy.wa.gov/wats/ViewListing.aspx?LISTING_ID=13123). This design successfully identified bacteria exceedances in Thornton Creek, but provided little geographic resolution to identify the location of sources of bacteria inputs. Thornton Creek also has slightly higher median values for nutrients such as total phosphorus levels, ammonia, and nitrate than other county streams.

A primary concern in the Thornton Creek basin is the potential human health risk and high levels of bacteria exposure at the public swimming beach. Thornton Creek discharges to Lake Washington in Mathews Beach Park within 50 m of the public swimming beach, which has on occasion been closed for bacteria exceedances http://green.kingcounty.gov/swimbeach/matthews-closure.aspx). The shallow delta at the confluence with Lake Washington is also a popular wading and swimming area in the park.

The most likely potential sources of bacteria to Thornton Creek are non-point sources, the sanitary sewers, or the stormwater drainage system. An additional potential and unconfirmed source of bacteria could be from homeless encampments in the green belts or the illegal dumping of RV wastes in this urban watershed. Some of these potential sources have been recently evaluated but none of the studies has been successful at identifying why Thornton Creek has perennially some of the highest bacteria counts of streams in King County, or where the sources of this bacteria enters the stream. There is no agriculture in the urban Thornton Creek watershed, and non point bacteria sources could be assumed similar to the adjacent Lyons Creek and McAleer Creek Both of these streams had much lower fecal coliform counts than Thornton Creek (King County 2002).

In the summer of 2010, SPU conducted a dry weather screen of all discharge points from the City's Municipal Separated Storm Sewer System (MS4) to Thornton Creek. As part of that effort, two residential illicit connections were detected and eliminated. In addition, there were several trigger values exceedances that resulted in follow up investigations. The frequent high bacteria counts collected during this study were all collected in the stream. If the stormwater drainage system is not the source of these high bacteria counts, locating the section of the stream where the bacteria enters the stream will help to determine what the actual source is and the conveyance to the stream.

This investigation assumes that the very high bacterial exceedances in Thornton Creek are an amalgam of identified and unidentified point sources and non-point sources. By identifying and subsequently controlling *E.coli* inputs, a reduction of potential human health risks may be achieved and simultaneously would result in a reduction of fecal coliform counts, helping to meet the current *WAC 173-201A* criteria.

As part of the current study, a subset of the Thornton Creek samples were analyzed for *Bacteroides* as an experimental method used to identify human contribution to the bacteria sources. The technique used in the study a membrane filtration technique used in conjunction with a quantitative polymerase chain reaction (qPCR) technique to isolate and identify human-specific*, Bacteroides thetaiotaomicron*. Bacteria belonging to the genus *Bacteroides* have been suggested as complimentary fecal indicators with *E.coli* or fecal coliforms because they make up a significant portion of the fecal bacteria population, have little potential for growth in the environment, and have a high degree of host specificity that likely reflects differences in host animal digestive systems (Kreader 1998).

The *Investigation of Bacteria Sources in Thornton Creek Basin* was funded by a Centennial Grant from Ecology to Seattle Public Utilities to facilitate the location of bacteria sources in the Thornton Creek watershed. The *Bacteroides* portion of the study was not funded by Ecology and was separately funded by Seattle Public Utilities (SPU) and King County Department of Natural Resources and Parks (KCDNRP). This investigation was a cooperative effort by Seattle Public Utilities (SPU), the City of Shoreline, King County Department of Natural Resources (KCDNR) and Parks, and the Washington Department of Ecology (Ecology).

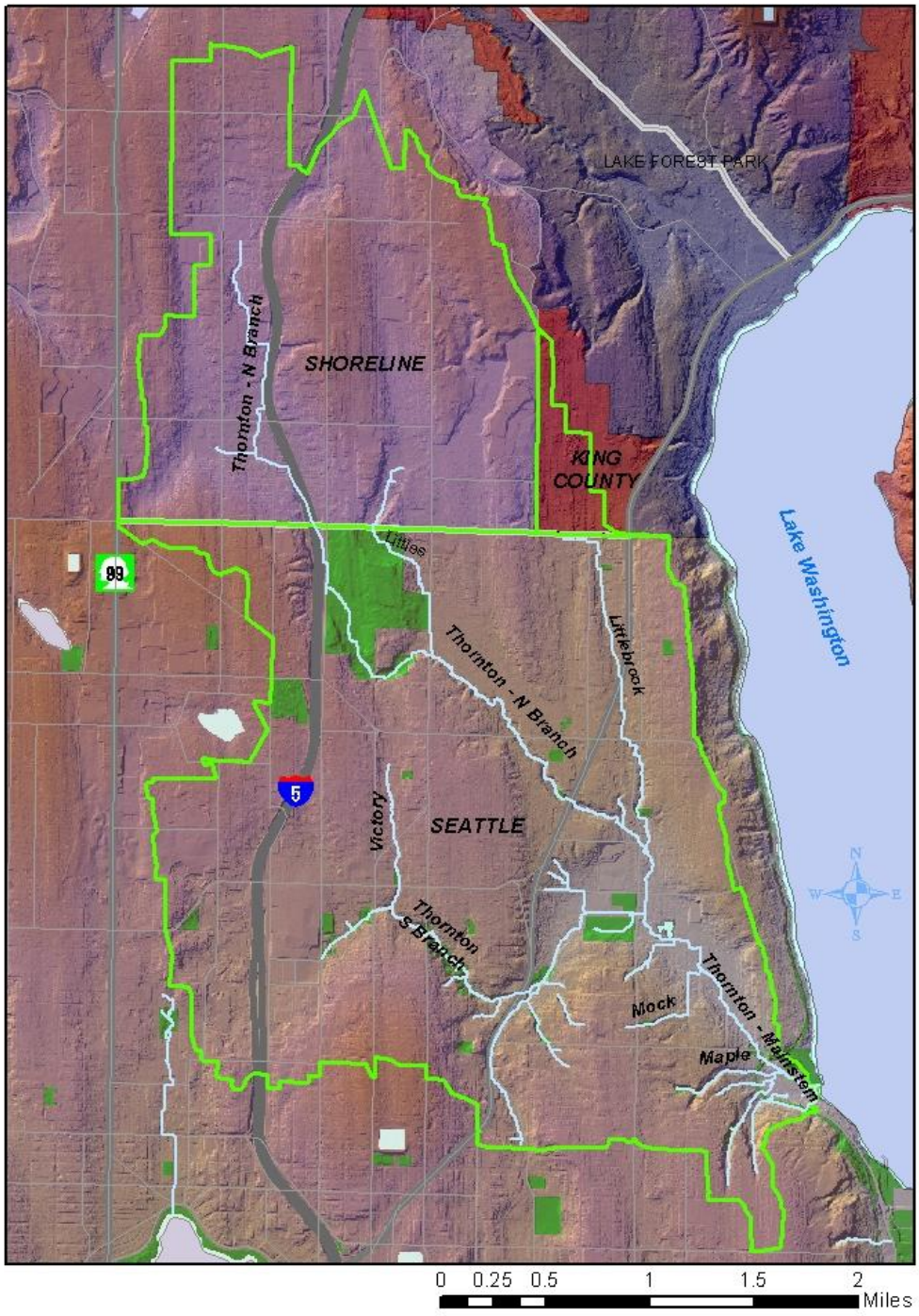


Figure 1. Thornton Creek watershed in the cities of Seattle (4695 acres, 67% of the watershed), Shoreline (2205 acres, 31% of the watershed) and unincorporated King County (118 acres, 2% of the watershed).

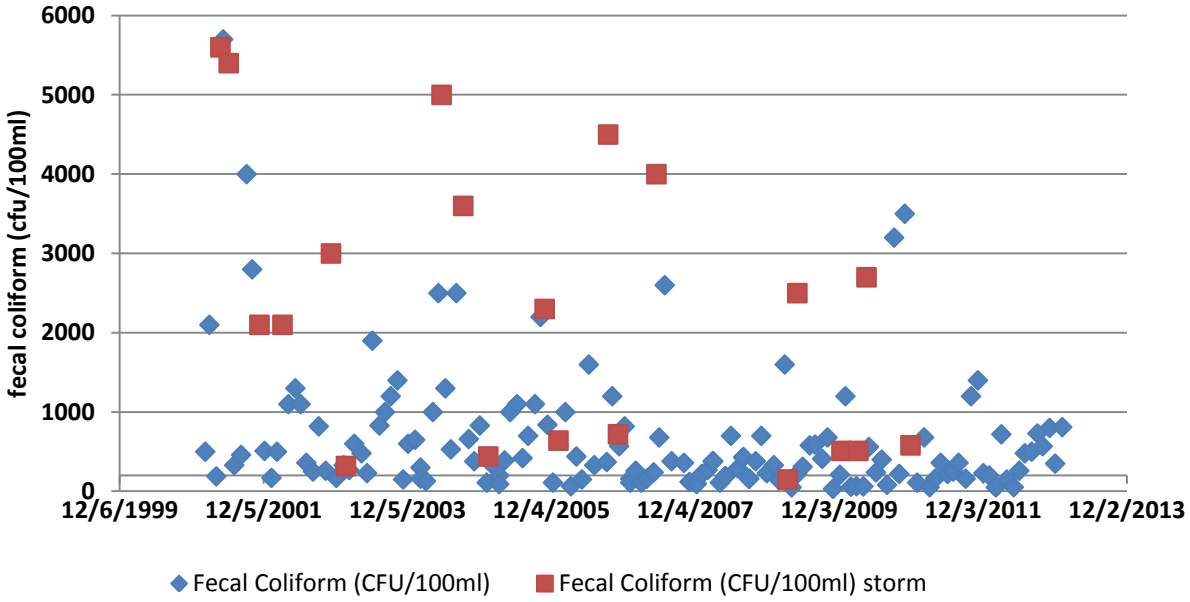


Figure 2. Fecal coliform from monthly ambient water quality data collected by King County 2000-2013 frequently exceeded WAC173-201A fecal coliform bacteria secondary contact criteria of >200cfu/100ml.

Methodology

Sample Site Selection

Multiple sampling sites within the Thornton Creek watershed were used to isolate shorter stream segments and delineate smaller portions of the basin that contribute bacteria to the stream. When the potential bacterial sources are located to somewhere within small sub-basin areas delineated by sequential sampling sites, more detailed source control investigations can be focused in smaller geographic areas to facilitate the location and potential control of the bacteria. Forty-five sampling sites were located throughout the basin to provide a sampling density high enough to delineate small sections of stream and sub basins where bacteria presumably enter the stream (Figure 3; Table 1). Differences between the sequential upstream and downstream bacteria sampling locations were used to identify potential stream segments where bacteria inputs occurred and help to differentiate locations where high bacteria counts were due to upstream bacteria flowing downstream. Selection of sampling locations was designed to isolate tributaries and shorter stream segments in order to track potential bacterial sources to as small a geographic area as practicable.

Sample sites were located to bracket short segments of Thornton Creek and were collected over different seasons and different times of day. Selection of sampling locations was constrained by crew safety, time to access particular locations and permission by property owners to sample on private property. Stream segments were delineated by upstream and downstream sites numbered sequentially from upstream to downstream Sub basins were delineated as topographic area and stormdrain networks between adjacent upstream and the next downstream site.

Sampling sites were defined first as a geographic information system (GIS) exercise using data layers for the Thornton Creek watershed, including stream network, watershed boundary, topography, property parcels and land cover/landuse data layers. Sampling sites were used as pour points to define relatively short stream segments and to topographically delineate upslope contributing areas, and define small sub-basins. Sites were located as far up the surface channels as possible, at the lowest accessible sections of each tributary and downstream of confluences and near the swimming beach in Lake Washington (Figure 4). Sites were located on public property where possible to minimize the need to coordinate permission and access to private property, but when sites were only accessible from private property, written permission to sample was obtained from the owner. Coordination with the Thornton Creek Alliance and Thornton Watershed Oversight Committee facilitated access to sampling locations on private property.

Upstream and downstream sampling sites were purposefully established to minimize the source search area in the event that a stream segment showed high levels of bacterial contamination. Samples were distributed throughout the watershed to maximize geographic coverage of the watershed and minimize the length of stream segments responding to potential bacterial sources. Decreasing the distance between sequential sampling sites tended to decrease sub-basin areas. At the uppermost sites where there was no upstream sampling location, all of the area that drains to the stream above the sample sites was delineated as a separate polygon. All polygons were intersected with multiple data layers including parcels, land cover, sanitary pipe networks, and storm drain networks.

To manage laboratory capacity, costs and maximize the number of locations in the watershed that could be sampled only single grabs were collected and single dilutions were conducted for each sample. The tradeoff for maximizing sampling locations was to decrease the accuracy of quantification of samples with higher bacteria counts.

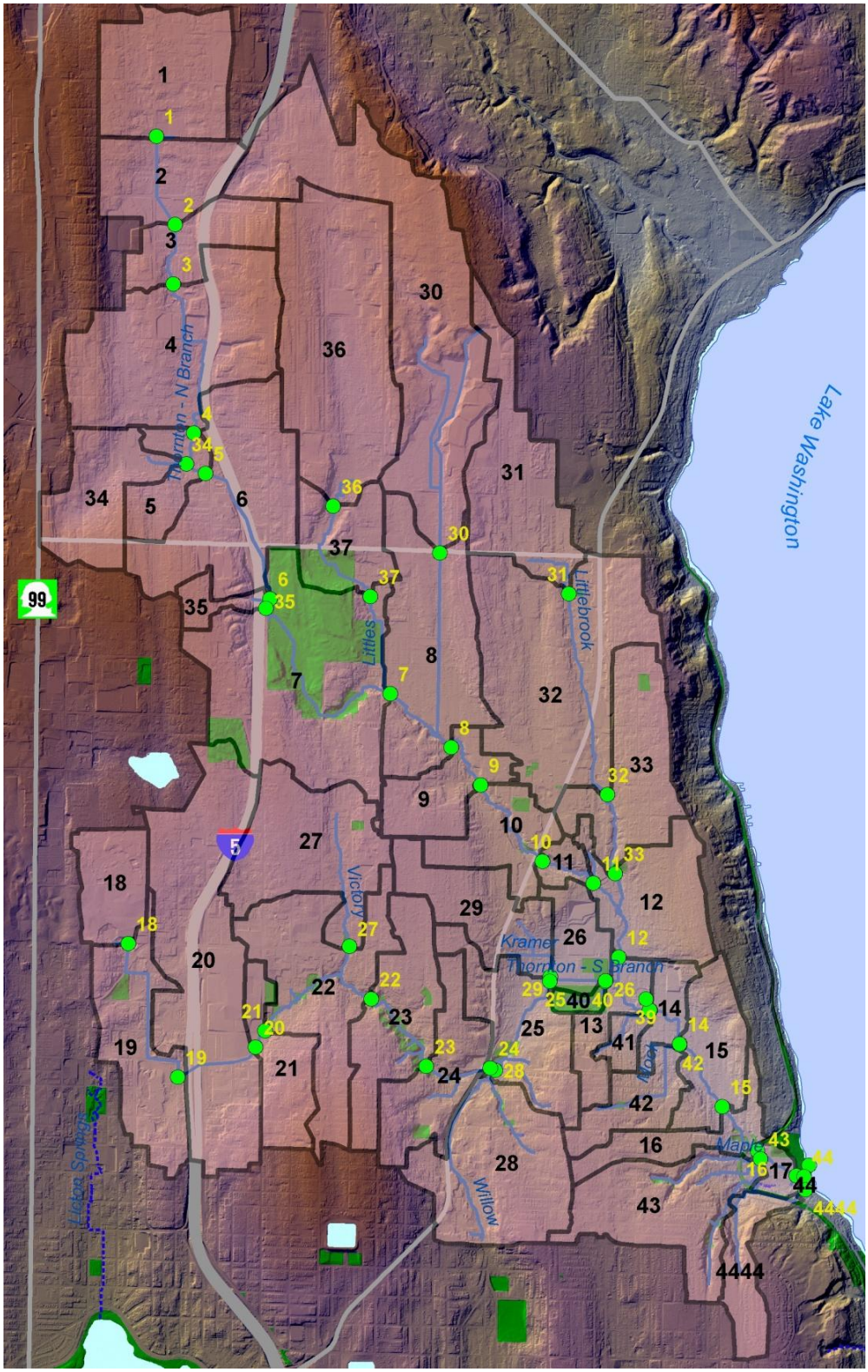


Figure 3. Location of sampling sites (yellow numbers) in the Thornton Creek basin. Sub basins that drain to each sample site have the same number (black numbers and outlines). Sub basins were delineated in GIS using topography and the storm drainage network.

Table 1. Sample locations for the Thornton Creek bacteria survey, coordinates are in NAD83 Washington State north. Sample numbering was from the furthest upstream site on the mainstem of Thornton Creek and sequential sequentially downstream (1-17), on the South Fork Thornton Creek from upstream to the confluence with the mainstem (18-26). Smaller tributaries were sequentially numbered in a clockwise patter from the west side of the watershed.

sample number	X_COORD	Y_COORD	waterbody	ownership	site description
1	1271145.328	280733.9572	Thornton main	City of Shoreline	NE corner N180th St & Meridian Ave N
2	1271584.23	278703.8648	Thornton main	City of Shoreline	outlet Ronald Bog at N end of Corliss Ave N
3	1271539.154	277336.9751	Thornton main	ROW	S side of N 167th St opposite of Corliss Pl N
4	1272014.363	273893.916	N of Twin Ponds	City of Shoreline	inflow Twin Ponds S of N 155th St SW of park lot
5	1272280.355	272955.7849	S of Twin Ponds	City of Shoreline	outflow to Twin Ponds imm upstrm of ped bridge
6	1273772.336	270069.8318	Thornton main	Sea Parks	dwnstm culvert 5h Ave NE next to Jackson GC
7	1276551.853	267875.2975	Thornton main	private	dwnstrm ped br at private res at 1519 NE 130th Pl
8	1277952.473	266640.5604	Thornton main	ROW	undev ROW 22 Ave NE N of NE 127th St
9	1278638.746	265766.7996	Thornton main	Lk Ct Baptist	Lake City Baptist Church
10	1280063.393	264007.2759	Thornton main	Seattle Parks	outfall downstream of Lake City Wy
11	1281231.983	263501.701	Thornton main	ROW	main upstream of 34th Ave NE
12	1281825.544	261796.1216	Thornton main	ROW	upstream of 110th St W of 35th Ave NE
13	1282534.267	260578.2681	Thornton main	ROW	mainstem E of 39th Ave NE N of NE 105th St
14	1283225.357	259798.4154	Thornton main	private	upstream of outfall D235-026 N of 43rd PL Feguson
15	1284214.296	258350.2392	Thornton main	ROW	downstream of 45th Ave NE bridge
16	1285013.138	257336.3289	Thornton main	ROW	USGS gage downstream of Sand Pt Wy
17	1285914.179	256759.2005	Thornton main	ROW	pedestrian br. on 51st St NE near mouth
18	1270501.338	262109.4942	S Fk Thornton	Evergreen Washelli	pond N of end of ROW N Burke Ave and W Meridian N
19	1271637.609	259030.0047	S Fk Thornton	NSCC	outfall wetland NSCC W I-5
20	1273437.067	259719.0605	Th Ck WQC	Thornton Pl TCWQC	downstream ped br in TCWQC
21	1273659.793	260101.7638	S Fk Thornton	Seattle Parks	downstream of outfall from TCWQC E 5th Ave NE
22	1276105.803	260831.6792	S Fk Thornton	Seattle Parks	S Branch downstream of Victory Ck
23	1277379.393	259281.0212	S Fk Thornton	ROW	ROW NE 102nd St W of 20th Ave NE Knerbkr

	X_COORD	Y_COORD	waterbody	ownership	site description
24	*1278857.051*	*259237.7413*	*S Fk Thornton*	*Seattle Parks*	*E of Lake City Wy W of dead end of NE 100th St*
25	*1280224.087*	*261238.4624*	*S Fk Thornton*	*ROW*	*W of 30th Ave NE N of NE 107th St*
26	1281521.246	261257.2261	S Fk Thornton	Sea Publ Schools	upstrm of br at N end of Mbrook CC park lot
27	1275599.98	262047.7939	Victory Creek	Seattle Parks	mouth of Victory Creek W NE 107th St
28	1278971.155	259187.8961	Willow Creek	Seattle Parks	Willow above mainstem N NE 100th St W Ravenna NE
29	1280242.841	261345.3637	Kramer Creek	ROW	Kramer Ck W 30th Ave NE across from NHHS
30	1277690.615	271122.3937	Hamlin Creek	ROW	S of NE 145th St W of 20th Ave NE
31	1280671.169	270180.3667	Littlebrook	Littlebrook	Littlebrook W of Ltbrk Pk
32	1281556.718	265550.6729	Littlebrook	Littlebrook	33rd green space
33	1281734.817	263726.35	Littlebrook	Parks	lower Littlebrook S of NE 155th St below outfall
34	1271842.114	273179.555	Twin Ponds	Shln Parks	W inflow to Twin Ponds
35	1273673.507	269845.6607	I-5 drainage	ROW	outfall D220-024 W side of 5th Ave E of I-5
36	1275229.635	272203.5282	Upper Littles	Shln Parks	park NE 147th St
37	1276089.286	270116.4426	Littles Creek	private	apt complex W of 15th Ave NE S of NE 143rd Ave
39	1282451.197	260833.7183	Meadowbrook Pond	SPU	Meadowbrook Pond at outfall
40	1281502.791	261233.8935	Meadowbrook Ck	SPU	sm stream below br Send of Meadowbrook CC
41	1282544.084	260566.997	Tributary E	private	drainage entering from S near Meadowbrook outfall
42	1283223.585	259778.6613	Mock Creek	private	outfall 43rd Pl and Ferguson
43	1285095.202	257143.8726	Maple Ck	ROW	sed pond Sand Pt Wy NE 93rd St
44	1286095.497	256731.5296	pond	Seattle Parks	outflow restoration pond
45	1286209.489	256995.8831	Lake Washington	Seattle Parks	LW N of Thornton Ck mouth
4444	1286134	256426.0625	Matthews Creek	Seattle Parks	Matthews Ck above duck pond at 44

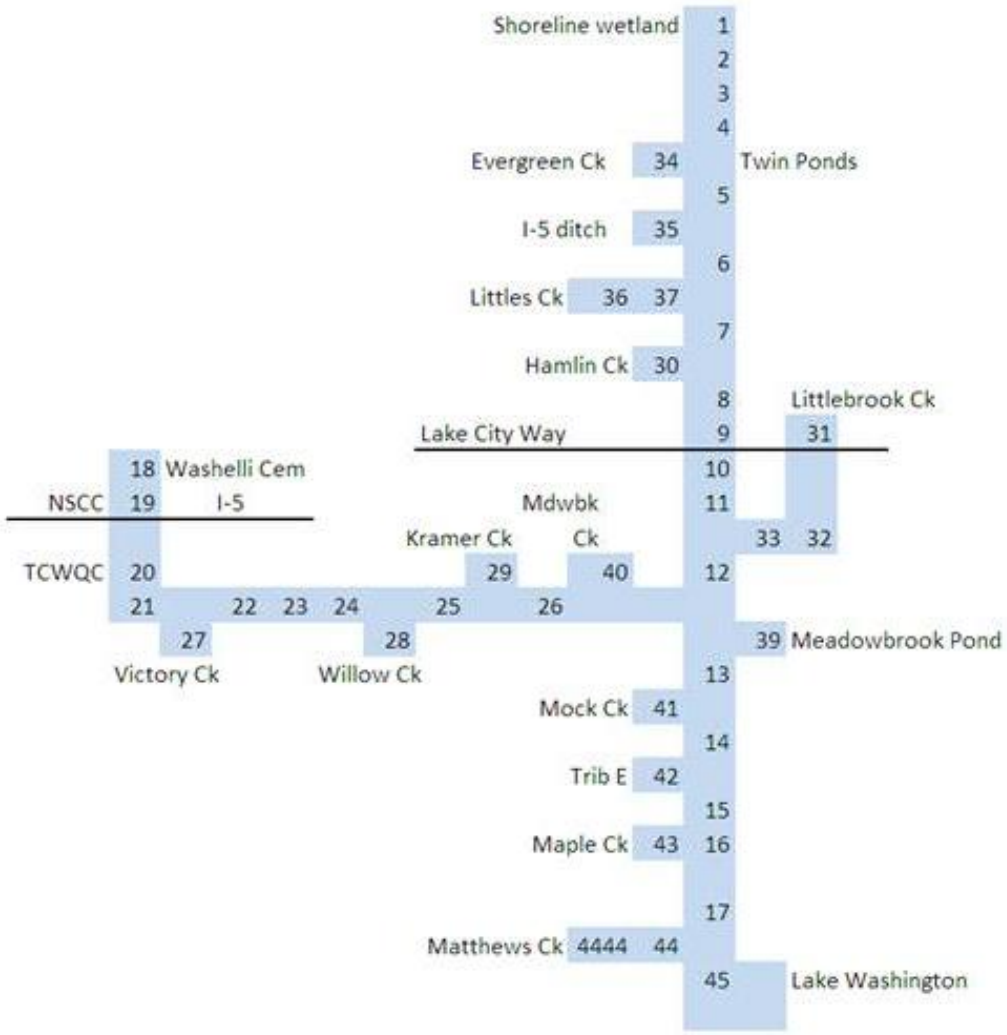


Figure 4. Schematic map of sampling locations in the Thornton Creek watershed. Sites are numbered from upstream to downstream 1-17 for the mainstem of Thornton Creek, Twin Ponds are between sites 4 and 5, Evergreen Ck (34), flows into Twin Ponds, a small ditch under I-5 (35), enters below 6, Littles Creek (36-37), enters between 6-7, Lake City Way discharges into the mainstem between 9 and10, Littlebrook Creek (31, 32, 33) enters the mainstem between 11-12, the South Fork confluence is between 12-13, Meadowbrook RD pond (39) drains between 12 and 13, Mock Creek (41) between 13-14, Tributary E (42) just below 14, Maple Creek (43), between 16-17, and most downstream site on Thornton Creek (17) flows into Lake Washington (45 Matthew Creek (4444) upstream of the restoration pond and the outflow (44) into the mainstem between (17) and the lake. On the South Fork of Thornton Creek (18-26) the upper most sampling site (18) drains from Washelli cemetery, the N Seattle CC (19), Thornton Creek Water Quality Channel (20), Victory Creek (27) enters between 21-22, Willow Creek (28) enters below 24, Kramer Creek (29) enters below 25 and Meadowbrook Creek (40) enters below 26.

Field Sampling

The sampling design focused on maximizing the density of data that could be collected and analyzed within the sampling periods and within the available laboratory capacity. Detailed driving directions, maps for every sample site access point, and allocation of sampling routes for each field team were developed prior to field sampling to minimize sample collection times. Bacteria samples were collected, stored, transported and analyzed according to the protocols identified in the QAPP (Appendix A). Pre-washed, pre-numbered collection bottles and associated field datasheets matched the individual sample collection runs. Sites to collect field replicates were randomly selected and replicate sample bottles prepared prior to each sampling run. Additional un-numbered sample bottles were also provided for collecting samples at serendipitous locations if field teams suspected a potential bacteria source that was not on the established sampling plan. This protocol also allowed flexibility to add additional samples based on results from previous sampling and field observations.

The selection of sampling dates was determined by the availability of King County Environmental Laboratory (KCEL) to process this number of samples and spread sampling events out over the year and to collect samples during both summer low flow period, and during the typical wetter high flow period (4/2012). An additional partial sampling event on October 14, 2012 sampled the first large rainfall event of after 49 consecutive days without rain. Daily rainfall, collected just south of the Thornton Creek watershed in Magnuson Park (RG02), was low prior to the August and September 2011 and July 2012 sampling events, and the April 2012 sampling was during a much rainier season (Figure 5).

Paired AM - PM samples were not collected during the 10/14/12 event because of logistic constraints. Bacteria, temperature, pH, dissolved oxygen and conductivity samples (Appendix B) were collected at each site during the AM and again in the PM on August 28 and September 22, 2011 and April 23 and July 10, 2012. Only bacteria samples were collected at a subset of sites on October 14, 2012 to sample the first rain event after 49 days without rain.

Field replicates were collected for ten percent of samples collected. For each sampling event, the 'Random Sequence Generator' at www.random.org was used to generate a randomized list for numbers between 1 and 45 (the number of sampling locations in the study). Each event had 27 randomly selected samples with fecal coliform bacteria analysis, divided up between the AM (first 14 samples) and PM (the next 13 samples) runs. Each run also had 10 field replicates (freps), divided equally between the AM and PM runs. The goal was to have 3 to 4 freps with fecal coliform bacteria per event. This goal was not met during the first event and the sampling was short on fecal coliform freps. All freps were selected by KCEL.

Three field crews of two individuals were assigned to sample a predetermined subset of sampling locations, based on overall time to sample and driving time between sampling locations. Sample bottles were pre-washed and labeled sample bottles were organized and allocated accordingly. Field data sheets with the same labsample numbers as the sample bottles were provided in order to collect narrative information and conventional data from the Hydrolab multiprobes. All field crews were required to rendezvous at Matthews Beach Park with the AM set of samples for transport to KCEL to meet holding times, provide the necessary physical space in the vehicles, and restock with pre-washed labeled bottles to collect the PM sample sets. This two phase delivery of samples to KCEL allowed sufficient time to filter the AM samples in the microbiology laboratory prior to the PM set of samples arriving in the evening, maximizing the capacity of the laboratory. Hydrolab mult-probes were calibrated between the AM and PM sample runs.

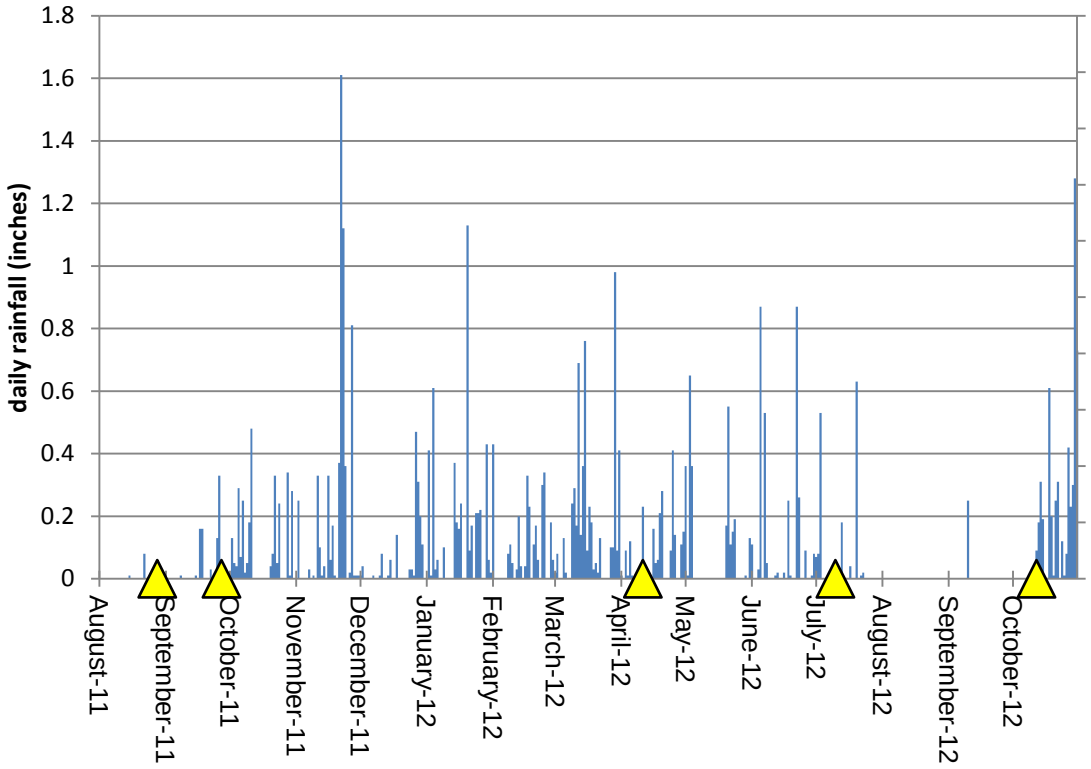


Figure 5. Bacteria sampling dates (designated by the yellow triangles) and daily rainfall at Magnuson park near Thornton Creek. August and September 2011 and July and October 2012 were sampled during dry weather low stream flow periods. April 2012 samples were collected during wet weather flows during a small rain event.

The total number of samples per event was set by the analytical capacity of the KCEL to process the samples (filtration and incubation capacity primarily) and the capacity of the available field crews to collect the samples and transport them to the KCEL (around 15 miles) within holding time. Holding time for the samples was 24 hours when held on ice, although all samples were analyzed well before the 24 hour holding times expired. The maximum number of samples was also constrained by the number of sampling locations that could be safely sampled within an approximate four hour period (to allow for two sampling of each location on each sampling day).

All bacteria samples were quantified by membrane filtration at the KCEL. The method used for fecal coliform testing by membrane filtration (MF) is Standard Method 9222 D, Standard Methods for the Examination of Water and Wastewater, 20th Edition. Dilutions were selected to provide a targeted recovery range of between 1 and 6,000 cfu/100ml. The method used for *E.coli* was SM 9213D, Standard Methods for the Examination of Water and Wastewater, 20th Edition, targeted recovery = between 1 and 8,000 cfu/100 ml.

A subsample from each bottle was membrane filtered and the filters were frozen for potential *Bacteroides* analysis. A subset of samples was selected after quantification of fecal coliform and *E.coli* counts were completed. Approximately eighty percent of the *Bacteroides* samples were allocated to samples that had the highest *E.coli* counts and the remainder allocated to samples that had low *E.coli* counts. While not a statistically based allocation, this distribution of samples was designed to investigate the efficacy of using

and potentially quantifying *Bacteroides* based on sampled *E.coli.* The SOP for *Bacteroides* quantification has been recently developed at the KCEL (King County, 2013) with a stated quantification of 1 cell/100ml.

Conventional parameters (temperature, pH, dissolved oxygen, conductivity) were measured synoptically at sampling locations using calibrated multiprobes following the KCEL Standard Operating Procedure (SOP) #205v4 Field Measurements using an Attended Hydrolab. Each multprobe was checked for calibration by KCEL during the noon sample pick up. No Hydrolab data was collected during the October 2012 sampling event due to staff shortages.

AM / PM Sampling

Bacterial sources are frequently episodic and variable, and in a stream tend to move downstream with the flow. To increase the likelihood of detecting transitory inputs and trace the sources back to where the bacteria enters this dynamic environment, samples were collected twice during each sampling event (AM and PM runs). While not verified, the assumption that the paired AM-PM sampling design was that anthropogenic sources of bacteria would be far more likely to show larger diel differences at the same location than would non-point or non-anthropogenic sources. If bacteria source(s) were persistent, it was assumed that elevated sampled bacteria counts would not change much over the approximately four hours between the AM and PM sampling. Comparison of the AM and PM bacteria counts at sequential sampling sites can be used to describe the downstream flow of both the water and entrained bacteria.

Episodic sources were more likely to be detected by calculating differences between AM and PM sampling at the same or nearby sampling sites. Large differences between AM and PM samples at the same site were assumed to indicate an increased probability of anthropogenic sources of bacteria. Changes in wastewater volumes are commonly observed and related to differences in human activity (Tchibanoglous et al. 2003) and if the sources of the bacteria in Thornton Creek were of human origin, these bacteria sources could exhibit similar diel variability. This potential change in bacteria was used as a piece of corroborating but not defining information in differentiating areas to search for anthropogenic sources as opposed to natural background, non-point or wildlife sources of bacteria that would be less associated with a daily schedule. This investigative approach is influenced by the movement of water and bacteria downstream, and comparing the pattern of AM and PM samples from sequential sites can sometimes provide more information than a comparison at the same site. Chronic or persistent bacteria sources should show both similar AM and PM bacteria counts and should not be influenced by downstream water movement.

Invasive New Zealand Mudsnails

Infestation of the lower portion of Thornton Creek by New Zealand Mud Snail (*Potamopyrgus antipodarum*) required a modification of the original sampling design. Typical designs for sampling bacteria are to collect samples from the most downstream sampling site and sample progressively upstream, decreasing the potential to re-sample the same packet of water. The current sampling design was modified to sample from upstream sites to downstream sites in order to conform to the New Zealand Mud Snail containment protocols that are in place in the Thornton Creek watershed. Samples were collected using extension poles where possible and when necessary to enter the stream boot decontamination procedures were followed before leaving the site (SPU 2012).

Source Location Approach

Detecting and differentiating specific stream segments and basins where bacteria enter the creek from stream segments primarily impacted from upstream flows was estimated by subtracting the upstream bacteria counts from the downstream bacteria counts for both AM and PM datasets. Detecting high bacteria counts at downstream locations provides useful information on the extent of impact from a bacteria source, but confounds locating specific sources of the bacteria as it is difficult to differentiate bacteria episodically added to the stream in a particular segment to bacteria flowing in from upstream.

When downstream bacteria counts were higher than upstream counts the stream segment delineated by the two sampling sites was considered a bacteria contributing or 'gaining' stream segment, with a higher probability that there was a bacteria source in the contributing sub basin delineated by that site and the sampling site immediately upstream. Conversely if downstream counts were lower than upstream counts, the stream segment was considered a 'losing' segment and the probability of there being a significant bacteria source in the sub basin draining to that particular stream segment was assumed to be small. The distance between sequential sampling locations determined the length of the stream segment and size of the contributing sub basin.

The approach conceptually views the stream as a sequential series of plug flow 'packets' of water continuously moving from upstream to downstream. A more realistic view of the water movement and mixing of bacteria is that there is a degree of partial mixing somewhere between plug flow and complete mixing. This simplification of the flow and mixing of the stream as water flows downstream is also assumed to be less accurate the further downstream the water moves and further apart sampling locations are and is a primary reason for attempting to minimize the distance between sequential sampling locations and isolate as many tributary inflows as logistically possible.

Synoptic collection of conventional water quality parameters (temperature, dissolved oxygen, pH and conductivity) provides additional data to differentiate the downstream flowing packets of water and potentially increase the probability of locating the furthest upstream section of stream where bacteria presumably entered the stream. Increased temperature, decreased dissolved oxygen, and changes in pH or conductivity can signal inputs of sanitary sewage into surface waters.

Using this design, sub-basins delineated as draining into 'gaining' stream segments are the smallest geographic search area with the highest probability of containing bacteria sources to the creek that are identified. Specific source identification will be concentrated in the sub-basins that drain to the highest and most frequent 'gaining reaches of the stream.

Results and Discussion

Thornton Creek *E.coli* bacteria samples exceeded criteria on each of the five sampling events in this study and often by a substantial amount. During this study, only 15 *E.coli* geometric means from the 46 sampling sites met the Oregon Department of Environmental Quality (ODEQ) *E.coli* criteria of 126 cfu/100ml, and those sites tended to be higher in the basin. The ODEQ criteria is not a regulation in Washington, but it is equivalent to the EPA recommended *E.coli* criteria for fresh recreation waters which replaced EPA's previously recommended bacteria criteria for fecal coliform of 200/100ml (EPA 1986).

This study relies primarily on sampling *E.coli* bacteria because it is a better indicator of potential human health risk than fecal coliform bacteria (EPA 1985, 2001). Locating and controlling sources of *E.coli* bacteria will concomitantly reduce fecal coliform bacteria and address Washington's WAC173-201A criteria. There is a relatively good correlation (r^2=0.73) between the *E.coli* and fecal coliform bacteria counts collected from the same samples in this study particularly at counts <1000 cfu/100ml (Figure 6). Several samples collected synoptically had *E.coli* > fecal coliform, which is sampling error influenced by collecting single grabs and analyzing for single dilutions. Single grab sampling was an intentional compromise in the experimental design to maximize the geographic coverage at the expense of collecting replicate samples and performing multiple dilutions. From a source location/identification perspective these sampling errors would not substantively change the results. A conservative accounting for the error in the counts of either *E.coli* or fecal coliform still result in samples orders of magnitude above criteria.

Only 7 of the 45 sampling sites met the WAC 173-201A fecal coliform criteria of geometric means <50 cfu/100ml for extraordinary primary contact and only 8 met the 200 cfu/100 ml for secondary contact (Table 2). Similar to the *E.coli* data, the sites that met criteria for fecal coliform tended to be in the upper watershed. The frequent fecal coliform bacteria exceedances (Figure 2) that resulted in listing segments of this stream as a category 5 water quality limited waterbody on the 303(d) list were collected low in the basin at the USGS flow monitoring station near Sand Point Way (site 16 in this study). The long-term ambient bacteria data at this site represented cumulative fecal coliform bacteria counts from the entire upstream watershed and provided very little geographic context for where the bacteria were entering the stream. The ambient data was useful in defining that there was a water quality problem in this watershed, but not the location of the problem

Bacterial enumeration techniques are imprecise and environmental conditions, such as rainfall, stream flow rate, wind and temperature will cause bacteria counts to vary temporally and spatially. Geometric means of bacteria counts provide more insight to long term or general water quality trends. Individual sample counts are frequently more useful than geometric means for describing the primary and secondary contact risk for recreation uses. Single sample maximum criterion is better for detecting episodic sources or making beach notification and closure decisions based on limited data (EPA 1986). The geographic density of sample sites in this study provided more detailed information on the specific location of the bacteria inputs to Thornton Creek even with the minimal replication in the design.

Fecal coliform is a functional definition of bacteria that are aerobic and facultative anaerobic, gram-negative-spore forming, rod shaped bacteria that ferment lactose with gas formation within 48 hours at 44.5 ^{o}C, and *E.coli* are definitionally fecal coliforms. Results of *E.coli* analysis can be used as a surrogate quantification for fecal coliform with the assumption that *E.coli* counts are $\leq$ fecal coliform counts. While *E.coli* is a more specific indicator of human fecal contamination than fecal coliform bacteria due to fewer false positive results, both of these indicator bacteria tests are subject to false positive results. To differentiate a potential human fecal contribution from other species feces, human specific *Bacteroides* qPCR analysis (King County 2013) was conducted on a subset of samples. This is an experimental microbial source tracking technique used to determine the presence/absence of human *Bacterioides* in water samples. It is important to determine the human fecal contribution because bacteria from human sources will have a higher human health risk than bacteria contributed by other sources (EPA 1986, 2001).

E.coli, fecal coliform and *Bacteroides* data collected during this investigation substantiate that Thornton Creek frequently exceeds bacteria criteria at multiple locations in the watershed. Based on the high counts of *E.coli* and the consistent detection of *Bacteroides*, it is likely that there is a persistent human contribution to these frequent bacteria exceedances. These results are consistent with the long term ambient monitoring data collected near the mouth of the stream. This study provides temporal, geographic detail to the recurrent high bacteria counts found in this stream and data indicating presence/absence of human sources.

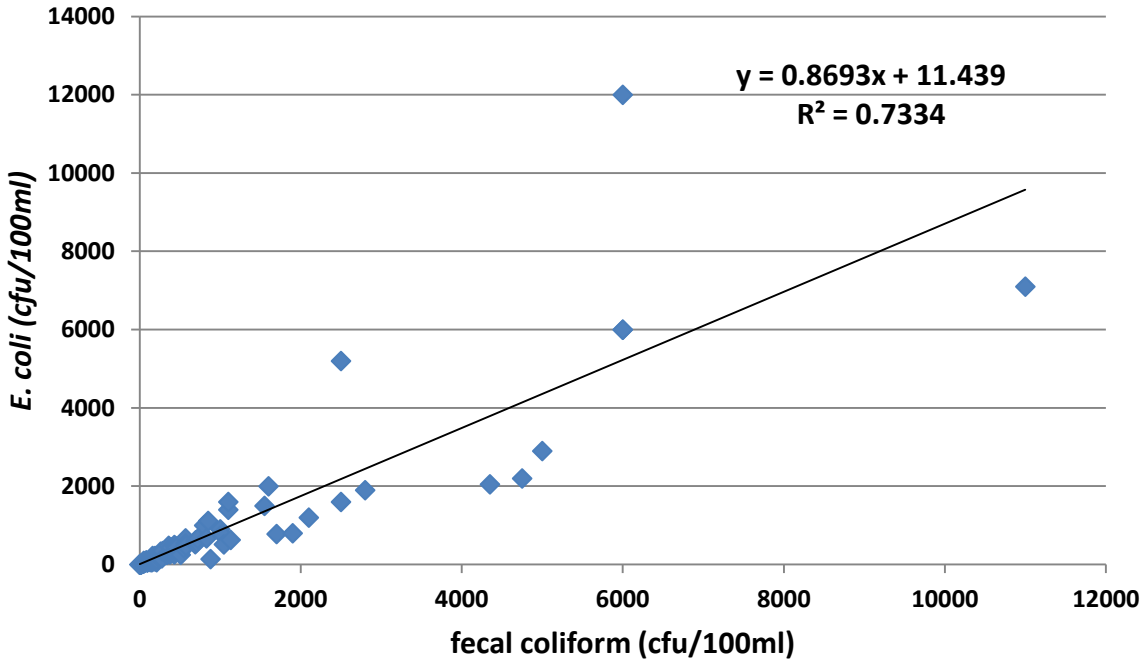


Figure 6. E.coli is < fecal coliform as all *E.coli* test positive for fecal coliform. This dataset has an r^2 of 0.73. Samples that have *E.coli* > fecal coliform tended to be samples with high bacteria counts.

Patterns of bacterial counts in Thornton Creek

The portions of the watershed where *E.coli* or fecal coliform bacteria counts met bacteria criteria tended to be in the upper watershed. The further downstream samples were collected the higher bacteria counts tended to be. Additionally, the further downstream in the watershed the greater the area that drained to the point where samples were collected and the cumulative influence of upstream sites more pronounced (Figure 7, Table 2). Most of the bacteria samples collected in the lower mainstem and South Fork of Thornton Creek exceeded criteria (Figures 8) and AM - PM differences also tended to be greater lower in the watershed with PM samples tending to be higher than AM samples.

Some of the smaller tributaries typically met bacteria criteria during most of the sampling events, but many of these same sites also had one or two large exceedances (Figure 8, Table 2). Exceedances in the smaller tributaries appeared to be independent of one another and did not always occur on the same sampling date. These episodic events in the smaller tributary sub-basins periodically contributed to the overall bacteria exceedances of Thornton Creek, but due to the episodic nature of these exceedances they are harder to detect and locate. Some of the smaller sub basins met bacteria criteria during each sampling event and can be considered to have very low probabilities of contributing to the observed bacteria criteria exceedances in this watershed. The smaller tributaries had smaller AM – PM differences than in the mainstem. The temporal and spatial variability in the bacteria counts also shows that a single

sampling site low in the watershed is at best a general indicator of bacteria loads in this watershed and frequent sampling may be necessary to detect episodic events.

Differences between bacteria counts at the various sampling sites, between sampling dates and between AM - PM samples was more common than a reoccurring pattern of bacteria in this watershed. Natural sources and chronic non-point sources would be expected to be consistently detectable close to the sources and show similar AM and PM bacteria counts. Low bacteria counts near chronic non-point sources are also less likely. Detecting consistent general patterns in bacteria counts is less likely in this urban watershed where land cover, human use activity patterns and infrastructure quality are highly variable throughout the watershed.

If the high bacteria counts in Thornton Creek are assumed to be from natural sources the counts would be similar to bacteria counts observed in adjacent watershed with similar land uses and cover. In the adjacent Lyon Creek and McAleer Creek, bacteria counts were much lower than in Thornton Creek (http://green. kingcounty.gov/WLR/Waterres/StreamsData/Data.aspx). No difference in AM and PM bacteria counts were observed in rural Boise Creek bacteria data (R. Timm pers com.). Bacteria counts from natural sources such as wildlife or from agricultural inputs are assumed to be more constant. Conversely very high bacteria counts, high observed diel changes in the bacteria counts and a disjointed distribution of high bacteria counts in the watershed is an indicator of possible human activity and can potentially be used to trace these anthropogenic sources of bacteria. To locate changing distributed inputs of bacteria a detailed look at the smaller sub basins defined by the dense sequential sampling sites provides the best information. The smaller the suspect pollutant contributing area becomes the higher the probability of locating and subsequently controlling the sources becomes.

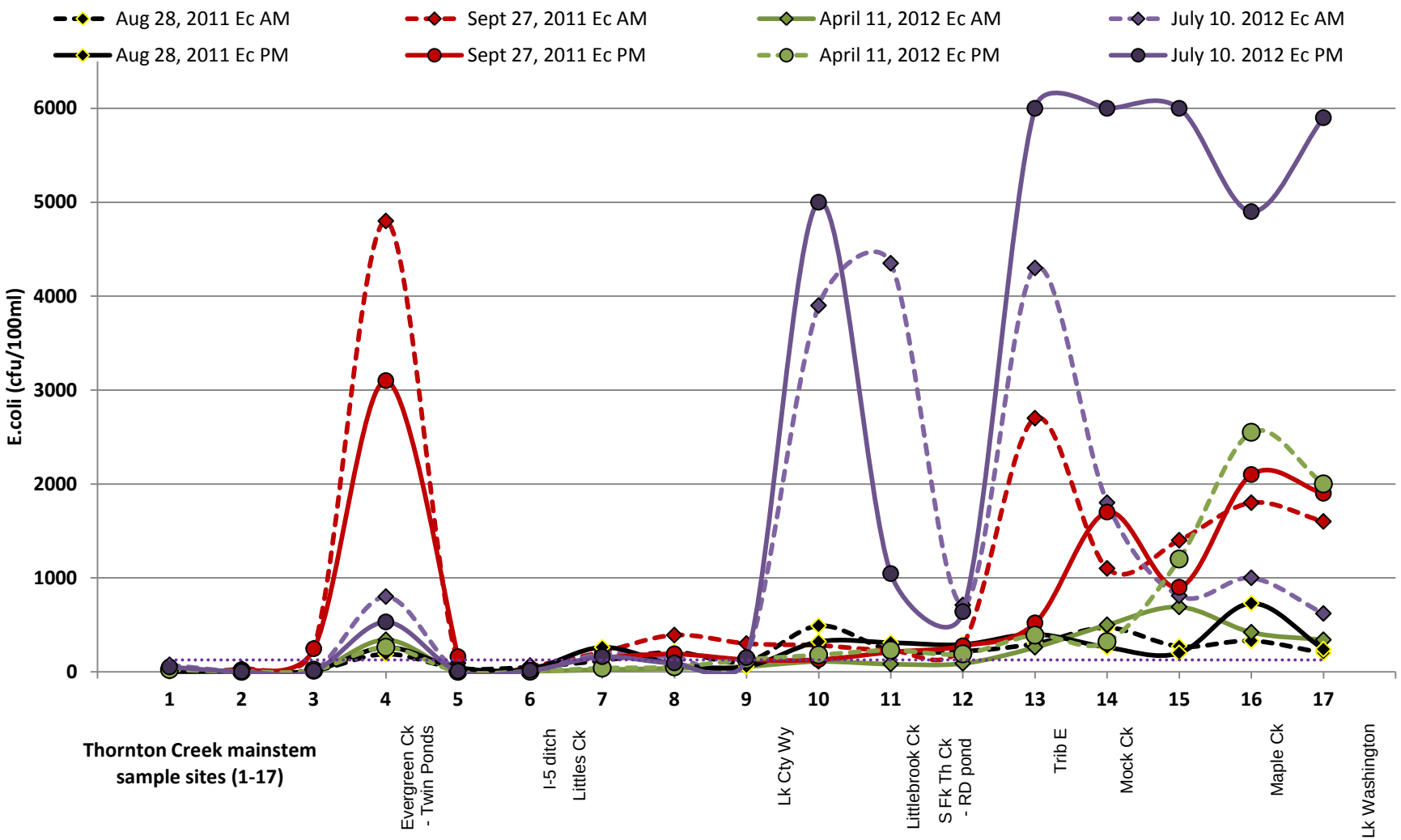

Aug 28, 2011 Ec AM
Sept 27, 2011 Ec AM
April 11, 2012 Ec AM
July 10. 2012 Ec AM
Aug 28, 2011 Ec PM
Sept 27, 2011 Ec PM
April 11, 2012 Ec PM
July 10. 2012 Ec PM
E.coli (cfu/100ml)
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Thornton Creek mainstem sample sites (1-17)
Evergreen Ck - Twin Ponds
I-5 ditch
Littles Ck
Lk Cty Wy
Littlebrook Ck
S Fk Th Ck - RD pond
Trib E
Mock Ck
Maple Ck
Lk Washington

Figure 7(a)

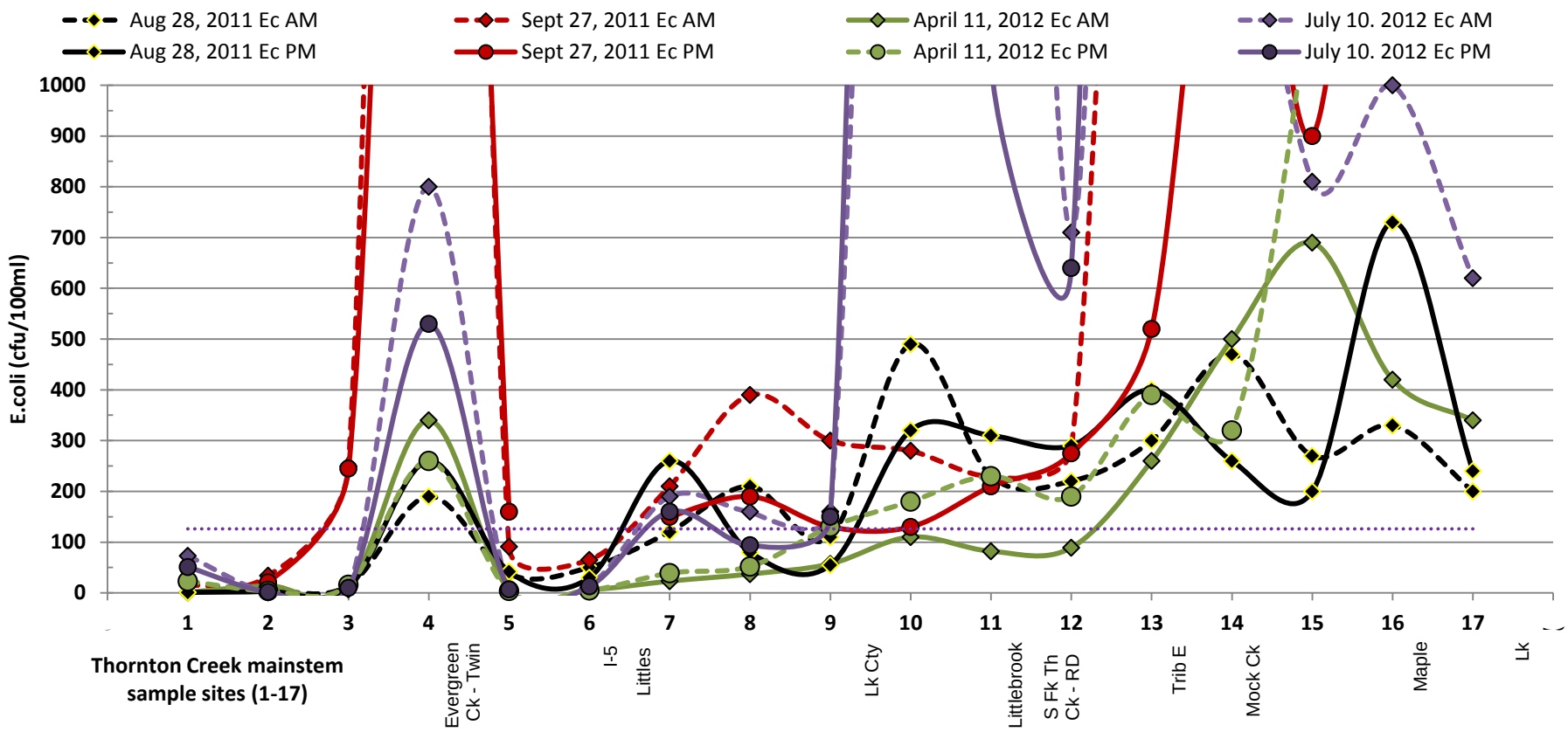


Figure 7(b)

Figure 7. Thornton Creek mainstem *E.coli* counts (cfu/100ml). Vertical labels indicate where tributaries enter the mainstem. Samples collected at the uppermost site (1), Twin Ponds (4-5), Littles Ck (between 6-7), Lake City Way (between 9-10), Littlebrook Ck (between 11-12), South Fork (between 12-13), Mock Creek (14), Maple Creek (between 16-17), and the mouth of Thornton Creek at Lake Washington (17). Increases in bacteria counts between adjacent sites were some of the primary data used for sub basin prioritization. Figures 7 a and b show the same data at two different scales. Most of the samples exceeded the ODEQ *E.coli* criteria of 126 cfu/100ml (indicated by the dotted purple line).

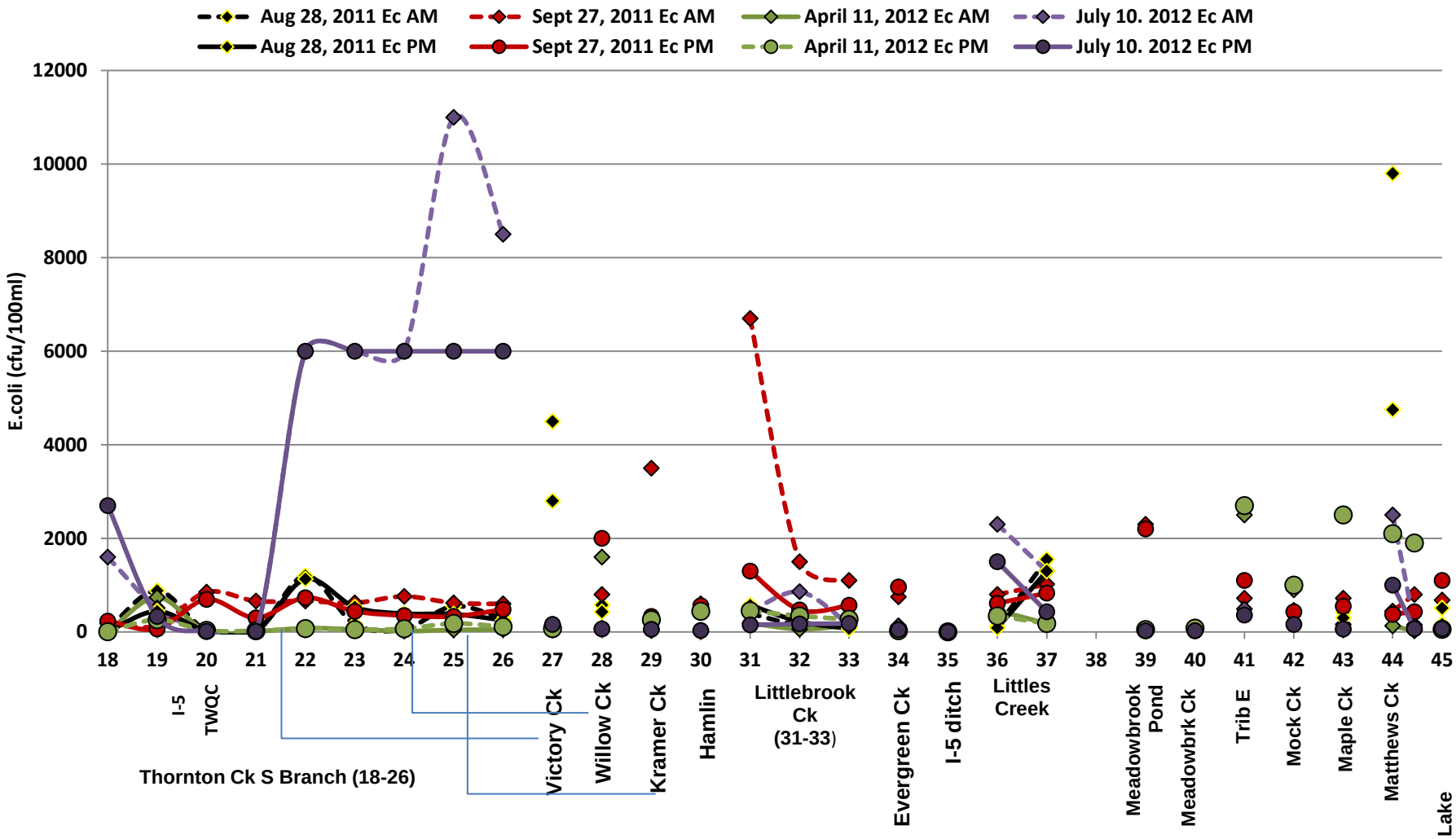


Figure 8. South Fork of Thornton Creek (18-26) *E.coli* counts. The upper most sampling site (18) drains from Washelli cemetery, the N Seattle CC (19), Thornton Creek Water Quality Channel (20), Victory Creek (27) enters between 21-22, Willow Creek (28) enters below 24, Kramer Creek (29) enters below 25 and Meadowbrook Creek (40) enters below 26. Increases in bacteria counts between adjacent sites were some of the primary data used for sub basin prioritization. Most of the samples exceeded the ODEQ *E.coli* criteria of 126 cfu/100ml (indicated by the dotted purple line).

Table 2. AM and PM *E.coli* , fecal (a) coliform (b), and Bacteroides (c) data in the Thornton Creek watershed on August 28, 2011, September 27, 2011, April 11, 2012, July 10, 2012 and October 14, 2012. Samples shaded in green meet ODEQ or WAC173-201A bacteria criteria.

Table 2(a)

	August 28, 2011		September 27, 2011		April 11, 2012		July 10, 2012		Oct 14, 2012			
site	AM	PM	AM	PM	AM	PM	AM	PM	rain event	geometric mean	max	n
***E.coli* cfu/100ml (a)**												
Thornton Creek mainstem												
1	17	1	14		1	23	73	51		11	73	7
2	6	3	34	21	14	4	1	2		6	34	8
3	14	11	250	245	10	16	7	10		24	250	8
4	190	260	4800	3100	340	260	800	530	3600	638	4800	8
5	37	42	91	160	6	4	7	7		20	160	8
6	50	30	65		6	5	15	13		18	65	7
7	120	260	210	150	23	39	190	160		113	260	8
8	210	80	390	190	37	52	160	94		117	390	8
9	110	55	300	130	57	130	160	150		120	300	8
10	490	320	280	130	110	180	3900	5000	1500	465	5000	8
11	230	310	230	210	82	230	4350	1045	1700	362	4350	8
12	220	290	285	275	89	190	710	640	1000	281	1000	8
13	300	400	2700	520	260	390	4300	6000	500	903	6000	8
14	470	260	1100	1700	500	320	1800	6000	1500	890	6000	8
15	270	200	1400	900	690	1200	810	6000	1000	851	6000	8
16	330	730	1800	2100	420	2550	1000	4900	1800	1216	4900	8
17	200	240	1600	1900	340	2000	620	5900	1750	881	5900	8

site	August 28, 2011 AM	August 28, 2011 PM	September 27, 2011 AM	September 27, 2011 PM	April 11, 2012 AM	April 11, 2012 PM	July 10, 2012 AM	July 10, 2012 PM	Oct 14, 2012 rain event	geometric mean	max	n
***E.coli* cfu/100ml (a)**												
South Fork Thornton Creek												
18	69	13	180	230	3	4	1600	2700	500	81	2700	8
19	880	440	140	63	740	260	510	330	300	320	880	8
20	32	21	850	695	10	32	33	13		52	850	8
21	14	15	660	300	12	24	14	13		35	660	8
22	1200	1130	660	730	81	71	6000	6000	620	779	6000	8
23	160	530	620	440	55	48	6000	6000	450	465	6000	8
24	60	390	760	350	17	67	6000	6000	2500	356	6000	8
25	550	380	620	330	44	180	11000	6000	1000	622	11000	8
26	280	250	600	480	51	110	8500	6000		525	8500	8
Victory Creek												
27	4500	2800	100	50	113	70	160	160		244	4500	8
Willow Creek												
28	575	430	800	2000	1600	340	82	63		427	2000	8
Kramer Creek												
29	130	160	3500	330	58	260	29	55		166	3500	8
Hamlin Creek												
30	17	23	600	560	7	440	11	30		58	600	8
Littlebrook Creek												
31	390	570	6700	1300	190	450	430	150		567	6700	8
32	150	220	1500	470	59	340	860	170		301	1500	8
33	160	71	1100	570	140	270	150	180		228	1100	8
Evergreen Creek, Shoreline												
34	23	21	750	960	25	25	130	44		77	960	8

site	August 28, 2011 AM	August 28, 2011 PM	September 27, 2011 AM	September 27, 2011 PM	April 11, 2012 AM	April 11, 2012 PM	July 10, 2012 AM	July 10, 2012 PM	Oct 14, 2012 rain event	geometric mean	max	n
***E.coli* cfu/100ml (a)**												
I-5 drainage												
35	2	4	16	7	1	1	1	3		3	16	8
Littles Creek												
36	120	86	800	610	460	530	2300	1500	3600	505	3600	8
37	1550	1300	1020	830	180	180	1300	430	7200	647	7200	8
Meadowbrook Pond												
39	11	2	2300	2200	60	50	52	24		67	2300	8
Meadowbrook Creek												
40	93	62	47	25	100	80	26	46	160	53	160	8
Trib E												
41			720	1100	2500	2700	490	360	4100	990	4100	6
Mock Creek												
42	210	200	430	430	900	1000	460	160		388	1000	8
Maple Creek												
43	420	300	720	550	160	2500	50	61		297	2500	8
Matthews Creek												
4444			800	430	24	1900	150	68		233	1900	6
44	9800	4750	445	375	130	2100	2500	1000	4200	1232	9800	8
Lake Washington												
45	160	510	680	1100	94	55	91	68		193	1100	8

meets Oregon DEQ *E.coli* 126 cfu/100ml criteria

Table 2(b) Fecal coliform bacteria

fecal coliform (cfu/100ml) (b)												
	August 28, 2011		September 27, 2011		April 11, 2012		July 10, 2012		Oct 14, 2012			
site	AM	PM	AM	PM	AM	PM	AM	PM	rain event	geometric mean	max	n
Thornton Creek mainstem												
1	1										1	1
2		2			11		3			4	11	3
3		8	225	190						70	225	3
4	130					240	1000		3500	315	1000	3
5											0	0
6					2						2	1
7		170	130	58	31			120		86	170	5
8	60		440	220				53		132	440	4
9						110		91		100	110	2
10								2900	785		2900	1
11					110		2050	515	860	488	2050	3
12	220		345	160		80	570		770	223	570	5
13					330			12000	730	1990	12000	2
14		260	1400	780	320				2100	549	1400	4
15	210				520				2100	330	520	2
16									2300		0	0
17			2000	800	260				3100	747	2000	3

fecal coliform (cfu/100ml) (b)												
	August 28, 2011		September 27, 2011		April 11, 2012		July 10, 2012		Oct 14, 2012	geometric		
site	AM	PM	AM	PM	AM	PM	AM	PM	rain event	mean	max	n
South Fork Thornton Creek												
18		12				1			740	3	12	2
19	140								410		140	1
20			1115	620						831	1115	2
21							11				11	1
22		630			80		6000		840	671	6000	3
23									480		0	0
24		290				70		6000	2000	496	6000	3
25							7100		870		7100	1
26					45						45	1
Victory Creek												
27		1900					74			375	1900	2
Willow Creek												
28	480					210		57		179	480	3
Kramer Creek												
29					41		23			31	41	2
Hamlin Creek												
30	14										14	1
Littlebrook Creek												
31		670						180		347	670	2
32						250					250	1
33	220		1600	540		180		160		353	1600	5
Evergreen Creek, Shoreline												
34							64				64	1

fecal coliform (cfu/100ml) (b)												
	August 28, 2011		September 27, 2011		April 11, 2012		July 10, 2012		Oct 14, 2012	geometric		
site	AM	PM	AM	PM	AM	PM	AM	PM	rain event	mean	max	n
I-5 drainage												
35						1	2			1	2	2
Littles Creek												
36						340			3300	340		1
37	1500		775	670				500	5500	790	1500	4
Meadowbrook Pond												
39		4				94				19	94	2
Meadowbrook Creek												
40		53	23	13	72				70	33	72	4
Trib E												
41					1600			480	5500	876	1600	2
Mock Creek												
42			260	340		900	440	110		329	900	5
Maple Creek												
43			660	420			70			269	660	3
Matthews Creek												
4444					22					22	22	1
44		2200	475	260		1200	5200		1900	1111	5200	5
Lake Washington												
45		250			58					120	250	2

meets WAC173-201A secondary contact criteria of 200 cfu/100ml criteria

Table 2(c) *Bacteroides*

***Bacteroides* (cells/100ml) (c)**												
	August 28, 2011		**September 27, 2011**		**April 11, 2012**		**July 10, 2012**		**Oct 14, 2012**			
site	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**	**rain event**	**geometric mean**	**max**	**n**
Thornton Creek mainstem												
1	130										130	1
2												
3	125										125	1
4			746	598					1406		746	2
5												
6												
7												
8		595									595	1
9		448									448	1
10							405	187			405	2
11							543	190	295		543	2
12												
13			1537				1442	2153			2153	3
14				1132	694		13050	2374	923		13050	4
15			1152		537	23180		3146			23180	4
16		332	999	696		19780	432	1448	2778		19780	6
17			1185	679		12610		4444	2885		12610	4

Bacteroides (cells/100ml) (c)												
	August 28, 2011		September 27, 2011		April 11, 2012		July 10, 2012		Oct 14, 2012	geometric		
site	AM	PM	AM	PM	AM	PM	AM	PM	rain event	mean	max	n
South Fork Thornton Creek												
18							573	294			573	2
19	28										28	1
20												
21												
22	331	553					85880	23309			85880	4
23		997					35720	18240			35720	3
24							18550	12940	1684		18550	2
25	380						3531	7126			7126	3
26							3531	5285			5285	2
Victory Creek												
27	2018	2822									2822	2
Willow Creek												
28	836			636	1873						1873	3
Kramer Creek												
29			64796								64796	1
Hamlin Creek												
30												
Littlebrook Creek												
31		1179	713	509							1179	3
32			474								474	1
33												
Evergreen Creek, Shoreline												
34												

Bacteroides (cells/100ml) (c)												
	August 28, 2011		September 27, 2011		April 11, 2012		July 10, 2012		Oct 14, 2012	geometric		
site	AM	PM	AM	PM	AM	PM	AM	PM	rain event	mean	max	n
I-5 drainage												
35												
Littles Creek												
36							3694	2402	2025		3694	2
37	11675	12800							788		12800	2
Meadowbrook Pond												
39			1965	4406							4406	2
Meadowbrook Creek												
40												
Trib E												
41				810	327	389			697		810	3
Mock Creek												
42							107330	8874			107330	2
Maple Creek												
43						614					614	1
Matthews Creek												
4444						435					43	1
44	14412	12538				6610	1974		1772		14412	4
Lake Washington												
45				1347							1347	1

Mainstem Thornton Creek and mainstem tributary basins

Upper Mainstem of Thornton Creek above Lake City Way

Sub basin 1, 2 and 3

The Shoreline sub basins 1, 2 and 3 do not appear to contribute very much bacteria or substantial flows to Thornton Creek and were <126 cfu/100ml except one sample. There was a small exceedance of *E.coli* ~250 cfu/100ml at site 3 in September 2011 (Figure 7; Table 2). The consistent low bacteria counts also resulted in very small AM – PM differences in the *E.coli* counts. These sampling sites are the uppermost in the mainstem of Thornton Creek so any flows and any bacteria loads sampled at these sites were contributed only from these sub basins.

Site 1 is the furthest upstream on the mainstem that could be located. Site 2 is immediately downstream of Ronald Bog and site 3 between Ronald Bog and Twin Pond Park. Between Twin Ponds and Ronald Bog, the North Branch of Thornton Creek flows through pipes under the Metro bus barn and electric substation. Further upstream the creek passes beside the solid waste transfer station and through backyards, roadside ditches, and culverts.

Downstream of Ronald Bog the mainstem at site 2 frequently had the highest temperatures of any of the sampling sites (Figure 9). Temperature consistently decreased downstream from site 2 to site 4, with the temperature change in July 2012 from ~23 ^{o}C at site 2 to 14^{o}C at site 4. Between sits 2 and 3 there was a 1 to 4 mg/L decrease in DO (Figure 10) and small increase in conductivity (Figure 11), pH (Figure 12). These water quality changes probably indicate groundwater inflow to this section of the stream.

Sub Basin 4

The stream segment between sites 3 and 4 flows past the solid waste transfer station, under the Metro Bus Barn and between I-5 and single family residences. Sub basin 4 in Shoreline straddles I-5 south of N 167th St to just north of the Twin Ponds (Figure 2). *E.coli* counts at this site exceed ODEQ criteria for every sampling event, and the September 27, 2011 samples were the highest counts collected in the watershed that day (Figure 7; Table 2). Both AM and PM samples were elevated on every sampling date with no particular pattern to whether AM or PM samples were higher. The fecal coliform samples collected at site 4 also exceed criteria except for the AM sample on August 28, 2011, which was also the lowest *E.coli* count (Table 2). Upstream loading from sub basin 3 is not likely to be the source of these high bacteria counts as the samples from sub basin 3 were consistently very low and only slightly elevated in September 2011.

In the stream segment between sites 2 and 4 there was a consistent decrease in temperature and DO each sampling event (figures 8 and 9) and no clear pattern in pH or conductivity (figures 10 and 11) in this stream segment. Concentrations of DO at site 4 were consistently <5 mg/L and in August 2011 <1 mg/L. These were the lowest concentrations of DO sampled in the watershed. The increased counts of *E.coli* and decreased DO would be consistent with an increased biological oxygen demand (BOD) in this segment of the stream. There is a very high likelihood that there is a persistent and significant source of *E.coli* entering Thornton Creek somewhere in sub basin 4 that drains to the stream segment between site 3 and site 4.

Sub basins 5, 6, 34 (Evergreen Creek), 35 (I-5 ditch)

Twin Ponds is between site 4 and site 5. The high bacteria loads to these ponds from site 4 at the north are attenuated before the outflow at the south end of the ponds where *E.coli* counts at site 5 were below criteria in every sample except for September 27, 2011 PM when counts only barely exceed criteria (160 cfu/100ml; Table 2). Evergreen Creek (site 34) drains into Twin Ponds from the west and had low *E.coli* counts except for the September samples (AM 750 PM 960 cfu/100ml; Table 2). Evergreen Creek feeds into the southwest corner of Twin Ponds. It drains a 364-acre watershed, which is primarily residential and includes Evergreen School. West and upstream of Twin Ponds, the creek flows through approximately 700 feet of wooded parkland before crossing under Meridian Ave N. This small tributary

may originate from a wetland at Meridian Park (N 170th St and Wallingford Ave N). However, it is difficult to locate the upper reaches of Evergreen Creek because the creek is either in backyard culverts or other subsurface flow. This creek enters twin Ponds along the southwest side, much closer to the outflow and site 5 and could potentially be responsible for the slight elevation in *E.coli* counts sampled at site 5 in September 2011. The attenuation of bacteria in Twin Ponds eliminated the upstream impact from site 4 on downstream sampling sites observed in other portions of the watershed with no intervening pond.

Temperature (Figure 9), DO (Figure 10) and pH (Figure 12) increased between sites 4 and 5 similar to that observed between sites 1 and 2 where Ronald Bog was between these sites. The changes are consistent with the increased solar exposure and photosynthesis in open water in Ronald Bog and Twin Ponds. Conductivity decreased as expected below a lake (Figure 11).

The next downstream segment between sites 5 and 6 of Thornton Creek did not have appreciable bacteria loading and had very low counts of both *E.coli* and fecal coliform (Table 2). Between these sites Thornton Creek flows nearly 2000 feet under I-5 and along the western boundary of Jackson GC. The above ground section of the stream has a healthy riparian cover of mature trees and is some of the most intact and least accessible sections of Thornton Creek. Temperatures consistently decreased (Figure 9) and DO increased (Figure 10) along this stream segment.

Site 35 sampled a small drainage ditch that flows under I-5 and flows into Thornton Creek just below site 6. This ditch collects surface drainage from along the hillside on the west side of I-5. While this ditch was full of trash and contributed to a drainage problem along 5th Ave NE, the water was consistently clear and the bacteria counts the lowest of any sites in the watershed. This small drainage has high DO (Figure 10) and low temperatures (Figure 9).

Sub basins 36, 37 (Littles Creek), 7

Below site 6, the mainstem of Thornton Creek crosses Jackson Golf Course and flows through undeveloped Seattle Parks property, Brook Haven Apartments and crosses15th Ave NE. Much of the riparian vegetation has been removed in the golf course and apartment complex, with some recent riparian planting in the golf course. The increased exposure of this section of the stream had increased temperature, DO and pH probably due to increased sunlight and primary productivity (figures 8-11).

Littles Creek confluence is immediately upstream of site 7. *E.coli* counts were consistently elevated at site 7, and while only about half of the samples at this site met ODEQ criteria, exceedances were small and the *E.coli* geometric mean of all samples was 113 cfu/100ml, below the 126 cfu/100ml criteria (Table 2). Littles Creek flows south along 12th Ave NE, collecting groundwater and runoff from a residential area. Littles Creek passes through Paramount Park and associated wetlands before crossing under NE 145th St and flowing through the Jackson Park Golf Course. During storms, some flows are diverted into a detention pond that also serves as a water hazard for golfers. This pond has a fountain in the lower section of the pond. After exiting the golf course, this tributary passes through some commercial property, and then enters a 30-inch pipe along 10th Ave NE. Littles Creek joins the North Branch. Input of *E.coli* from Littles Creek is the probable source of the small increase in *E.coli* at site 7.

Littles Creek has only about 10-20 percent of the flow of the mainstem at their confluence. The upper site (36) is in the City of Shoreline North Crest Park. The dark surface growth on the cobbles shows no sign of disturbance or gravel movement associated with high flows. The lower Littles Creek site (37) is in a condominium development on 15th Ave NE. Both Littles Creek sites were consistently >126 cfu/100ml. Only the August 2011 samples at the upper site (36) met criteria. Samples collected the same day immediately downstream (37) were an order of magnitude higher (AM = 1550, PM = 1300 cfu/100ml; Table 2). Between these two sites is single family residential development in Shoreline north of NE 145th St and the stream then flows through the NE corner of Jackson GC and into the condo development. There appears to be inputs of *E.coli* in the section of Littles Creek between the two sampling sites as well as from above the upper site in North Crest Park. Temperature and DO increased from the upper site to the lower site with temperature always <18^{o}C (Figure 9) and DO > 6 mg/L (Figure 10) which is not indicative of a substantial BOD loading.

Sub basins 30 (Hamlin Creek), 8, 9

Hamlin Creek joins the mainstem near 20th Ave NE just south of NE 130th St. This sub-basin covers 405 acres. It includes Hamlin Park, a large forested park, the adjacent commercial and educational facilities, and the surrounding residential neighborhood. Hamlin Creek flows year-round; most of its length has been ditched along 20th Ave NE. There is little quality habitat along Hamlin Creek ditch. Much of the runoff from above the park soaks into the sandy soils within Hamlin Park (SPU 2001).

Hamlin Creek (30) was sampled immediately S of NE 145 St and flows in an open ditch through a single family residential neighborhood into the mainstem just N of NE 127th St and upstream of the mainstem site 8. In upper Hamlin Creek, both the AM and PM September 2011 *E.coli* counts (AM =600, PM =560 cfu/100ml) and the PM count in April (AM =7, PM =440 cfu/100ml) exceeded ODEQ *E.coli* criteria. No water quality changes (figures 9-13) were noted between the AM and PM samples that could account for the large PM *E.coli* increase although the PM conductivity was quite a bit lower than the AM sample (Figure 11). No other differences in the conventional parameters were obvious.

Lake City Way

Lake City Way is a major arterial in the northeast part of Seattle that has extensive commercial development, automobile dealerships and auto repair shops. The mainstem of Thornton Creek above Lake City Way frequently met or only slightly exceeded the *E.coli* criteria (sites 1-9, with the exception of site 4 above Twin Ponds). Small exceedances of the *E.coli* criteria occurred at site 8 with AM counts tending to be higher than PM counts and a similar pattern was observed immediately downstream a site 9 just below NE 125th St (Table 2). With the exceptions of site 4 above Twin Ponds and Littles Creek, samples collected in the mainstem and mainstem tributaries above Lake City Way either met or only slightly and intermittently exceeded the ODEQ *E.coli* criteria. Downstream of Lake City Way every *E.coli* sample collected in the mainstem on every sampling date except April 2012 exceed the ODEQ *E.coli* criteria and frequently by an order of magnitude or greater. From a water quality perspective Lake City Way defines a boundary between the upper mainstem with relatively good water quality and the lower mainstem with degraded water quality.

Lower Mainstem of Thornton Creek below Lake City Way

Sub basin 10, 11, 12, 31-33 (Littlebrook Creek)

This section of the mainstem of Thornton Creek runs from just above Lake City Way to just upstream of the confluence with the South Fork of Thornton Creek. Sub basins 10 and 11 drains an area covering just over a mile of Lake City Way between NE 125rd St and NE 115th St with commercial development and several blocks of single family residential to the west of Lake City Way and N of Thornton Creek. Sub basin 12 is primarily single family residences and includes the confluence of the mainstem of Thornton and Littlebrook creeks. While bacteria counts downstream of Lake City Way were consistently above criteria, the physical structure of the channel and riparian zone is some of the most intact in the watershed.

In both August 2011 and July 2012 there were large increases in *E.coli* counts between the site immediately upstream (9) and downstream (10) of Lake City Way. The July 2012 fecal coliform data increased from 91 cfu/100ml to 2900 cfu/100ml at site 10 (Table 2b) Storm drains from Lake City Way discharge to Thornton Creek between these two sampling sites. In August 2011, site 9 *E.coli* counts were below criteria and immediately downstream at site 10 there was a 4-6 fold increase in *E.coli* counts. Only in April 2012 AM samples were any samples collected below this point below the ODEQ *E.coli* criteria. The abrupt increase in *E.coli* counts at site 10 observed in August 2011 and July 2012 did not occur in the September 2011 or April 2012 sampling events. A similar pattern in both fecal coliform and *E.coli* bacteria counts on widely separated sampling days, not observed at other sites or on others sampling days is assumed to be another indication that this is an episodic but recurring bacteria load.

Several on-going audits by the SPU IDDE Program are occurring in this sub basin (N. Hart pers comm.). The current audits focus primarily on auto washing associated with the car dealership along Lake City Way in this sub basin. While auto maintenance activities may account for the suds observed in the stream and potentially the lack of benthic fauna in the stream, these sources would not be considered as primary sources of the large increases in *E.coli* observed in this stretch of the stream. Based on the bacteria increases the sub basin draining to this location is highly suspect for having undetected bacteria sources and are most likely from the Lake City Way drainage.

Littlebrook Creek begins near the City limits at NE 145th St (sites 31) and flows south, mainly through pipes and culverts, as it passes through the Lake City business district. It flows above ground at several sites, usually adjacent to apartment buildings. Little Brook enters a stormwater detention pond, then (site 32), flows through a steep ravine for several blocks before it joins the North Branch near NE 113rd St. The North Branch flows south for several more blocks (site 33) before joining the South Branch between sites 11 and 12.

Littlebrook bacteria counts were above criteria but this stream has an apparent 'diluting' effect on the bacteria counts of the mainstem at site 12 (Figure 7) primarily because of the high bacteria counts in the mainstem (Table 2). This dilution effect was not observed during the September 2011 sampling, when *E.coli* counts in Littlebrook Creek were the highest sampled in that tributary (AM 6700-1100 and PM 1300-570; Table 2) and flows low. The high September 2011 *E.coli* in Littlebrook Creek contributed to the increased *E.coli* counts in the mainstem. There was a decrease in conductivity downstream of the confluence of Littlebrook Creek, particularly in the September 2011 samples where Littlebrook Creek had lower conductivity than sampled on the other sampling dates (Figure 11).

There was no Lake City Way impact observed in Littlebrook Creek probably because the first site (31) frequently had high *E.coli* counts and the site below Lake City Way (32) is below the SPU detention pond at NE 125th St which increased travel time between upstream site 31 and site 32 similar to what was observed at site 4 and 5 in the upper watershed. None of the three sites on Littlebrook Creek met bacteria criteria, and the headwaters sub basin 31 had *a* high *E.coli* count (AM 6700 PM 1300 cfu/100ml; Table 2) which implied an ephemeral bacteria source in this sub basin.

The pattern of *E.coli* in the mainstem from site 10 all the way to the lake appears to be strongly confounded by loading of bacteria from upstream sites flowing downstream. It is more difficult to differentiate actual local increases or decreases in bacteria counts at downstream sampling sites from episodic loads that enter upstream sites and flow downstream. The downstream increases in *E.coli* counts were observed at different distances below Lake City Way on the different sampling days and there is no information available to separate out local additions of bacteria from bacteria entering further upstream and flowing downstream.

The confounding of the downstream sites from upstream sites makes the straight count data in this section of the stream less useful by itself for identifying and locating inputs of bacteria at the downstream sampling sites. Comparing the differences between the patterns of the AM and PM counts provide additional information in detecting the signal of a bacteria source from the elevated background bacteria counts in this section of the stream. This approach is also confounded by downstream flows. Even though *E.coli* and fecal coliform counts in the lower mainstem of Thornton Creek are consistently above either the ODEQ *E.coli* or WAC 173-201A criteria, it may be more efficient to initially focus on locating and controlling the upstream and tributary sources which could decrease the overall background bacteria counts and potentially make it easier to differentiate potential sources in the section of stream from potential background bacteria from upstream.

The comparison of AM and PM bacteria counts has been shown to be a useful technique in locating episodic loading of bacteria (Ecology 2009). The patterns of both the September 2011 and July 2012 *E.coli* counts (Figure 7) from site 9 downstream to Lake Washington below site 17 exhibit a downstream shifting pattern of *E.coli* counts responding to the flow of the stream. The increases and decreases in bacteria counts from upstream sites to sequential downstream sites can be viewed as the signal of downstream plug flow of bacteria.

The shifting patterns of bacteria between AM and PM bacteria counts in the mainstem below site 10 are different from the consistent increase/decrease pattern at site 4 and 5, and to a lesser extent below the detention pond on Littlebrook (31-32). This contrasts the differences between the influence of a pond between sites 4 and 5 and the influence of stream flow and downstream transport of bacteria below site 10 down to Lake Washington.

Sub basin 13, 39 (Meadowbrook Pond)

Site 13 is immediately below the Meadowbrook RD pond (39) and the confluence with the South Fork of Thornton Creek. Outflow from the pond is through a pipe that leads directly to Lake Washington so has no impact on the bacteria counts in the lower section of the mainstem, and the *E.coli* counts sampled in the pond (site 39) were below criteria (<60 cfu/100ml) except during the September 2011 (AM 2300 PM 2200 cfu/100ml).

The influence of the South Fork (sites 18-26) on *E.coli* counts at this location was most dramatic in the July 2012 sampling. High counts in the South Fork (>6000 cfu/100ml) contributed to the high counts (>6000 cfu/100ml) below site 12 particularly in the PM samples. Synoptic PM fecal coliform counts collected on July 10 2012 (12000 cfu/100ml) were the highest fecal count of any of the samples collected during the study, which both corroborates the high *E.coli* counts and presents the possibility that the *E.coli* counts may have been higher than the quantified >6000 counts**.** The influence of the inflow of the South Fork can also be seen in the decreased conductivity in September 2011 when conductivity decreased from >200 to ~170 μsiemens and persisted all the way to Lake Washington (Figure 11). No reason for the decreased conductivity has been established.

Sub basin 14, 15, 41 (Trib E), 42 (Mock Creek)

It is difficult to differentiate local contributions of bacteria and changes in water quality in these sub basins from the very high bacteria loads from the upstream sites. If there are local sources of *E.coli* in this section of the mainstem of Thornton Creek, locating these sources will only be possible when upstream bacteria sources are removed. Every bacteria sample collected at both of these sites >126 cfu/100ml E.coli. In July 2012 this section of Thornton Creek had AM and PM E.coli counts of >6000 cfu/100ml, but the source of this bacteria appeared to originate upstream.

The small tributaries, Trib E and Mock Creek, along this stretch of the mainstem of Thornton Creek also did not meet the ODEQ *E.coli* criteria (Table 2). The highest *E.coli* counts sampled at both of these tributary sites was in April 11, 2012 during a small rain event and when it had rained the previous two days. The increased *E.coli* counts in these small developed basins may be indicative of a relatively rapid wet weather flow response and increased bacteria loading. The mainstem with a much larger drainage area responded less to the small rain event and had a much lower overall bacteria counts in the April 2012 samples than these small sub basins. There was also a greater increase between the AM and PM temperatures on April 2012 in these small basins than at the other sampling sites on this date (Figure 9). Both of these sub basins have relatively little flow and their contribution to the bacteria counts in the mainstem are marginal, but these basin should be looked at to discern the source of the high *E.coli* from these small sub basin of single family residences. Mock Creek joins the Main Branch near NE 103rd St just west of 40th Ave NE. Mock Creek drains 44 acres of single family residential neighborhoods. Mock Creek flows year round. The lower 1,250 feet of the creek are located in a storm drain along 40th Ave NE. The creek drops into the storm drain near NE 98th St.

Sub basin 16, 17, 43 (Maple Creek), 44-4444 (Matthews Creek and pond), 45 (Lake Washington)

Site 16 is located immediately downstream of Sand Point Way at the USGS gaging station and the long term King County ambient monitoring station where the historic bacteria data was collected (Figure 2). Bacteria counts at this site were consistent with historic data and exceeded bacteria criteria for every sample collected (Figure 7, Table 2). Similar to the long term ambient bacteria data collected at this site,

the high bacteria counts collected during every sampling event confirm that this section of Thornton Creek consistently exceeded criteria, and the bacteria most probably originates from inputs upstream.

Maple Creek sub basin (43) drains a relatively small southeast portion of the watershed and discharges into Thornton Creek just downstream of site 16 and immediately below the culvert on NE 93rd St. Maple Creek exceeded ODEC *E.coli* criteria every sampling event, except during the July 2012 low flow sampling (AM 50 PM 61 cfu/100ml). April PM *E.coli* counts in this stream were 2500 cfu/100ml (Figure 8) and PM conductivity decreased from ~250 to <200 μsiemens (Figure 11). This small stream also carries a very high sediment load requiring the removal of ~10 yd^3/yr (G. Lockwood, pers comm.). This small stream should not have these high bacteria counts or this high sediment load and the source of these problems should be investigated.

Site 17 is the lowest mainstem site in the watershed and is immediately below the pedestrian bridge near the mouth of Thornton Creek to Lake Washington. Flows here are slow and there is an observable backwater effect where the creek mouth enters Lake Washington. Every sample at this site exceeded ODEC *E.coli* criteria, although the counts tended to decrease from counts at the immediately upstream site 16 except for the July 2012 PM sample. The difference between the AM and PM samples in the July 2012 sampling was the largest difference sampled (AM = 620 PM = 5900 cfu/100ml), and probably represent the large slug of bacteria that was flowing downstream in Thornton Creek late in the morning on July 10, 2012.

The decreased bacteria counts on the other sampling dates were probably due to wind mixing of Lake Washington water into this section of the stream and diluting the bacteria near the mouth. The current mouth of Thornton Creek is a low gradient artificial channel that prior to 1917 and the lowering of the lake was the bottom of the lake. Prior to the 1930's this was the mouth of Matthews Creek and was straightened and channelized which provides a straight fetch from Lake Washington.

Matthews Creek (4444) flows through the constructed pond in Matthews Beach Park and discharges into Thornton creek (44) below site 17 and upstream of the lake. Because of the high bacteria counts from the August 2011 sampling (AM = 9800 PM = 4750 cfu/100ml) an additional sampling site was placed above the pond (4444) from the September sampling onwards to determine if these high counts were due to the waterfowl observed in the pond on every visit or from loading higher in this sub basin. Comparing the *E.coli* counts at 44 with the upstream 4444 counts did not clarify this situation; upstream was higher in September 2011, and high in April 2012, but lower in July 2012. Observations in this watershed below where Thornton Creek flows through a pond suggested that bacteria removal by the pond outweighs the additional loadings from waterfowl use of the ponds (Herrera 2007). The April 2012 difference (AM = 24 PM = 1900 cfu/100ml) is very large and taken with the relatively high counts from the September 2011 samples indicates that there is a source of loading to Matthews Creek above the duck pond and the high counts at 44 in August 2011 may not have been solely attributable to waterfowl and this sub basin should be given a high priority for further source investigations.

South Fork Thornton Creek (18-26) and tributaries

The South Branch of Thornton Creek drains 2,332 acres in Seattle. This branch is also sometimes known as Maple Leaf Creek. Victory Creek, Willow Creek, and Kramer Creek are tributaries to this branch. Water begins its flow to the South Branch west of I-5 near the Evergreen-Washelli Cemetery, A storm drain along Meridian Ave N picks up groundwater and surface runoff, and discharges it to a ditch leading into a storm surge pond at the North Seattle Community College. Water exits the surge pond, then crosses under I-5 and is joined by a small tributary and runoff from I-5 and the Northgate shopping area in the constructed Thornton Creek Water Quality Channel. The creek flows northeasterly through Thornton Creek Parks #6 and #2, a group of park properties adjacent to the creek. Numerous storm drains feed into the creek, some of which flow year round. At 12th Ave NE, a small tributary called Victory Creek joins the South Branch. The South Branch flows southeast through a residential area with more storm drains discharging into the creek. The South Branch picks up water from Willow Creek, Kramer Creek and a

small creek restored near the Meadowbrook Community Center, before joining the North Branch at NE 107th St and 35th Ave NE.

Sub basins 18, 19

Sub basin 18 is the southern wooded portion of the Evergreen Washelli Cemetery and was the furthest upstream site in the South Fork Thornton Creek. The sampling site is immediately downstream of the cemetery fence north of Burke Ave N. This site is influenced by ground water seepage, and had extensive growths of orange iron bacteria and elevated conductivity (Figure 11), especially in April when soils were more saturated. Temperature, DO, pH and conductivity (figures 9-13) at this site was comparable to site 1 at the uppermost site of the mainstem which was also groundwater dominated. The unique pattern *E.coli* counts met criteria on August 2011 and April 2012, were slightly elevated in September 2011 and on July 2012 were very high (AM = 1600 PM = 2700 cfu/100ml; Table 2).

Site 18 was selected as the baseline uppermost site for the South Fork to establish upstream bacteria counts and other than the high July 2012 counts appears to fulfill this intent. Some of the conventional parameters that were synoptically sampled along with the bacteria had values that were unexpected in this watershed. Conductivity at site 18 had the highest values and largest range (452-163 μsiemen/cm) of any sampling site in the watershed and affected downstream conductivity in the South Fork all the way to the confluence an into the mainstem of Thornton Creek. The April 2012 conductivity was higher than nearly all other samples collected by nearly 50 percent. These samples are wet season rainy day samples when the component of groundwater and contributed conductivity would be expected to be at a minimum. Conversely, the September 2011 samples, which were the latest collected in the summer when groundwater would be expected to contribute the majority of flow at this location, had the lowest conductivity (Figure 11). Dissolved oxygen (Figure 10) was consistently lower than most sites, and would be consistent with groundwater making up much of the flow at this location. Additionally, pH (Figure 12) for almost all of the sampling events were the lowest values measured in the watershed and appears to influence the pH of the South Fork downstream, though not to the extent that the conductivity appears to.

The gardening waste maintenance area of the cemetery is immediately upstream of this site and encampments were observed in the forested area. The July 2012 *E.coli* counts are far above expected levels from the low level of activity expected in a cemetery in this headwaters basin. The conductivity of the Seattle water supply (~65 μsiemens/cm) is lower than all of the values seen in Thornton Creek, and perhaps the water quality at site 18 is influenced by irrigation practices in the cemetery, although no data on these activities were collected as part of this study.

Site 19 is the inflow to the detention pond on the North Seattle Community College campus just west of I-5. This site was selected to represent the main channel of the South Fork of Thornton Creek, but more recent GPS mapping of the drainage shows the flow entering the pond at the north end, not at the middle where samples were collected. Water at site 19 drains the parking lot and North Seattle Community College campus and does not represent an intermediate flow between the headwaters of the South Fork at site 18 and the next downstream site 20 on the east side of I-5.

E.coli counts at site 19 were <200 cfu/100ml August 2011 and April 2012 from 330- 800 cfu/100ml (Table 2) and only represent the local drainage and not an intermediate sample along the South Fork of Thornton Creek. Site 19 had greater AM - PM differences in temperature and temperature maxima than at any other site in the South Fork on each sampling date except for the coolest samples from April 2012 (Figure 9). The September 2011 AM temperature was 14.7^{o}C and PM 17.5 ^{o}C and the AM - PM differences were not seen at other sites. This temperature change is from the campus drainage into the pond and not Thornton Creek. Dissolved oxygen concentrations (Figure 10) tended to be lower in the AM samples and pH higher (Figure 12).

Sub basins 20 (Thornton Creek Water Quality Channel), 20

Site 20 is in the Thornton Creek Water Quality Channel (TCWQC). *E.coli* counts met criteria and decreased from upstream every date except for September 2012 (AM 850 PM 695 cfu/100ml), which were also the only samples above the ODEQ *E.coli* criteria. The elevated counts sampled at this site in

September persisted downstream to the confluence with the mainstem. This site has a frequent blue-gray discolorization of the water, which when tested did not have elevated bacteria counts. The cause of the color change has not been determined but is not sewage. The April 2012 temperature increased AM and PM from ~10.4^{o}C to 12.2^{o}C, while not a large change it was a change from the coolest to warmest temperatures in the South Fork (Figure 9). The temperature change indicates that warmer water is entering the drainage system and because no other sites had similar AM - PM differences this heat input appears to be from a local artificial source and not a basin-wide weather related change.

Sub basin 21, 22, 29 (Victory Creek)

Site 21 is in the undeveloped Seattle Park 6 immediately downstream of the TCWQC. This site met criteria every sampling date except September 2011, which was apparently caused by the high upstream *E.coli* counts (Figure 8). Sub basin 21 did not have substantial inputs of bacteria.

Victory Creek (27) enters the South Fork of Thornton Creek between sites 21 and 22. Site 22 is located just upstream of the 15th Ave NE bridge. Victory Creek, joins the South Branch between Parks #2 and #6 near NE 108th St, one and a half blocks east of Roosevelt Way NE. Victory Creek drains a 197-acre area, which includes many commercial businesses, apartments, and single family homes.

Between sites 21 and 22 in August 2011 *E.coli* counts increased from very low counts at 21 (AM = 14 PM = 15 cfu/100ml) to well over criteria at site 22 (AM = 1200 PM = 1130 cfu/100 ml). This increase appeared to be due to the high counts from Victory Creek on this date (AM = 4500 PM = 2800 cfu/100ml). August 2011 was the only sampling of Victory Creek that were >160 cfu/100ml which is over the ODEQ criteria, but not by much (Table 2). The April samples at sites 21, 22 and 27 were all below criteria (Table 2). The high August 2011 bacteria counts were apparently an episodic event that was not detected during any of the other sampling events.

Sub basin 22 is a mix of single family residences, multifamily residences and commercial land use. Some of the residences are below the grade of the sewer and need to pump their sanitary discharge up-gradient into the sewer (Starsted, pers comm.) There is also a beaver pond on the mainstem of Thornton Creek above the confluence with Victory Creek. The highest *E.coli* counts in the South Fork of Thornton Creek were sampled at site 22 (>6000 cfu/100ml) in July 2012. Immediately upstream *E.coli* counts at site 20 (AM = 14 PM = 15 cfu/100ml) were some of the lowest bacteria counts in the entire watershed. The *E.coli* counts at site 22 were reported as >6000 cfu/100ml and were as high as quantifiable with the single dilution used with this study. *E.coli* counts from Victory Creek on the same day were low (AM = 160 PM = 160 cfu/100ml) (Figure 8, Table 2). These high July 2012 counts persisted all the way downstream to the confluence of the South Fork with the mainstem and downstream to Lake Washington (figures 6 and 7). The actual *E.coli* counts could have been higher than the reported >6000, which was the maximum quantifiable number due to the single dilution used in the analytical procedure.

In August 2011 *E.coli* counts also increased abruptly between site 21 (AM = 14 PM = 15 cfu/100ml) and site 22 (AM = 1200 PM = 1130 cfu/100ml) (Table 2). Downstream of site 22 the *E.coli* counts resembled a pulsed plug flow, low at sites 23 and 24 and up again at sites 25 and 26. No substantial increase in this section of the South Fork occurred in April 2012.

There appears to be a large and periodic input of bacteria in this sub basin. If the beaver pond was the source of the bacteria, the high counts should be consistently high not periodically high. Another potential source of the high bacteria is the transient encampments that are located in this undeveloped park. This study has not substantiated that encampments are a source of bacteria to Thornton Creek.

Site 21 and 22 are the first site in the South Fork where DO concentrations approached saturation (Figure 10). Conductivity at site 22 was a noticeably higher in April 2012 AM, and did not resemble either the upstream or downstream sites. The AM - PM difference at this site was the largest sampled in the study. The data appears to be valid, but none of the other conventional parameters exhibited this response. No explanation for this data point currently comes to mind.

Sub Basin 23, 24, 25, 26, 28 (Willow Creek), 29 (Kramer Creek), 40 (Meadowbrook Creek)

Site 23 is located at the planned SPU Knickerbockers riparian reconnection project site and is upstream of Lake City Way. Site 24 is immediately downstream of Lake City Way in a constructed artificial boulder fish ladder. Blue-white suds were observed in Thornton Creek immediately below Lake City Way after every rainfall event, and no suds were observed upstream at site 23 during the same sampling event. Benthic invertebrate sampling at site 24 conducted to evaluate New Zealand Mudsnail distribution collected no benthic invertebrates, while at the site immediately upstream (23) was the location of the only stonefly collected in Thornton Creek, and while circumstantial may indicate a localized problem at this site.

The change in bacteria counts downstream of Lake City Way was not as extreme in the South Fork as it was in the mainstem (figures 6 and 7). *E.coli* counts increased between sites 23 and 24 and the July 2012 samples remained at the maximum quantifiable level along with the rest of the stream, but all counts remained above 500 cfu/100ml except during April 2012 (AM 17 PM 67 cfu/100ml; Table 2).

Willow Creek (28) and its tributary drain 396 acres, including a portion of Lake City Way and Ravenna Ave, many single family homes, a few businesses, and several schools. Willow Creek joins the South Branch, just downstream of site 24. Willow Creek met the ODEQ *E.coli* criteria in July 2012 the same day the adjacent South Fork counts were >6000. During each of the other sampling events Willow Creek exceeded *E.coli* criteria. There appears to be a persistent bacteria source in sub basin 28 that should be prioritized for further investigation.

Site 25 just west of Nathan Hale High School had bacteria counts influenced by the upstream sites. Little definitive can be discerned about local bacteria sources along this stretch of the stream from the existing dataset due to the confounding high upstream bacteria counts flowing downstream. Comparing the bacteria counts at site 25 and Kramer Creek (site 29) shows influence of upstream sources of bacteria sources. These sites were only 10 m apart and sampled within five minutes of each other, but the bacteria counts were frequently orders of magnitude different.

Kramer Creek (29) drains 69 acres, which include a section of Lake City Way and nearby homes. This tributary flows year-round. A ditch one to two foot deep along 30th Ave NE is interrupted by driveway culverts. The substrate of the open channels is composed of fine sediment and sand. *E.coli* counts in Kramer were typically low except during September 2011 (AM = 3500 PM = 330 cfu/100ml). The water in Kramer Creek during all of the sampling events was very clear with no sign of discoloration or turbidity. This small stream in summer was assumed to be primarily a groundwater stream with no obvious surface inflows. The high September 2011 *E.coli* counts presumably originated in this sub basin, and based on the low counts in the other samples at this site appeared to be an isolated event.

The conductivity in Kramer Creek is lower than most of the upstream portion of the South Fork. This is curious particularly in September 2011 when groundwater would be expected to make up most if not all of the flow and conductivity was low compared to the rest of the stream readings (AM 93 PM 101 μsiemens/cm; Figure 11) and comparable to Lake Washington conductivity. If the source of the high *E.coli* sampled on the same day were sewage, conductivity would be expected to increase and DO (Figure 10) would be expected to decrease, which was not observed.

Meadowbrook Creek (40) is a restored stream located at the bottom of a hill just west of the Meadowbrook Community Center. This creek flows through a series of constructed small ponds and wetlands before it discharges into the South Fork just below site 26. This small tributary and met the ODEQ *E.coli* criteria on every sampling event and had the lowest geometric mean *E.coli* in the South Fork portion of the watershed.

Sub basin 26 is primarily Nathan Hale High School and site 26 is located just upstream of the culvert under 35th Ave NE. Similar to site 25 bacteria counts at site 26 appear to be influenced by high bacteria counts from the upstream sites and until the upstream sources are removed, little definitive can be discerned along this stretch of the stream from the existing dataset. The South Fork of Thornton Creek enters the mainstem at this point and a restoration work referred to as the 'Confluence Project' is planned for the area.

Matthews Swimming Beach (near site 45)

The *E.coli* loading in sub basin 22 in the middle portion of the South Fork on July 10, 2012 resulted in counts >6000 cfu/100ml sampled all the way downstream to just above Lake Washington (site 17). This bacteria load apparently did not move north into Lake Washington (45) during the sampling period on July 10, 2012 (*E.coli* counts AM 91 PM 68 cfu/100ml) or to the Matthew Beach swimming area. The fecal coliform count at the beach on July 9, 2012 was only 43 cfu/100ml and the next week on July 16, 2012 13 cfu/100ml (http://green.kingcounty.gov/swimbeach/). During the summer flows are negligible at the mouth of Thornton Creek and wind from the lake can push lake water into the creek channel. While infrequent, summer storm events can increase flow into the lake and result in higher bacteria counts both north and south of the mouth of the stream (Herrera 2007; King County 2013).

The high counts of bacteria sampled in Thornton Creek during this study did not result in high bacteria counts at Matthew Beach when sampled by King County. Herrera (2007) suggest that Thornton Creek is a major source of bacteria to the area south of the mouth but may not be to the north where the swimming area is located. Distribution of bacteria near the mouth of Thornton Creek and Matthews Beach is variable and influenced by recent wind directions. In the past, the high bacteria counts that resulted in closing the beach occurred synoptically with high counts in Thornton Creek (http://green.kingcounty.gov/swimbeach/matthews-closure.aspx . Every time high bacteria count samples were collected at the beach, bacteria counts in the creek were high as well, but bacteria counts at the beach are not high every time counts in the creek are high and the wind does not blow the same direction all the time.

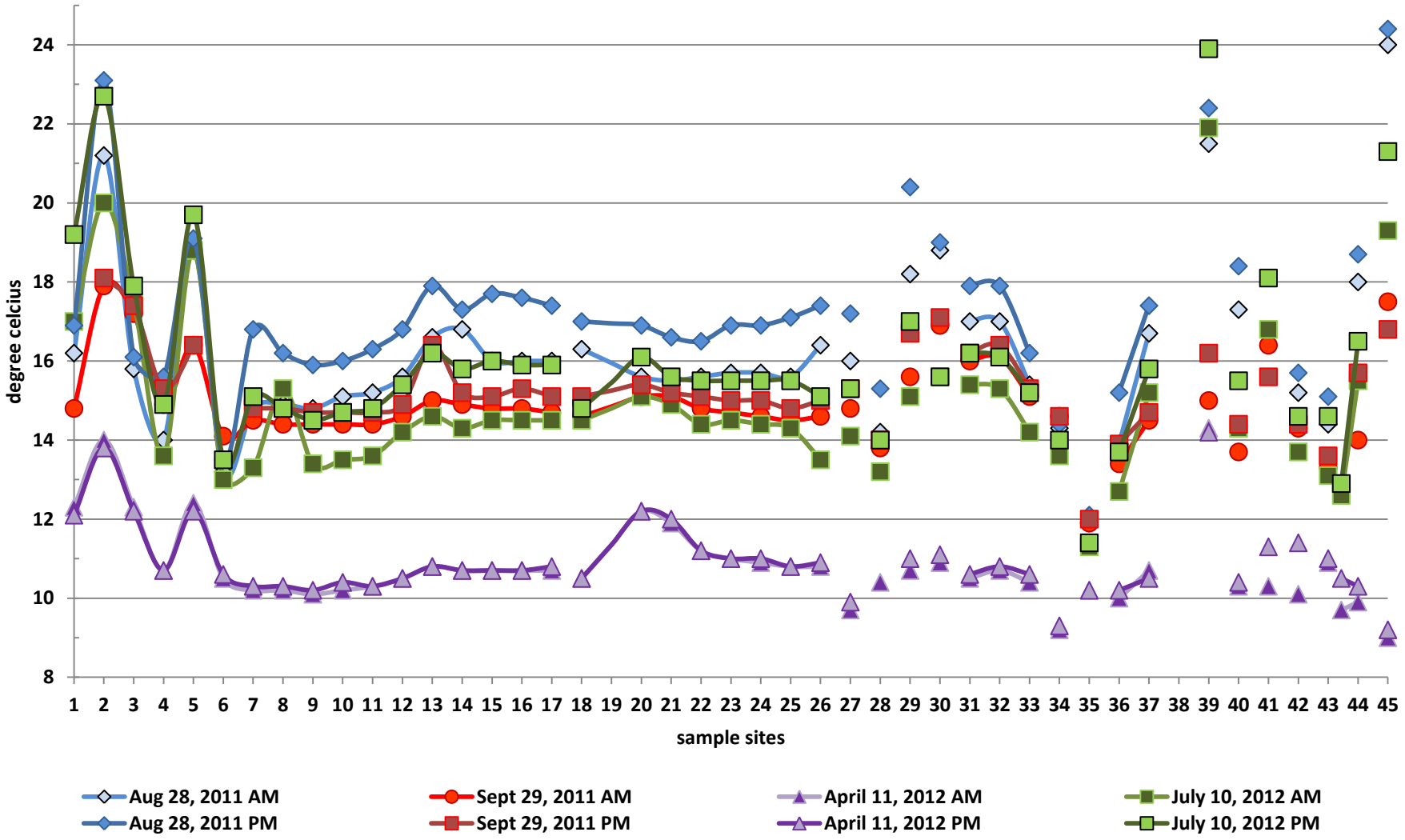


Figure 9. Morning (AM) and afternoon (PM) temperature (^{o}C) in Thornton Ck mainstem (1-17),south fork (18-26), Victory Ck (27), Willow Ck (28), Kramer Ck (29), Hamlin Ck (30), Littlebrook Ck (31-33), Evergreen Ck (34), I-5 ditch (35), Littles Ck (36-37), Meadowbrook Pond (39), Mock Ck (40), Trib E (41), 39th Ave(42), Maple Ck (43), Matthews Ck (44), and Lake Washington (45).

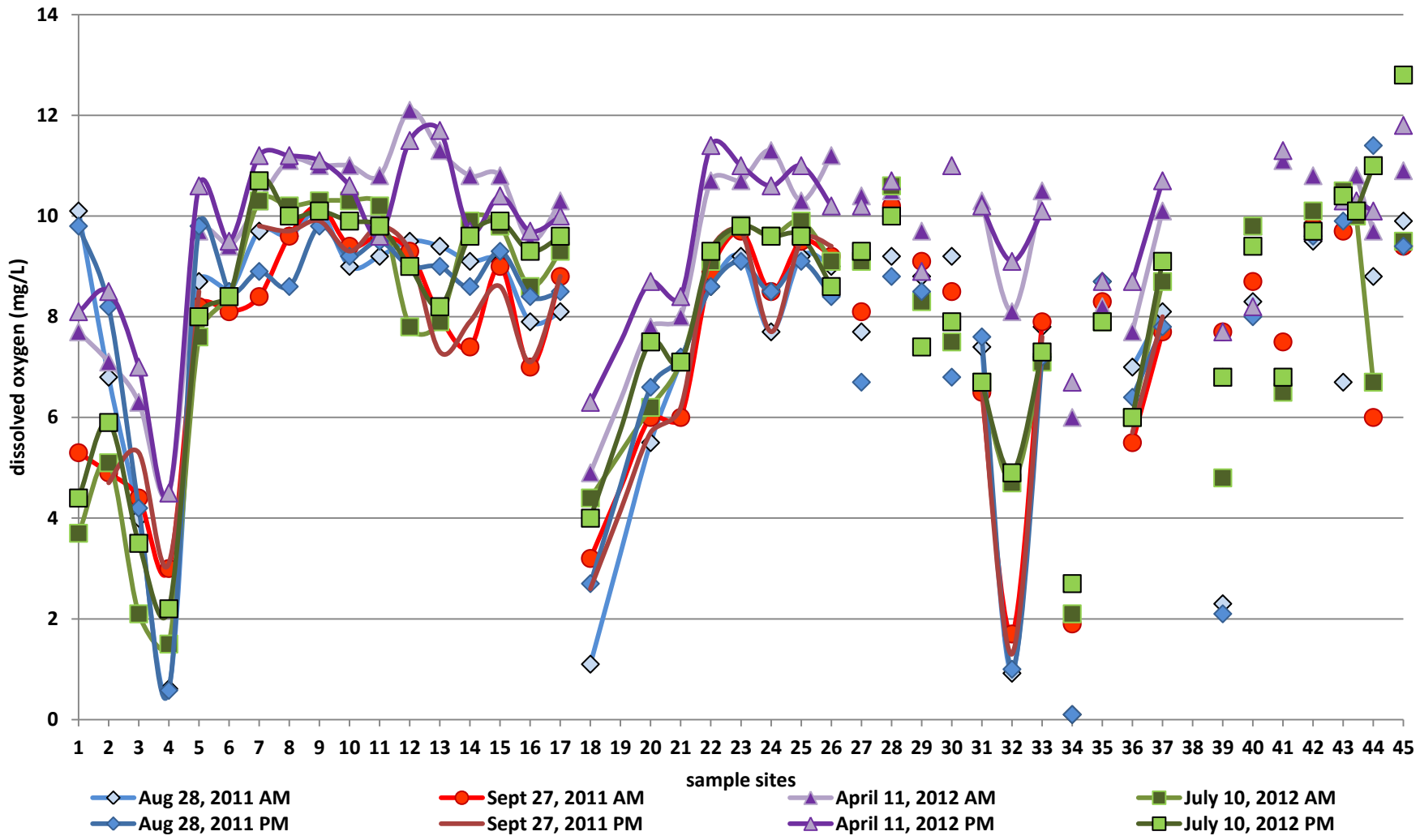


Figure 10. Morning (AM) and afternoon (PM) dissolved oxygen (mg/L) in Thornton Ck mainstem (1-17),South Fork (18-26), Victory Ck (27), Willow Ck (28), Kramer Ck (29), Hamlin Ck (30), Littlebrook Ck (31-33), Evergreen Ck (34), I-5 ditch (35), Littles Ck (36-37), Meadowbrook Pond (39), Mock Ck (40), Trib E (41), 39th Ave(42), Maple Ck (43), Matthews Ck (44), and Lake Washington (45).

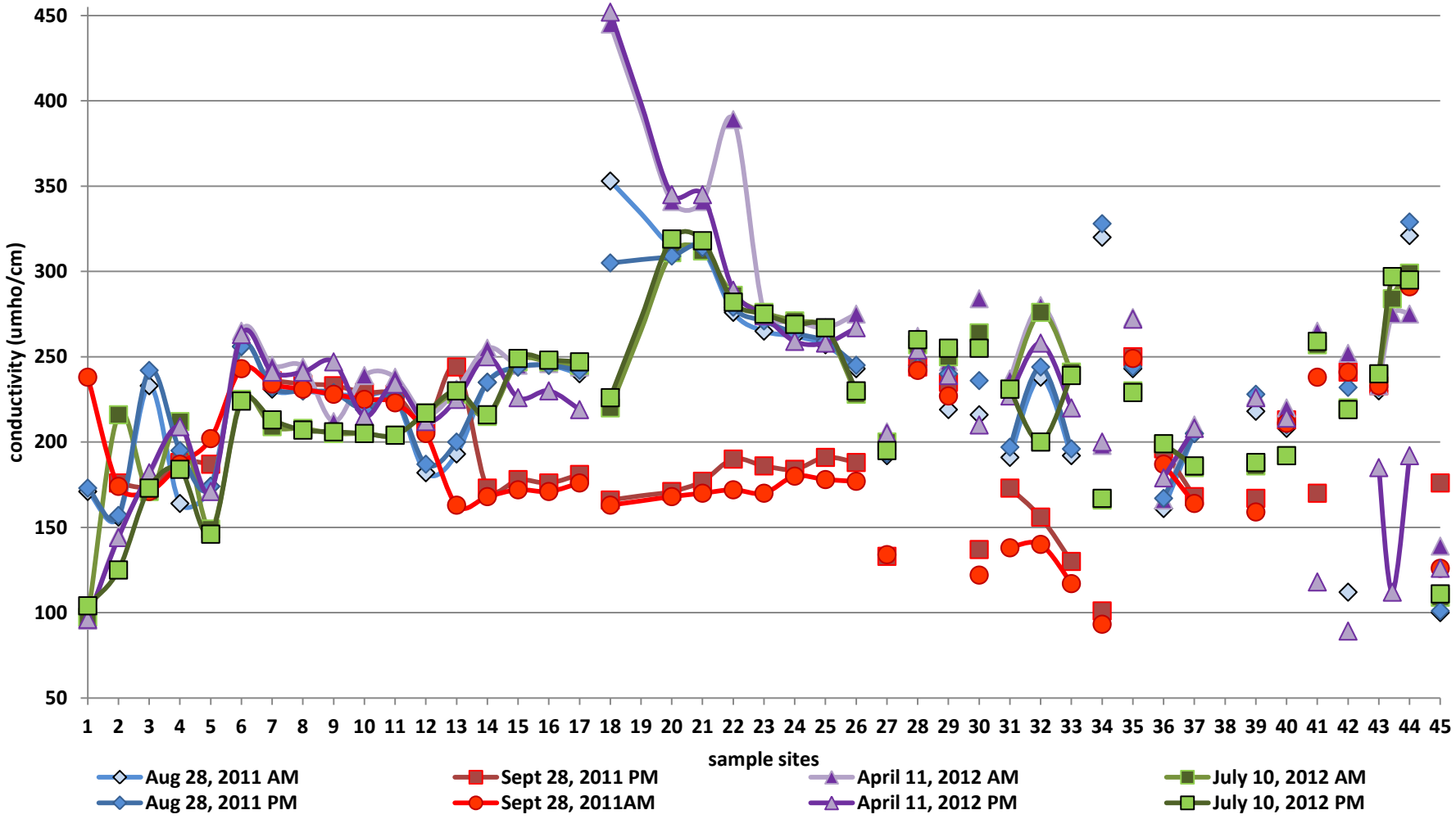


Figure 11. Morning (AM) and afternoon (PM) conductivity (μmho/cm) in Thornton Ck mainstem (1-17),south fork (18-26), Victory Ck (27), Willow Ck (28), Kramer Ck (29), Hamlin Ck (30), Littlebrook Ck (31-33), Evergreen Ck (34), I-5 ditch (35), Littles Ck (36-37), Meadowbrook Pond (39), Mock Ck (40), Trib E (41), 39th Ave(42), Maple Ck (43), Matthews Ck (44), and Lake Washington (45). The decrease at site 13 is downstream of the confluence of the South Fork (18-26) and the low conductivity from that branch of Thornton Creek in September 2011.

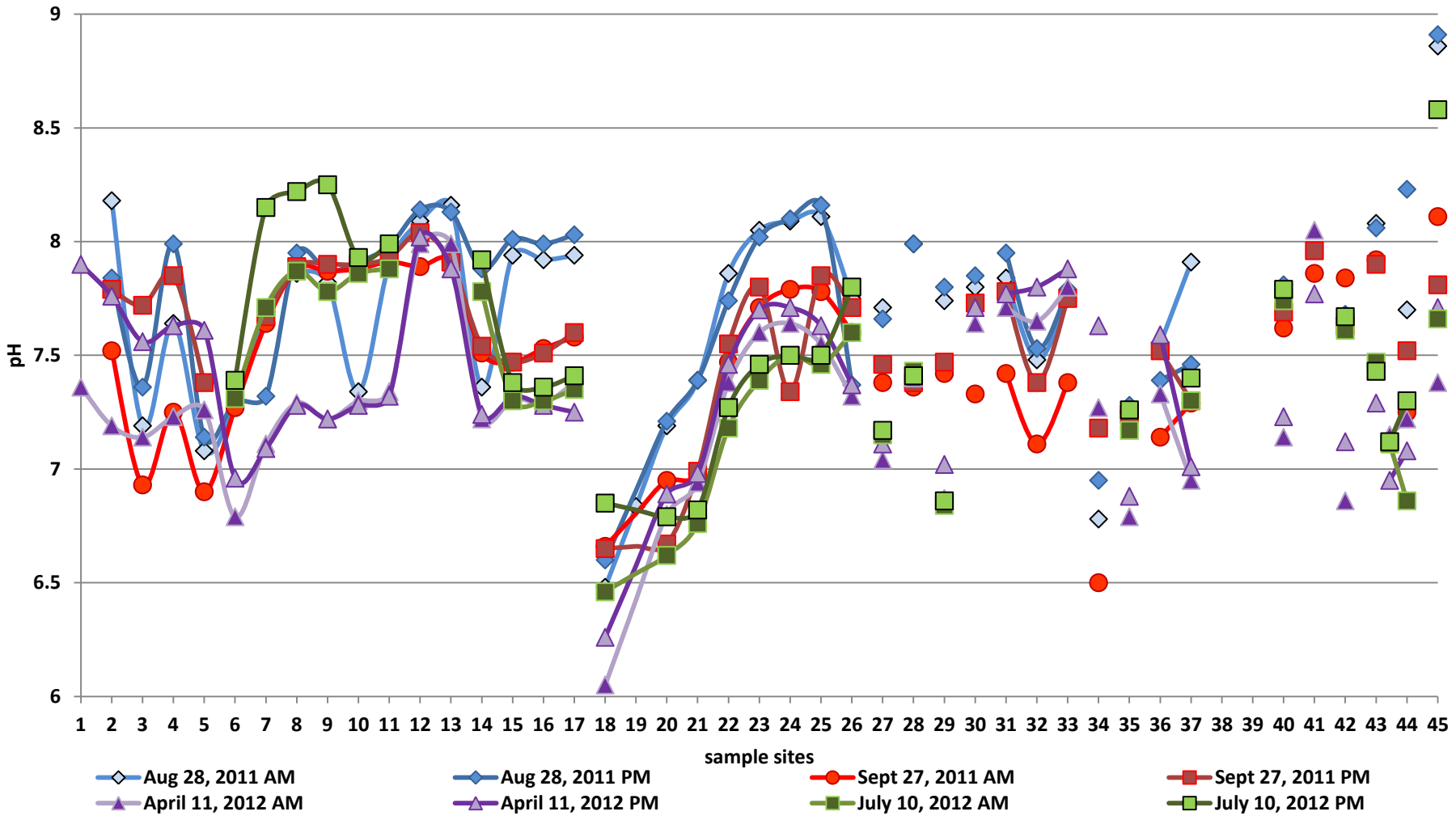


Figure 12. Morning (AM) and afternoon (PM) pH in Thornton Ck mainstem (1-17),south fork (18-26), Victory Ck (27), Willow Ck (28), Kramer Ck (29), Hamlin Ck (30), Littlebrook Ck (31-33), Evergreen Ck (34), I-5 ditch (35), Littles Ck (36-37), Meadowbrook Pond (39), Mock Ck (40), Trib E (41), 39th Ave(42), Maple Ck (43), Matthews Ck (44), and Lake Washington (45).

Precipitation Patterns Influence on Bacteria in Thornton Creek

Between July 23 and October 11, 2012 there was only .03 inches of rain at the Seattle Tacoma International Airport, the driest two-and-a-half-month period in Seattle in 90 years. This extended dry period provided an opportunity to collect an additional partial set of bacteria samples to compare with the rest of the data set and test the 'seasonal first flush' in Thornton Creek. Samples were collected on October 11, 2012 between 1400-1545h during the early part of the first rain event after the extended dry period (Figure 13). Unfortunately, no data were collected immediately before the rain event. Counts collected during the event can only be compared to bacteria counts from the other sampling events. Due to logistical constraints no synoptic conventional data was collected.

Prior to the October 2012 sampling, April 11, 2012 was the only other wet season data collected during this study. Compared to the other sampling events, bacteria counts from April were some of the lowest of any of the sampling events in this study (figures 6 and 7). The *E.coli* counts from the October 14, 2012 storm event increased in the upper portion of the mainstem and the subset of tributaries sampled (figures 13 and 14). In the lower section of the mainstem downstream of the confluence with the South Fork, the October *E.coli* counts were intermediate between the April AM and PM *E.coli* counts (figures 13 and 14) and appeared to be influenced by upstream flows. Site 4 just upstream of Twin Ponds was an exception with October *E.coli* counts of 3600 cfu/100ml an order of magnitude higher than the April 2012 samples (AM 340 PM 260 cfu/100ml; *Bacteroides* 1406 cells/100ml) and comparable to the highest counts sampled at this location.

The rain effect on bacteria counts appeared to be higher in the smaller tributaries and was at least an order of magnitude higher than the April 2012 bacteria counts at these locations. Littles Creek *E.coli* counts at site 36 (3600 cfu/100ml) and 37 (7200 cfu/100ml) had the highest counts sampled in this small stream. *Bacteroides* data indicates that these high *E.coli* counts probably had a human component (2025 and 788 cell/100ml). The downstream *E.coli* counts were twice the high upstream counts and this section of stream flows through a short stretch of single family residences north of N 145th St and then through the Jackson Golf Course where it then runs through a short section of multi-family residences. There are no obvious natural sources that would explain these high counts in this section of stream apparently mobilized during this rain event.

A comparison of two small sub basins, Tributary E (site 41, 25.3 acres) and Meadowbrook Creek (site 40, 14.2 acres), were sampled within ten minutes of each other and had very different bacteria counts. Meadowbrook Creek which drains the wooded hillside and baseball diamonds behind the Meadowbrook Community Center had low *E.coli* (160 cfu/100ml) and fecal coliform (70 cfu/100ml) that nearly met the bacteria criteria. Just downstream Trib E drains approximately five blocks of fully sewered single family residential and had *E.coli* counts of 4100 cfu/100ml, fecal coliform counts of 5500 cfu/100ml and *Bacteroides* counts of 697 cells/100ml. These two sub basins are approximately the same size but have different landcover. The large differences in bacteria counts in the in these two basin looks like a 'seasonal first flush' phenomena in the developed basin (41) and not in Meadowbrook Creek (40) that is in open space. The *Bacteroides* of 697 cells/100ml indicates a probable human source component.

Matthews Creek (site 44, 76.7 acres) drains the most southeast portion of the Thornton Creek watershed and discharges into the stream below site 17 near Lake Washington. This was the last site sampled during the October 14, 2012 storm, so this stream experienced a longer period of rain than any of the other sites sampled. The *E.coli* count (4200 cfu/100ml) was only exceeded by the lower Littles Creek site. The fecal coliform count was 1900 cfu/100ml, and *Bacteroides* was 1772 cells/100ml. The *E.coli* count should not be greater than the fecal coliform counts from the same sample and the discrepancy gives another indication of the sampling error associated with the single grab design of this study. Even considering the error, the high bacteria counts and large *Bacteroides* result indicate that there is probable human source contribution in the storm flow at this site.

In the mainstem of the South Fork sites 22 (*E.coli* 620, fecal coliform 840 cfu/100ml) and 23 (*E.coli* 450, fecal coliform 480 cfu/100ml) had relatively small increases in bacteria. While these bacteria counts are well above criteria they were some of the lowest counts from any of the sites sampled during the rain event. This is in contrast to the July dry weather sampling when site 22 had the highest increase in bacteria which was observed all the way to Lake Washington (Figure 8). These relatively low counts, if counts of over 400 cfu/100ml are to be considered 'low, increased nearly five-fold at the next downstream site 24, which is immediately downstream of Lake City Way.

The large increase in bacteria counts between the upstream site 23 and this site on October 14, 2012 (*E.coli* 450, fecal coliform 480 cfu/100ml) and further downstream site 24 (*E.coli* 2500, fecal coliform 2000 cfu/100ml) coincides with drainage off of Lake City Way entering the stream. Site 24 had significant soap suds that were not present immediately upstream. Sampling occurred during the early part of the rain storm (Figure 13) and site 24 drained a sub basin with more commercial landuse along Lake City Way and impervious surfaces than the sub basins upstream. More impervious basins would respond more quickly to a rain event.

Other studies observed similar responses to what was observed in Thornton Creek. A rainfall simulation study conducted along roads in Brisbane, Australia (Barry et al. 2004) indicated the presence of a seasonal first flush in small basins. The Australia Department of Environment and Conservation has since stated that first flush is "most readily observed on small catchments or individual premises, particularly if a high proportion of the catchment is impervious Tucker (2007), found what was termed a "high inconsistency" in the occurrence of first flush. Taebi and Droste (2004), observed a relatively weak first flush for some parameters, no correlation for some, and an increase in the first-flush load of TSS when the intensity and duration of a storm event increases. Hathaway and Hunt (2011) investigated the first flush effect for indicator bacteria and TSS in stormwater runoff. Analyses suggested there was a significant first flush effect for fecal coliform and TSS, although the first flush effect for fecal coliform was relatively weak. For *E.coli* and enterococci, no significant first flush effect was noted. Overall, the first flush effect was not always present for indicator bacteria and, if present, tended to be weak. They posited that stormwater runoff presents a potential public health hazard due to elevated indicator bacteria levels for all portions of the storm event.

The bacterial indicators in the October samples in this Thornton Creek were well above criteria and the *Bacterioides* data indicates a probable human source to the high counts. The levels of bacteria collected during this storm event show a response in the small tributary streams, and the response was far less in the mainstem of the stream. The basinwide bacteria counts during this first rainfall event after 49 days without rain was only slightly elevated over the April 2012 wet weather sampling event and lower than counts in the dry weather sampling. Other than the previously mentioned response in the smaller sub basins there was no substantial first flush phenomenon in Thornton Creek on October 14, 2012.

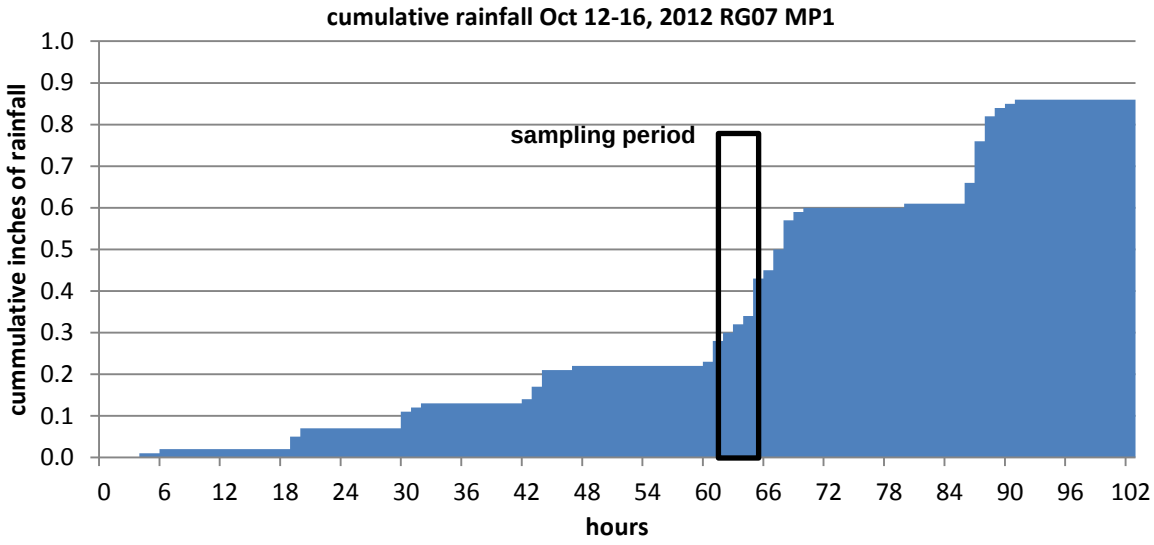


Figure 13. Cumulative rainfall in northeast Seattle from October 12-16, 2012. Bacteria samples were collected between 1400-1745h on October 14, 2012 as indicated as sampling period.

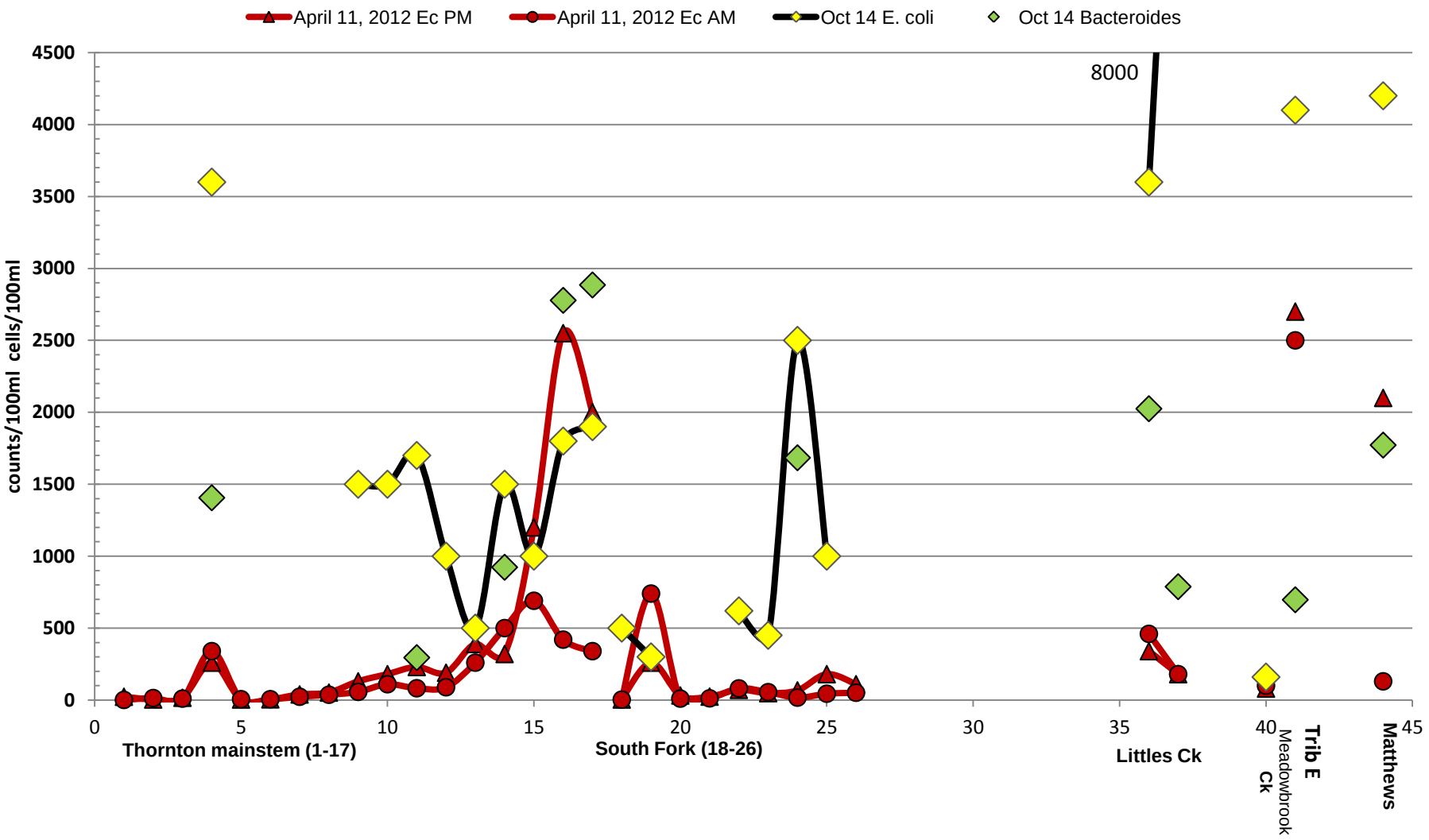


Figure 14. *E.coli* and Bacteroides collected on October 14, 2012 during the first rain event in 49 days. At the mainstem sites *E.coli* counts were typically higher at the same sites than in the April 2012 sampling. In the smaller tributary sites the October counts were much higher than the April 2012 samples.

Table 3. Bacteria samples collected between 1400-1745h on October 14, 2012 during the first rain event after 49 consecutive days without rainfall.

October 14, 2012 first rainfall event in 41 days			
sample site	***E.coli* (cfu/100ml)**	**fecal coliform (cfu/100ml)**	***Bacteroides* (cells/100ml)**
4	3600	3500	1406
10	1500	785	
11	1700	860	295
12	1000	770	
13	500	730	
14	1500	2100	923
15	1000	2100	
16	1800	2300	2778
17	1750	3100	2885
18	500	740	
19	300	410	
22	620	840	
23	450	480	
24	2500	2000	1684
25	1000	870	
36	3600	3300	2025
37	7200	5500	788
40	160	70	
41	4100	5500	697
44	4200	1900	1772

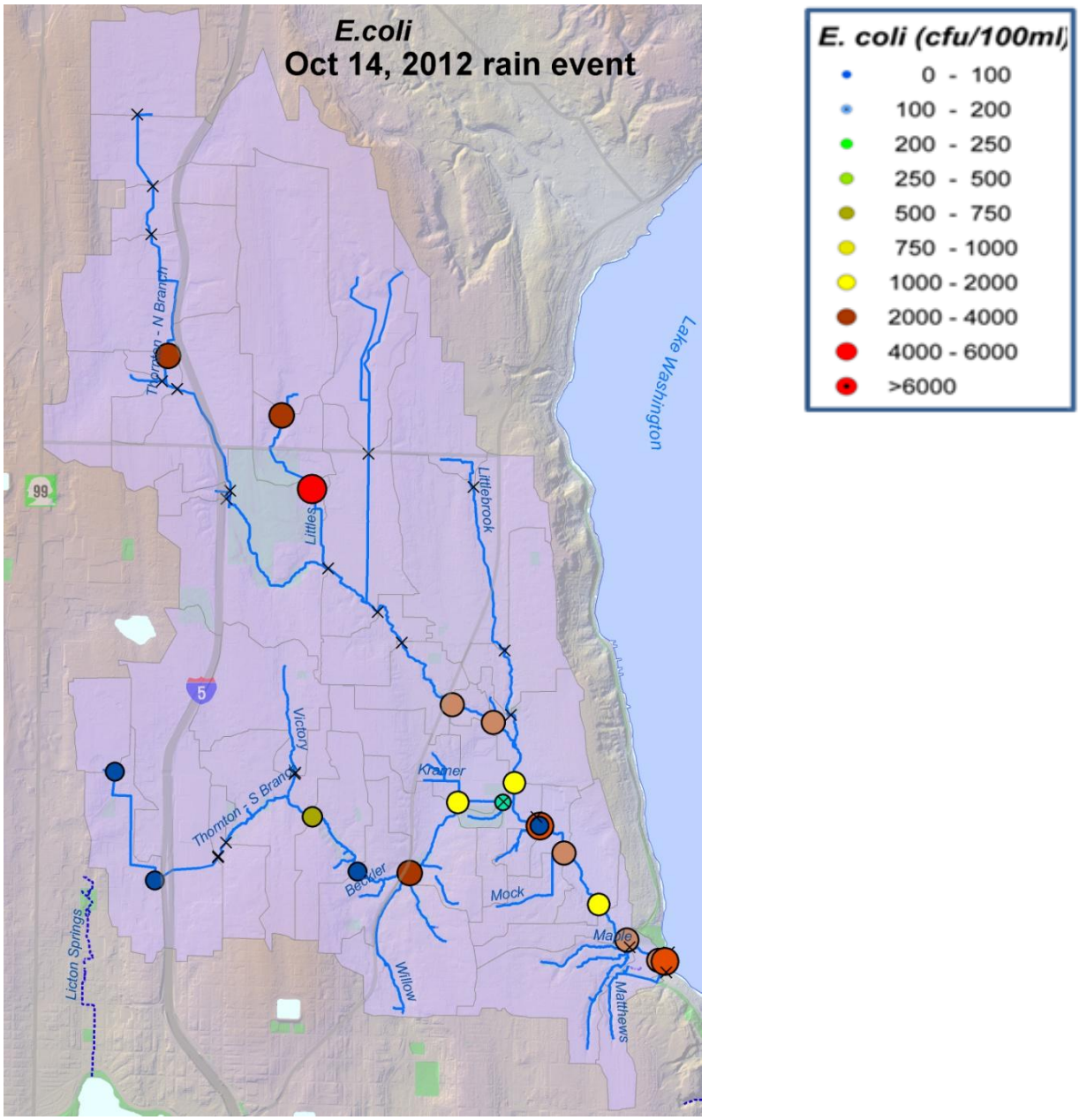


Figure 15. *E.coli* bacteria counts collected on October 14, 2012 between 1400-1745h during first rain event in 49 days. Site where no samples were collected signified with 'X'.

Comparing AM and PM sampling

People tend to follow daily patterns and these patterns are often observed in changes in sanitary sewer flows. The closest example of sanitary flow patterns (Figure 16) is from an adjacent sanitary basin NUB025-025. The diel pattern of regular changes in the sanitary flows is obvious. To differentiate potential sanitary contributions from general background non-point sources of bacteria, one of the analyses used is comparison of the difference between morning (AM) and afternoon (PM) bacteria counts (figures 16 and 17; Table 4) based on the assumption that if sanitary flows impact the creek they would potentially result in noticible differences in the bacteria data collected at different times of the day at the same location and if non-point sources were the primary sources of bacteria less of a diel pattern would occur.

Paired data of AM and PM *E.coli* counts at each site were ranked by PM samples for all three sampling events which provides a graphic representation of the differences. Ranking by AM sites would give the same results. The assumption was that bacteria from a non-point source would be diffuse and potentially have relatively lower overall counts (~≤ geometric mean) and there would be little difference between the AM and PM bacteria counts. Non-point or natural bacteria sources are not likely to follow a schedule and will be less likely to closely follow a pattern associated with time of day. By sampling twice in one day (8 AM - noon and 1PM - 5PM) the probability of detecting an episodic source of bacteria is doubled.

The AM - PM differences in the paired samples for a sampling event help identify episodic sources over the minimum four hours between the AM and PM sampling runs. A large difference between AM and PM counts could result from diel differences in water usage and sanitary flows, and would potentially indicate an episodic bacteria source that may indicate a point source. If Both the AM and PM bacteria counts are high, the high bacteria counts could indicate a chronic problem such as leaking pipes or cross connections and because the bacteria counts were consistently high would be easier to detect. Non-point sources should not have large differences over the four hour sampling period.

The AM - PM differences alone are not assumed to be definitive indications of anthropogenic sources, but the differences are used as additional information in attempting to locate bacteria sources. Downstream flow of water and bacteria has obvious impacts on downstream bacteria counts and the most useful information is the furthest upstream large AM - PM differences observed on the different sampling events.

If the AM - PM bacteria count difference are indicative of anthropogenic sources these differences should be more pronounced in urban watersheds than rural or agriculturally influenced watersheds. Timm (unpublished King County data) implemented a similar AM - PM sampling design in more rural Boise Creek near Enumclaw, Washington and did not detect substantial AM - PM bacteria in that watershed. While he waited for the cows to come home, they apparently did not do so on a four hour schedule. Identifying morning bacteria 'spikes' was based on the paired bacteria counts ordered by AM bacteria counts (Figure 19) and using an approximate change of +/-100%.

The most definitive results from the AM - PM differences was during the July 2012 sampling. The large increases observed between sites 21 and 22 (Figure 19) that progressed all the way downstream to Lake Washington also had large and consistent increases at sequential downstream sites in the South Fork and in the mainstem sites downstream of the confluence with the South Fork. The large increase between the immediate upstream site (21) and site 22, the large AM - PM differences at the downstream sites and large *Bacteroides* cell counts (Table 4) all indicate a large input of bacteria with a high potential human fecal component that impacted the stream all the way to the lake.

The AM - PM differences in the April sampling were frequently larger in smaller tributary streams, similar to the results from samples collected during the October 2012 rain event sampling. The April 11, 2012 sampling was after two days of moderate rain when soils were relatively saturated. Hamlin Creek, Victory Creek, Willow Creek, Mock Creek, Littles Creek and Littlebrook Creek all had larger counts in the afternoon than morning sampling (Table 4). Lower Littles Creek had higher AM counts as did Matthews Creek, but the Matthews Creek site is below the pond at the mouth of the stream. Smaller sub basins with higher relative amounts of impervious surface seem to respond more quickly than the larger mainstem.

During the low flow dry weather sampling on September 27, 2011 nearly all of the AM samples were less than or about the same as the afternoon samples with the exceptions primarily in some of the smaller tributaries and at the Lake Washington site. The single high *E.coli* sample in Kramer Creek had a PM count 3170 higher than the AM sample. This large difference and that this date was the only date when the bacteria counts in this creek were high points to this being an episodic and non-natural input of bacteria to this stream. Similarly, Evergreen Creek in Shoreline had a similar pattern on the only date that this site had very high bacteria counts. No natural change in flow or weather would explain why these small streams had these large changes in bacteria counts between the AM and PM sampling.

On the same date, higher afternoon *E.coli* counts in Lake Washington (AM 680 PM 1100 cfu/100ml) were the highest of any of the Lake Washington samples. These samples were collected after the King County swimming beach monitoring program had concluded for the season, and were much higher than the highest 270 cfu/100ml fecal coliform collected at the beach during the entire summer of 2012. The beach samples were collected approximately 160 m north of where the lake sample was collected for this study. The nearly doubling of the bacteria count at the same location in approximately four hours close to the beach provides some information on the temporal error the individual grab monitoring of the swimming beach incorporates.

Not surprisingly during the dry weather sampling in August and September the smaller tributaries responded independently of each other. During the wet season sampling in April and October during the regional rain event several of the same tributaries respond in a similar way. Littlebrook Creek, Littles Creek, Maple Creek, and Matthews Creek had higher AM counts, while Kramer Creek and Evergreen Creek higher PM counts. The lack of an overall pattern implies local effects within the small sub-basins responsible for the high counts and large changes in bacteria counts. When evaluated along with the geographic distribution (figures 6 and 7) and *Bacteroides* cell counts (Table 2) inputs of human sources of bacteria are the most likely explanation for the high bacteria counts.

Sites that do not have bacteria pollution were also identified by very small or no AM - PM differences and reoccurring low bacteria counts. The upper mainstem of Thornton Creek above site 4, the drainage from I-5 near the Jackson Golf Course, Meadowbrook Pond and Meadowbrook Creek are sub basins that have good water quality as defined by bacteria counts.

The patterns of AM and PM differences (figures 17 and 18; Table 4) follow the patterns of *E.coli* from upstream to downstream (figures 6 and 7). Sites in the upper watershed had lower AM and PM counts and the differences between these low counts were not large and the sampling error introduced with the low statistical power of single grabs could constitute a majority of the differences. At sites lower in the stream where the accumulated loads of bacteria from upstream substantially contributed to the downstream bacteria counts, AM - PM differences were frequently large and both AM and PM counts high.

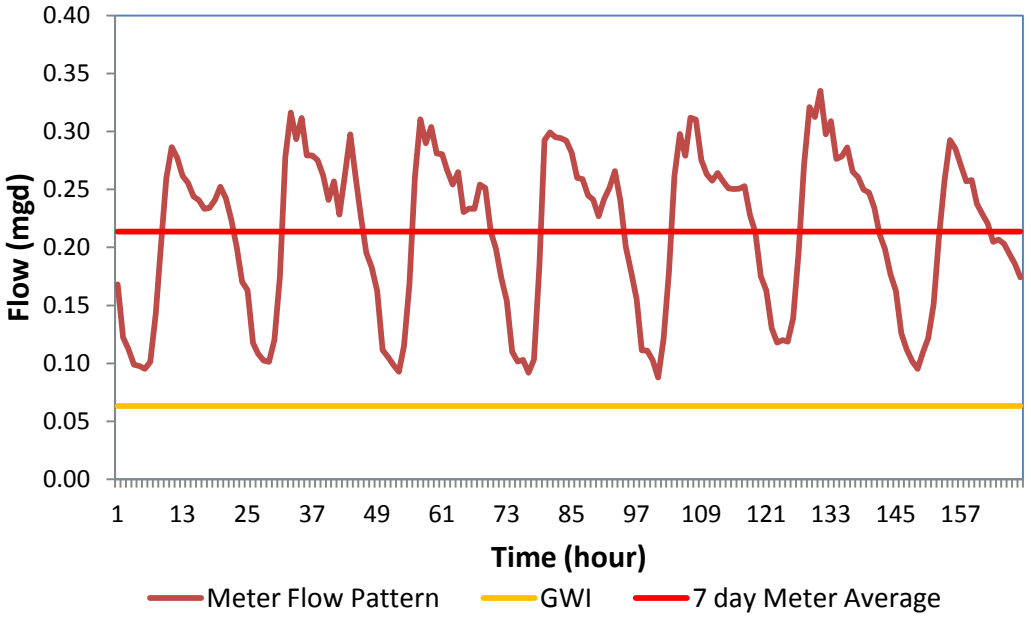


Figure 16. Annual weekly average metered sanitary flow in an adjacent basin just south of Thornton Creek, including estimated ground water inflows (GWI).

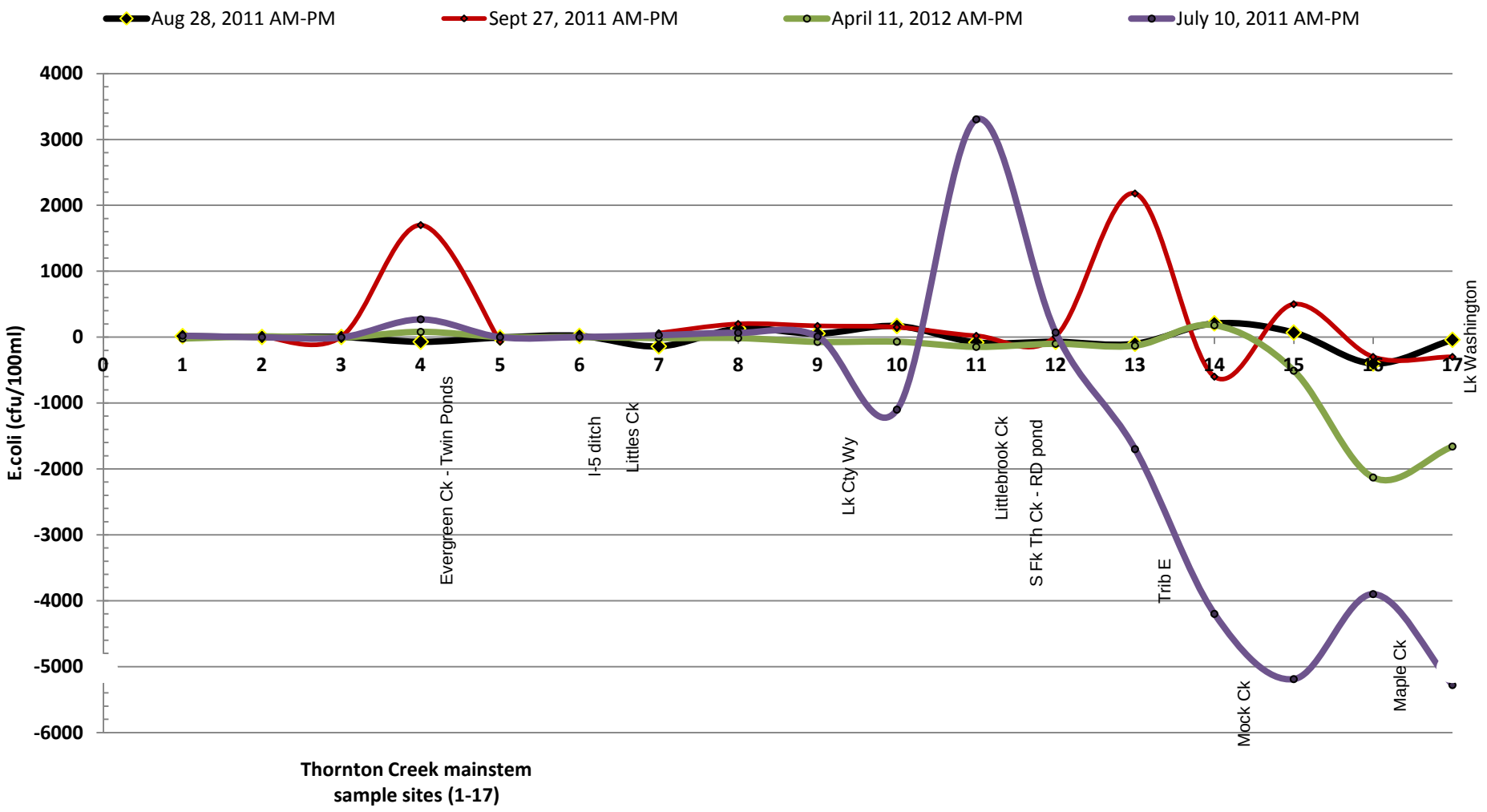


Figure 17. *E.coli* differences (AM counts minus PM) counts at the same sampling locations in Thornton Creek mainstem. The difference positive when AM counts > PM counts and differences are less than zero when PM counts > AM counts.

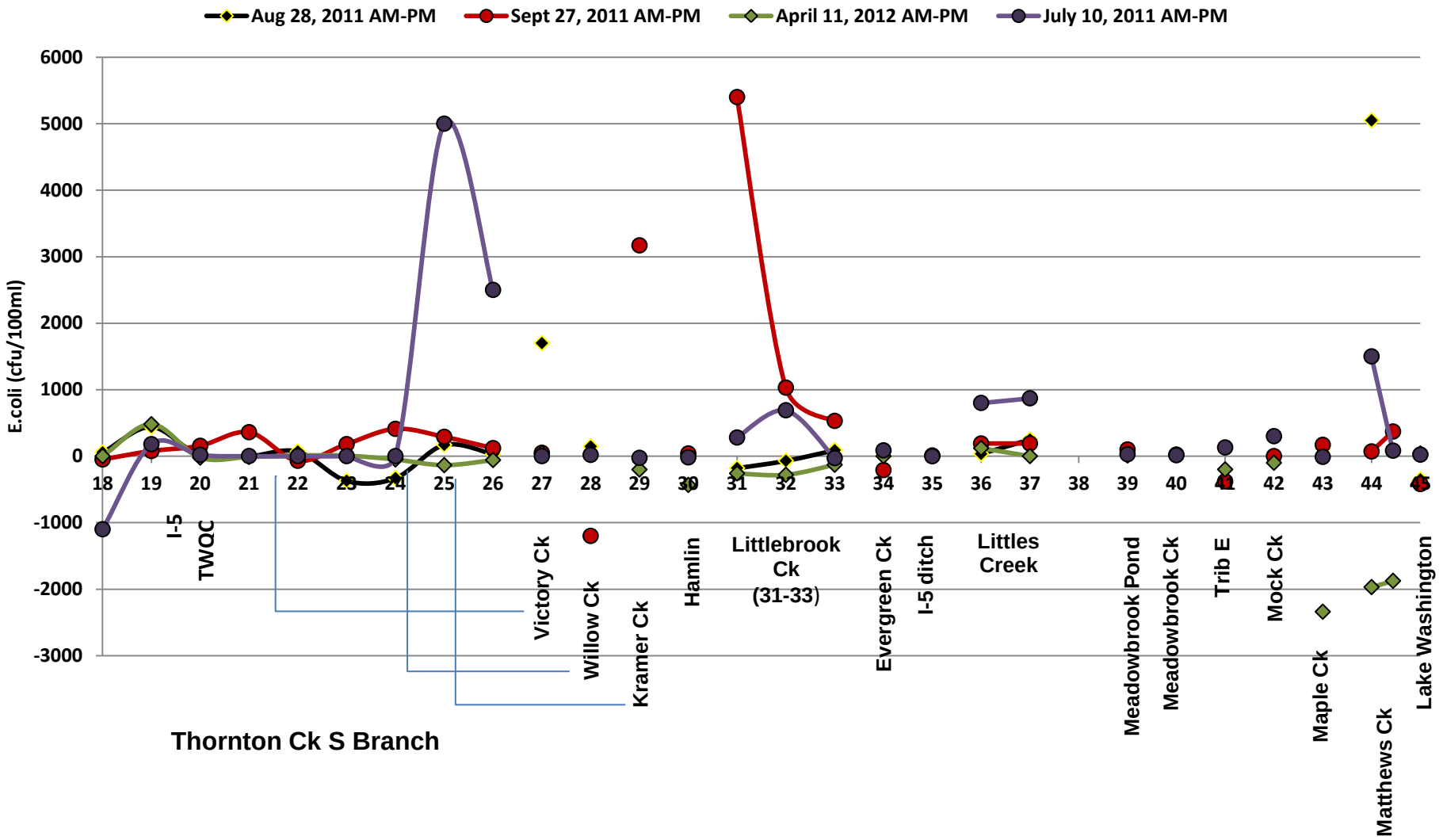


Figure 18. *E.coli* differences (AM counts minus PM) counts at the same sampling locations in Thornton Creek South Fork and tributaries. The difference positive when AM counts > PM counts and differences are less than zero when PM counts > AM counts.

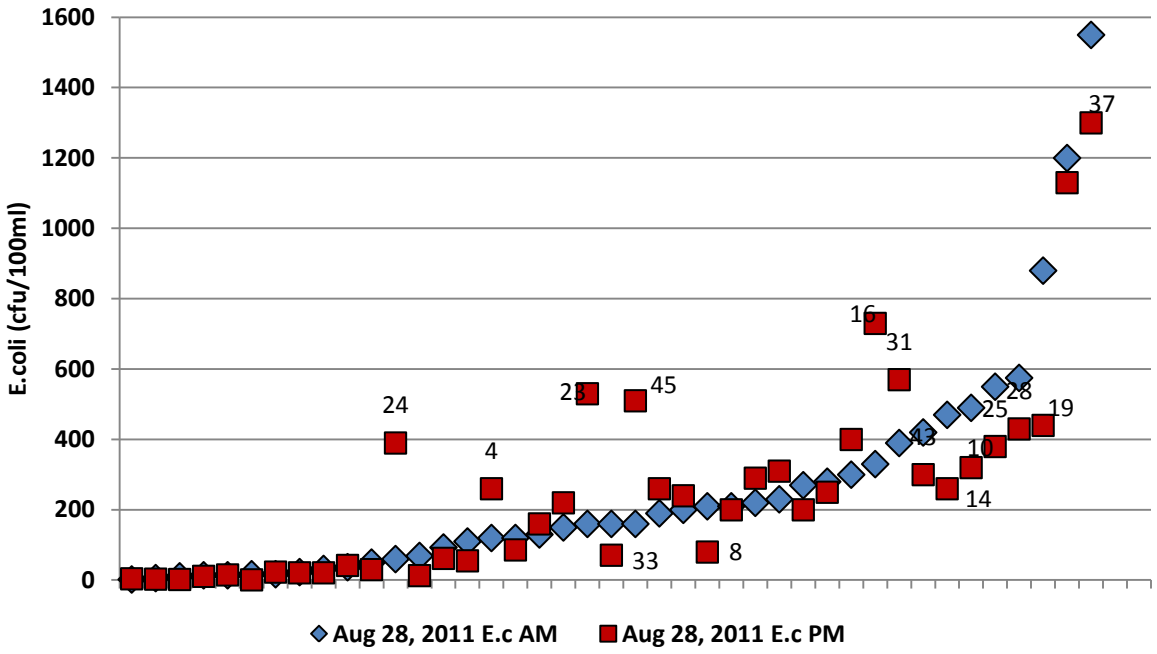


Figure 19(a)

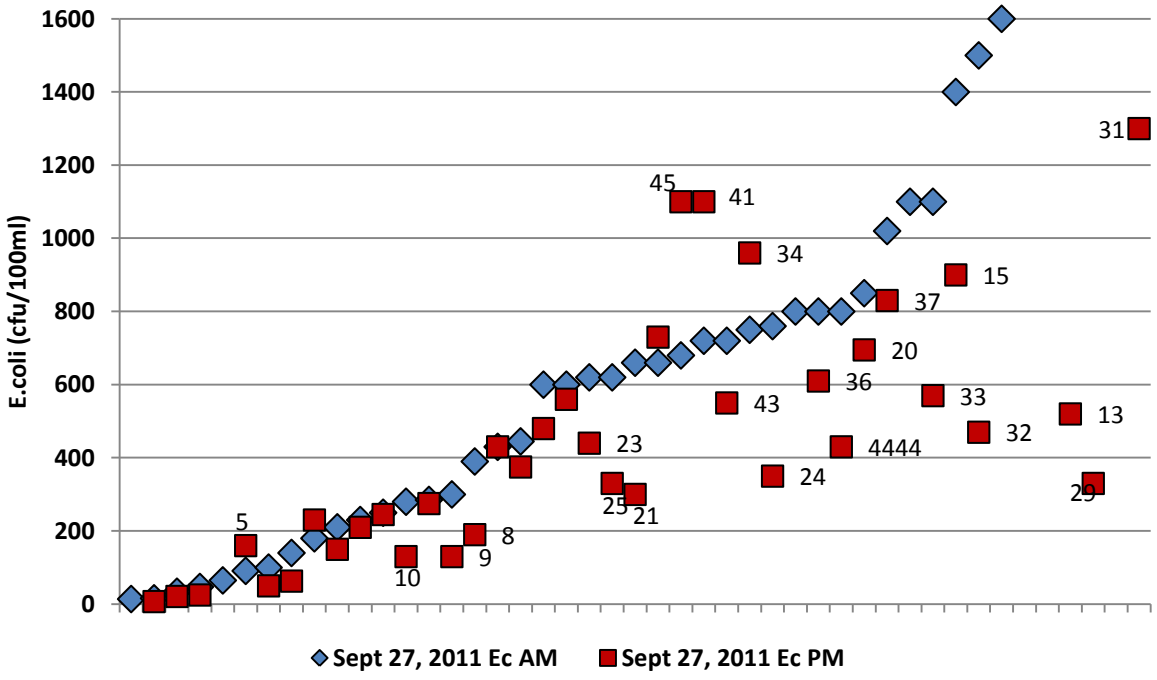


Figure 19(b)

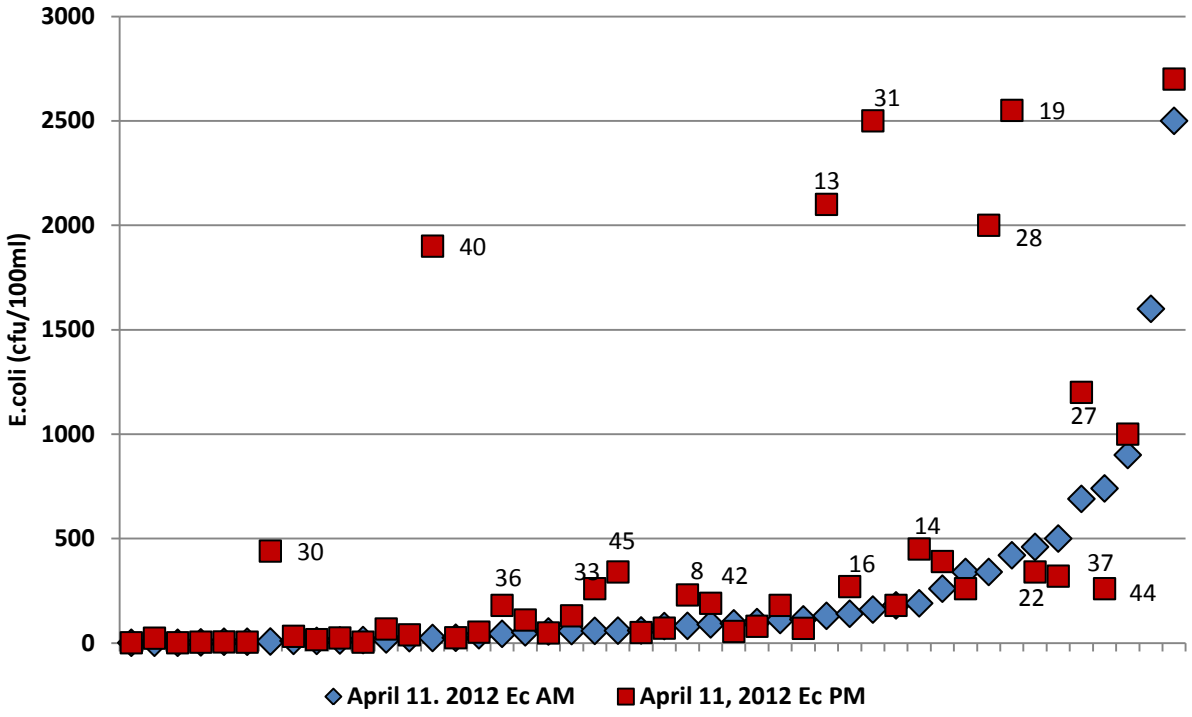


Figure 19(c)

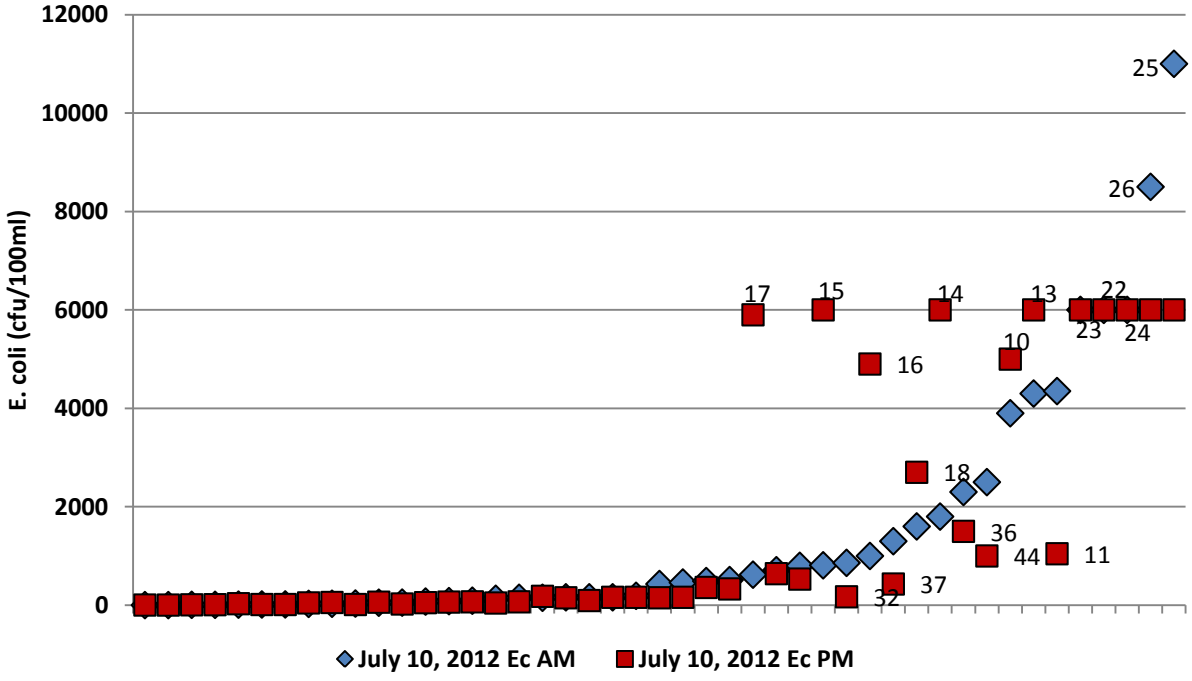


Figure 19(d)

Figure 19. *E.coli* counts (cfu/100 ml) for all samples ranked by AM samples to emphasize sampling sites with much higher AM bacteria counts, indicating morning episodic events. Several of the PM *E.coli* counts were reported as >6E3 (>6000) based on the dilution used in the analysis and these counts could have been higher.

Table 4. AM - PM *E.coli* differences at all Thornton Creek sampling sites. Differences highlighted in yellow were greater than 110% of AM counts.

site	28-Aug-11	27-Sep-11	11-Apr-12	10-Jul-12
Thornton mainstem (1-17)				
1	16		-22	22
2	3	13	10	-1
3	3	5	-6	-3
4	-70	1700	80	270
5	-5	-69	2	0
6	20		1	2
7	-140	60	-16	30
8	130	200	-15	66
9	55	170	-73	10
10	170	150	-70	-1100
11	-80	20	-148	3305
12	-70	10	-101	70
13	-100	2180	-130	-1700
14	210	-600	180	-4200
15	70	500	-510	-5190
16	-400	-300	-2130	-3900
17	-40	-300	-1660	-5280
South Fork Thornton (18-26)				
18	56	-50	-1	-1100
19	440	77	480	180
20	11	155	-22	20
21	-1	360	-12	1
22	70	-70	10	0
23	-370	180	7	0
24	-330	410	-50	0
25	170	290	-136	5000
26	30	120	-59	2500
Victory Creek				
27	1700	50	43	0
Willow Creek				
28	145	-1200		19
Kramer Creek				
29	-30	3170	-202	-26
Hamlin Creek				
30	-6	40	-433	-19
Littlebrook Creek				
31	-180	5400	-260	280
32	-70	1030	-281	690
33	89	530	-130	-30

site	28-Aug-11	27-Sep-11	11-Apr-12	10-Jul-12
Evergreen Creek				
34	2	-210	0	86
I-5 drainage				
35	-2	9	0	-2
Littles Creek				
36	34	190	120	800
37	250	190	0	870
Meadowbrook Pond				
39	9	100	10	28
Meadowbrook Creek				
40	31	22	20	-20
Trib E				
41		-380	-200	130
Meadowbrook Creek				
42	10	0	-100	300
Maple Creek				
43	120	170	-2340	-11
Matthews Creek				
4444	No data	370	-1876	82
44	5050	70	-1970	1500
Lake Washington				
45	-350	-420	39	23

Bacteroides

This study uses the *Bacteroides* results as a confirmational test for the presence or absence of human source bacteria in the stream. This method is a membrane filtration technique that is used in conjunction with a quantitative polymerase chain reaction (qPCR) technique to isolate and identify human-specific, *Bacteroides thetaiotaomicron*. The genus *Bacteroides* are gram negative, non-endospore-forming bacillus bacteria. *Bacteroides thetaiotaomicron* is an anaerobic organism that is common in human fecal material. *Bacteroides* comprise a significant component of human fecal material and therefore are an abundant target of human fecal contamination. Their presence in environmental waters can be an indication of recent human pollution due to their short survival time and inability to reproduce in the environment (King County 2013).

The method used to identify human-Bacteroides at the KCEL is *intended to provide supplemental information only; the data generated from this testing should not to be used for regulatory purposes or enforcement actions* (King County 2013*)*. This method is used to differentiate human vs. non-human fecal contributions in water matrices. The genus *Bacteroides* are gram negative, non-endospore-forming bacillus bacteria. *Bacteroides thetaiotaomicron* (species) is an anaerobic organism that is commonly found in human fecal material. *Bacteroides* comprise a significant component of human fecal material and therefore are an abundant target of human fecal contamination. Their presence in environmental waters can be an indication of recent human pollution due to their short survival time and inability to reproduce in the environment (King County 2013). The human-specific genetic marker enumerated with this procedure could not be detected in any of the other animal fecal samples (dogs, horses, cows, pigs) analyzed with the conventional PCR and real-time PCR assay. Survival of *Bacteroides* cells depends primarily on temperature and predation (Kreader, 1995), and these bacteria can survive for up to 6 days under oxygen stress condition (Avelar et al., 1998. Human-specific *Bacteroides* marker indicative of human fecal pollution will be detected up to this period after a discharge event (Avelar et al. 1998).

Bradley and colleagues (1998) monitored *Bacteroides fragilis*, total coliforms and thermotolerant coliforms in recreational waters and found no correlation between this *Bacteroides* species and the indicator organisms commonly used. How to coordinate and use the large amount of quantified fecal coliform and *E.coli* bacteria data with the more recent *Bacterioides* data now being collected has not been worked out. *Bacteroides* data in this study (Table 5) is used as an additional line of evidence for the potential contribution of human fecal material to the *E.coli* and fecal coliform bacteria data. This study also found no correlation between *E.coli* and *Bacteroides* (Figure 20). *Bacteroides* was detected in every sample selected for analysis. Cell counts of less than 400 are thought to be of potential secondary contamination and not directly from human feces, so counts >400 are considered more reliable for identifying recent human fecal contamination (King County, 2013), and counts of <1000 cell/100ml are used as a more conservative threshold (Bouchard and Abella, 2013 pers com.).

Every sample tested for *Bacteroides* tested positive (Table 5) even samples that had very low fecal coliform or *E.coli* bacteria counts although these samples with low *E.coli* and fecal coliform counts had some of the smallest *Bacteroides* cell counts of the samples analyzed. Many of the samples that had exceptionally high *E.coli* counts had high *Bacteroides* counts as well, but there was no correlation between *E.coli* and *Bacteroides*. How to reconcile the use of these various indicators in a quantitative manner when they are not correlated has not been worked out. All of the indicators are currently used to provide information on human health risk from bacteria in this waterbody. For this study the *Bacteroides* is considered as corroborative evidence of human source contribution to the high counts of both fecal coliform and *E.coli* frequently sampled in this stream.

The presence of human fecal bacteria in Thornton Creek based on the positive results of the *Bacteroides* tests are not fully in agreement with the conclusions in the Thornton Creek and Matthews Beach Microbial Source Tracking Study (Herrera 2007). In the 2007 study, human source isolates using ribotyping were present at low levels at every sampling site and their conclusions were human contributions were small (Herrera 2007) which is somewhat in agreement with the present study. The lack of attributed significant human sources in the Herrera (2007) study during winter storm flows suggested that sanitary or

combined sewer overflows were not a major source of fecal coliform bacteria during the sampled storm events (Herrera 2007). This is consistent with the low counts of *E.coli* sampled during the April 2012 sampling event which was not a storm sampling but was during higher flows and the local rainy season. There are no combined sewers in Thornton Creek and the SPU IDDE study did not locate significant inputs of bacteria via the storm drains, so if the data in this study is accurate there is a persistent and significant source of fecal bacteria in Thornton Creek that may not be associated with the storm drains. The current data from Thornton Creek indicates a high potential of frequent and multiple sources of human fecal bacteria enter this stream.

Table 5. *Bacteroides* samples with synoptically collected *E.coli* and fecal coliform counts (cfu/100ml). Positive *Bacteroides* samples associated with fecal coliform counts that do not exceed WAC173 201A secondary contact or *E.coli* counts that do not exceed the Oregon DEQ *E.coli* criteria of 126 cfu/100ml are highlighted in yellow.

August 28, 2011						
	AM			PM		
site	*E.coli* (cfu/100ml)	fecal coliform (cfu/100ml)	*Bacteroides* (cells/100ml)	*E.coli* (cfu/100ml)	fecal coliform (cfu/100ml)	*Bacteroides* (cells/100ml)
44	9800		14412	4750	2200	12538
37	1550	1500	11675	1300		12800
27	4500		2018	2800	1900	2822
28	575	480	836	430		
25	550		380	380		
22	1200		331	1130	630	553
1	17	1	130	1		
3	14		125	11	8	
19	880	140	28	440		
31	390			570	670	1179
23	160			530		997
8	210	60		80		595
9	110			55		448
16	330			730		332
September 27, 2011						
site	**AM**			**PM**		
29	***3500***		***64796***	***330***		
39	2300		1965	2200		4406
13	2700		1537	520		
17	1600	2000	1185	1900	800	679
15	1400		1152	900		
16	1800		999	2100		696
4	4800		746	3100		598
31	6700		713	1300		509
32	1500		474	470		
45	680			1100		1347
14	1100	1400		1700	780	1132
41	720			1100		810
28	800			2000		636
April 11, 2012						
site	**AM**			**PM**		
28	1600		1873	340	210	
14	500	320	694	320		
15	690	520	537	1200		23180
41	2500	1600	327	2700		389
4444	24	22		1900		435
43	160			2500		614
44	130			2100	1200	6610
17	340	260		2000		12610
16	420			2550		19780

cont.

July 10, 2012						
	AM			PM		
site	*E.coli* (cfu/100ml)	fecal coliform (cfu/100ml)	*Bacteroides* (cells/100ml)	*E.coli* (cfu/100ml)	fecal coliform (cfu/100ml)	*Bacteroides* (cells/100ml)
42	460	440	107330	160	110	8874
22	6000	6000	85880	6000		23309
23	6000		35720	6000		18240
24	6000		18550	6000	6000	12940
14	1800		13050	6000		2374
36	2300		3694	1500		2402
25	11000	7100	3531	6000		7126
40	8500		3531	6000		5285
44	2500	5200	1974	1000		
13	4300		1442	6000	12000	2153
18	1600		573	2700		294
11	4350	2050	543	1045	515	190
16	1000		432	4900		1448
10	3900		405	5000	2900	187

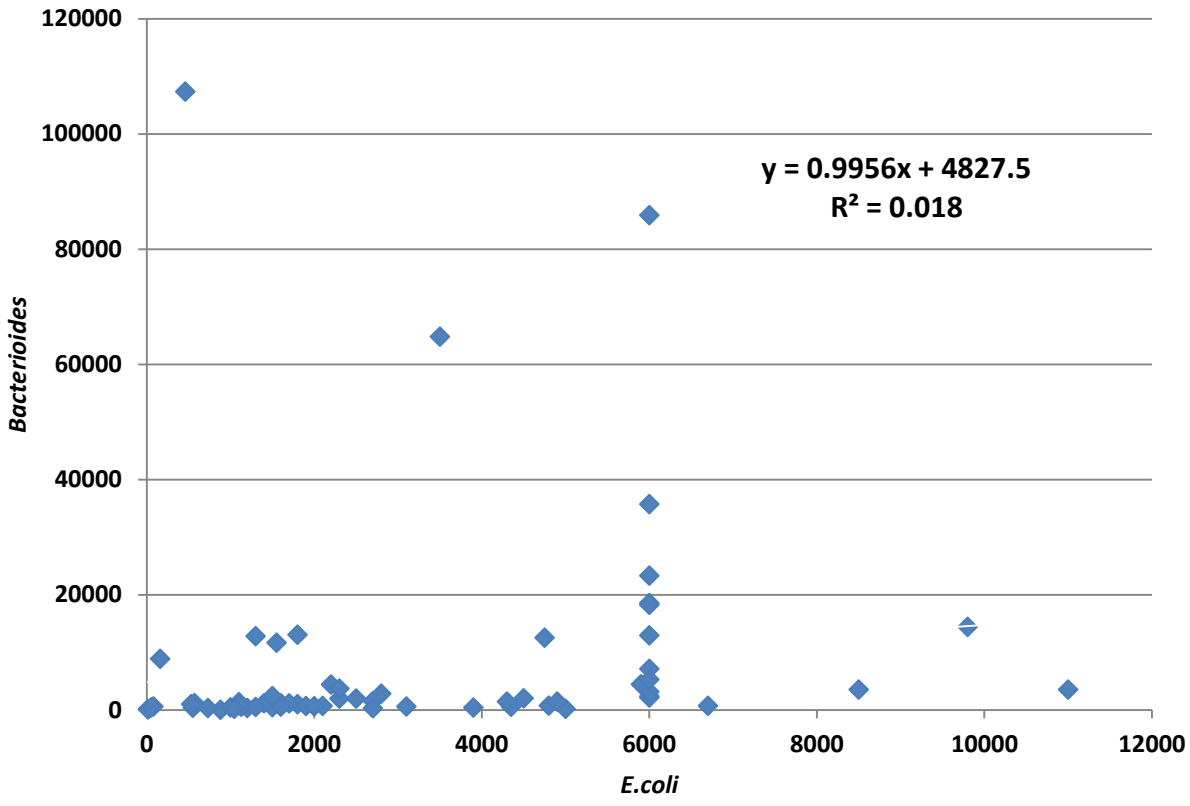


Figure 20. There was no correlation (r^2 = 0.018) between *E.coli* and Bacteroides from samples collected in this study.

Sub basin Prioritization for Local Source Investigation

Ranking sampling sites by *E.coli* counts for each sampling event provides a method to prioritize both sites that consistently had low bacteria counts and sites with consistently high counts that should have priority in receiving additional detailed source tracking. The sub basins with *E.coli* geometric means for all samples <ODEQ criteria are coded in green, sites with *E.coli* geometric means >126 and <500 are coded in yellow, and *E.coli* geometric means >500 in red (Table 5). The sub basins in red have the greatest impact from high *E.coli* bacteria whether the source of bacteria is in the basin or from sources upstream and would be listed as category 5-water quality limited on Ecology's 303(d) list.

High bacteria counts from upstream sources can degrade downstream water quality even in sections of stream that either have no additional inputs of bacteria or actually see a die-off of bacteria from upstream. To locate and control the source of bacteria it is necessary to account for the upstream bacteria contributions. *E.coli* counts from an upstream site were subtracted from the *E.coli* counts from the next sampling location immediately downstream. Positive values were defined as 'gaining reaches' where a source of bacteria entered the section of stream somewhere between the two adjacent sampling sites. Negative values indicated a decrease in bacteria in the section of stream between the adjacent sampling sites. Small differences are interpreted as the bacteria are just passing through.

On each sampling event the upstream minus downstream *E.coli* counts for both the AM and PM were assigned to the sub basin draining to the downstream sampling site (figures 20-23). A sub basin with large downstream minus upstream bacteria counts is most likely to have local sources of bacteria entering the stream reach between the two sample sites. Sub basins with large differences are prioritized for detailed source identification. This approach also provides the geographic distribution of sub basins that are not likely to be major contributors to the bacterial loading of Thornton Creek even if those sections of stream have high bacteria counts.

The identification of sub basins that had consistently low contributions of *E.coli* were the easiest to identify. The upper mainstem sub basins 1, 2 and 3 in Shoreline did not contribute much bacteria to Thornton Creek, with only a onetime small exceedance of *E.coli* ~250 cfu/100ml at site 3 in September 2011. Evergreen Creek (34) that drains to Twin Ponds only exceed criteria in September of 2011. The I-5 drainage (35) and Meadowbrook Creek (4) consistently had very low bacteria counts. Continued attention to water quality in these sub basins should protect the quality in these sections of stream.

The prioritization of sub basins suspected of having high bacteria sources (figures 20-23) was based on the sub basins where the bacteria source were suspected of originating. The sections of stream that exceed criteria due to upstream inputs, and not because of bacteria sources within the sub basin, were not prioritized for initial source identification work. Removing the upstream bacteria sources is assumed to be the most effective way to address high bacteria counts in the downstream sections of the stream (Table 5; figures 20-23).

To address the high bacteria counts in Thornton Creek, a relatively small number of sub basins should be initially looked at in more detail. These were best identified during the July 2012 dry weather sampling (Figure 24). Sub basin 22 between the Thornton creek Water Quality Channel and just upstream of the 15th Ave N Bridge (Figure 24) had the largest and most abrupt change in bacteria in the watershed. Sub basin 22 has very mixed land use including commercial, single family residences, multifamily residence and Seattle Park 6. Park 6 lacks sanitary facilities and is frequently used for unauthorized camping which is hypothesized as a potential *E.coli* source. *E.coli* counts during the April 2012 rainy season sampling were the lowest in this sub basin (Figure 23) and may be associated with seasonal usage patterns in this green space. Victory Creek (27) had high *E.coli* counts in September 2011, but relatively low counts during the rest of the sampling. Upstream site 23 had consistently low *E.coli* counts (Table 2).

Table 6. Summed ranks of *E.coli* counts at all sampling sites for all sampling dates except for the October 2012 rain event sample. Sites in green had geometric means the ODEQ criteria of <126 cfu/100ml, yellow >126 and <500, and red >500. Sites are not independent.

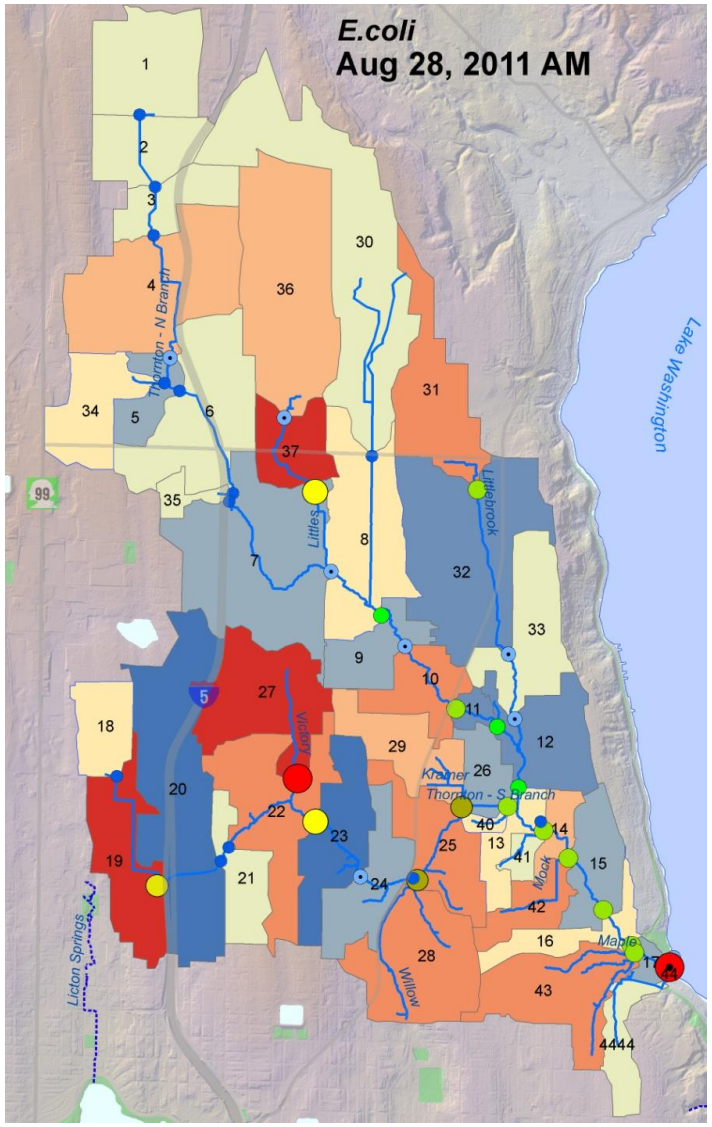
site	sum of ranks	average of ranks	sd	*E.coli* geometric mean	Sub basin priority
Thornton Creek mainstem (1-17)					
1	87	10.9	14.2	11.1	
2	27	3.4	2.8	5.9	
3	55	6.9	3.6	23.9	
4	259	32.4	8.0	638.3	1
5	50	6.3	3.6	20.1	
6	95	11.9	13.6	17.8	
7	127	15.9	6.6	113.1	
8	134	16.8	4.4	117.4	
9	132	16.5	5.0	119.6	
10[a]	212	26.5	11.9	465.5	1
11	202	25.3	10.1	362.1	
12	191	23.9	6.4	280.6	
13[b]	279	34.9	5.5	885.9	
14	281	35.1	4.7	890.3	
15	267	33.4	6.9	850.5	
16	301	37.6	4.0	1215.9	
17	265	33.1	7.5	881.0	
Thornton Creek South Fork (18-26)					
18	114	14.3	13.1	81.4	
19	211	26.4	13.5	320.2	
20[c]	116	14.5	10.6	52.1	
21	78	9.8	6.3	34.9	
22	263	32.9	10.2	778.7	1
23	214	26.8	11.5	465.3	
24	203	25.4	12.9	355.5	
25	234	29.3	12.3	621.8	1
26	223	27.9	10.9	516.4	
Victory Creek					
27	184	23.0	14.2	244.5	
Willow Creek					
28	262	32.8	11.9	441.5	2
Kramer Creek					
29	166	20.8	10.3	166.0	
Hamlin Creek					

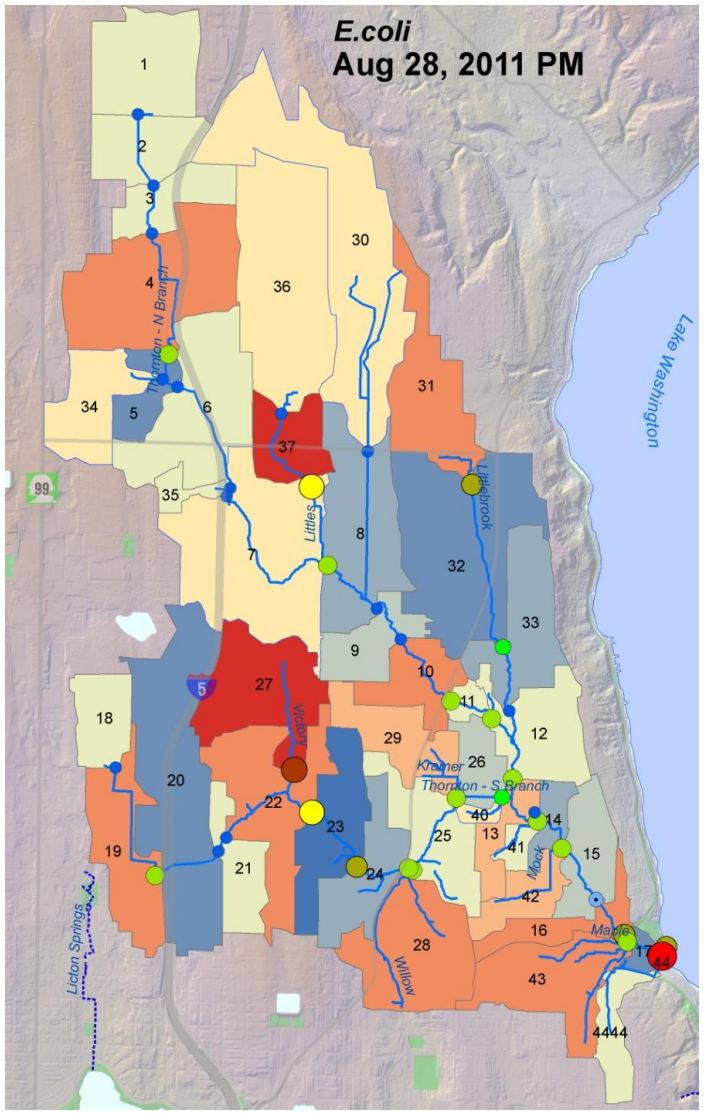
site	sum of ranks	average of ranks	sd	*E.coli* geometric mean	Sub basin priority
30	118	14.8	11.1	58.3	
Littlebrook Creek					
31	268	33.5	7.7	567.0	1
32	210	26.3	6.7	301.5	2
33	203	25.4	7.1	227.9	2
Evergreen Creek					
34	128	16.0	9.8	77.1	
I-5 drainage					
35	13	1.6	1.1	2.7	
Littles Creek					
36	235	29.4	8.3	477.8	2
37	267	33.4	5.7	647.5	1
Meadowbrook Pond					
39	143	17.9	15.9	67.2	
Meadowbrook Creek					
40	101	12.6	7.9	53.5	
Trib E					
41	205	34.2	8.8	990.3	2
Mock Creek					
42	206	25.8	9.4	370.8	2
Maple Creek					
43	214	26.8	10.0	297.2	
Matthews Creek					
44	263	32.9	10.1	1231.8	2
4444	141	23.5	9.9	233.0	2
Lake Washington					
45	191	23.9	8.3	192.3	

a-downstream of Lake City Way

b- lower mainstem below confluence with S Fork

c-Thornton Creek Water Quality Channel





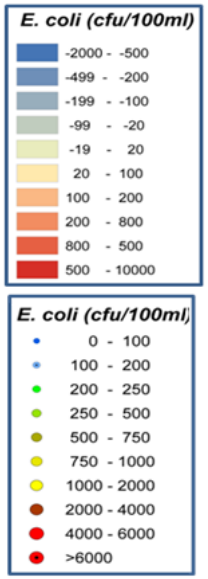
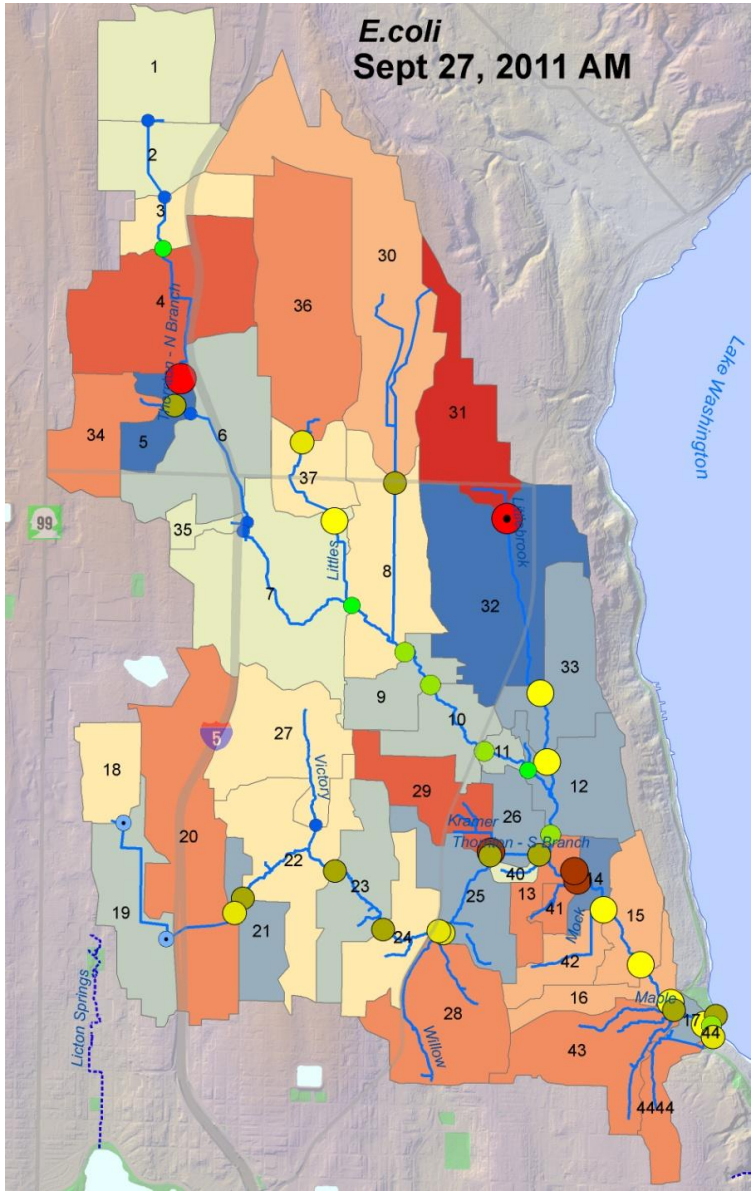
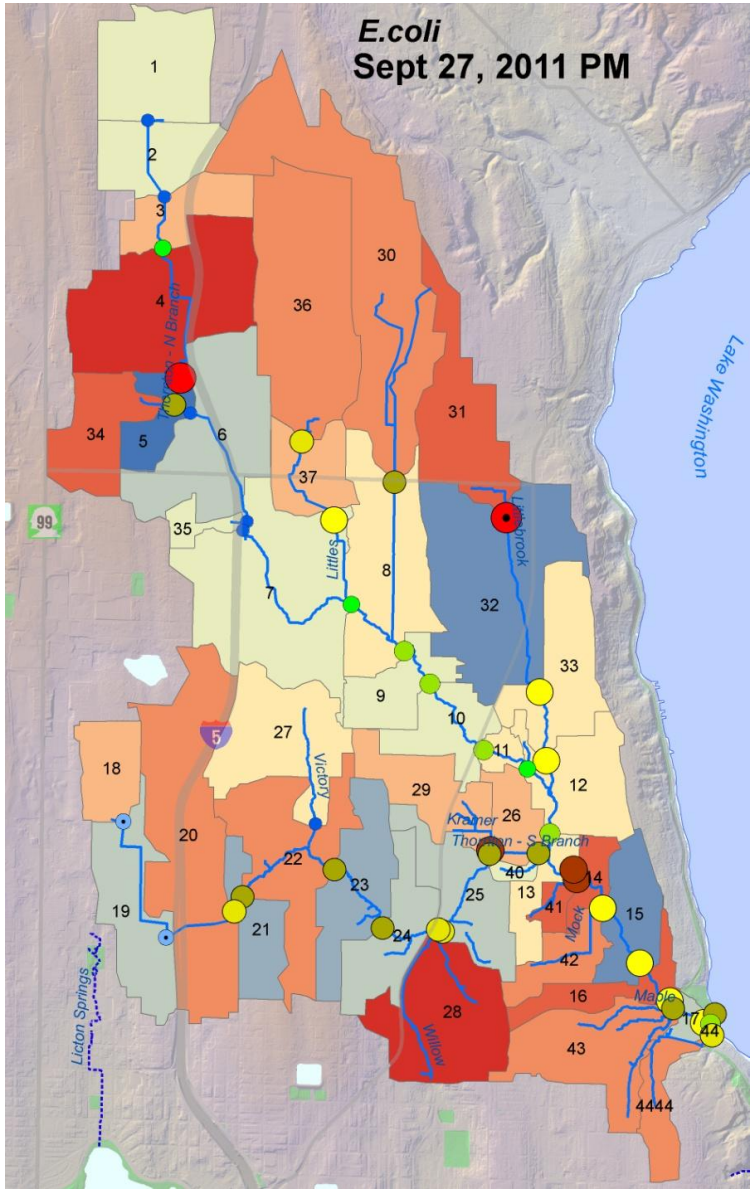


Figure 21. August 28, 2011 AM and PM E.coli counts at each sampling location. Sub basin polygons are colored according to *E.coli* differences calculated as downstream minus upstream from adjacent sampling locations. Darker red colors indicate sub basin suspected of contributing *E.coli* at the time of sampling.





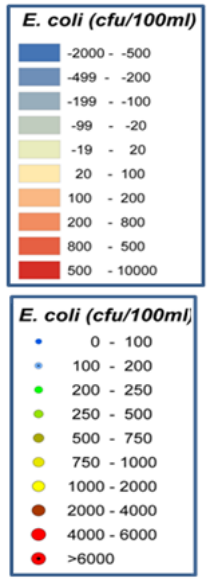
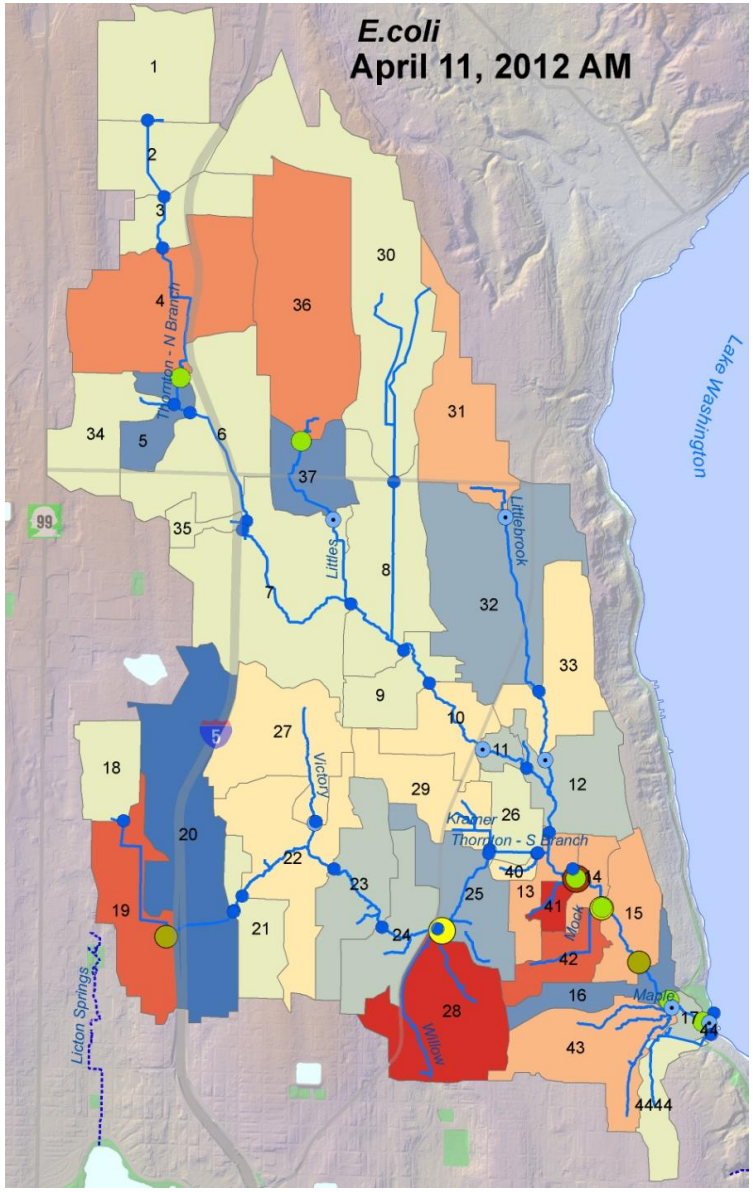
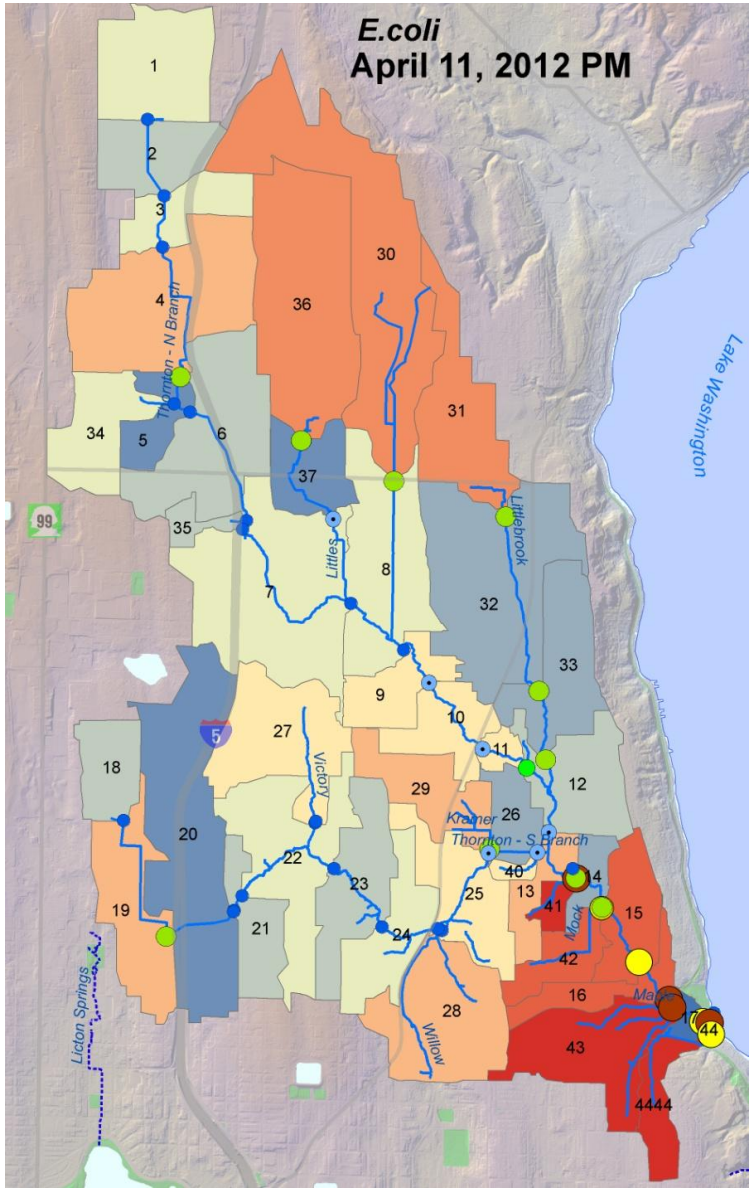


Figure 22. September 27, 2011 AM and PM E.coli counts at each sampling location. Sub basin polygons are colored according to *E.coli* differences calculated as downstream minus upstream from adjacent sampling locations. Darker red colors indicate sub basin suspected of contributing *E.coli* at the time of sampling.





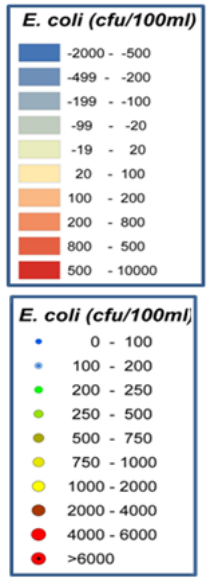
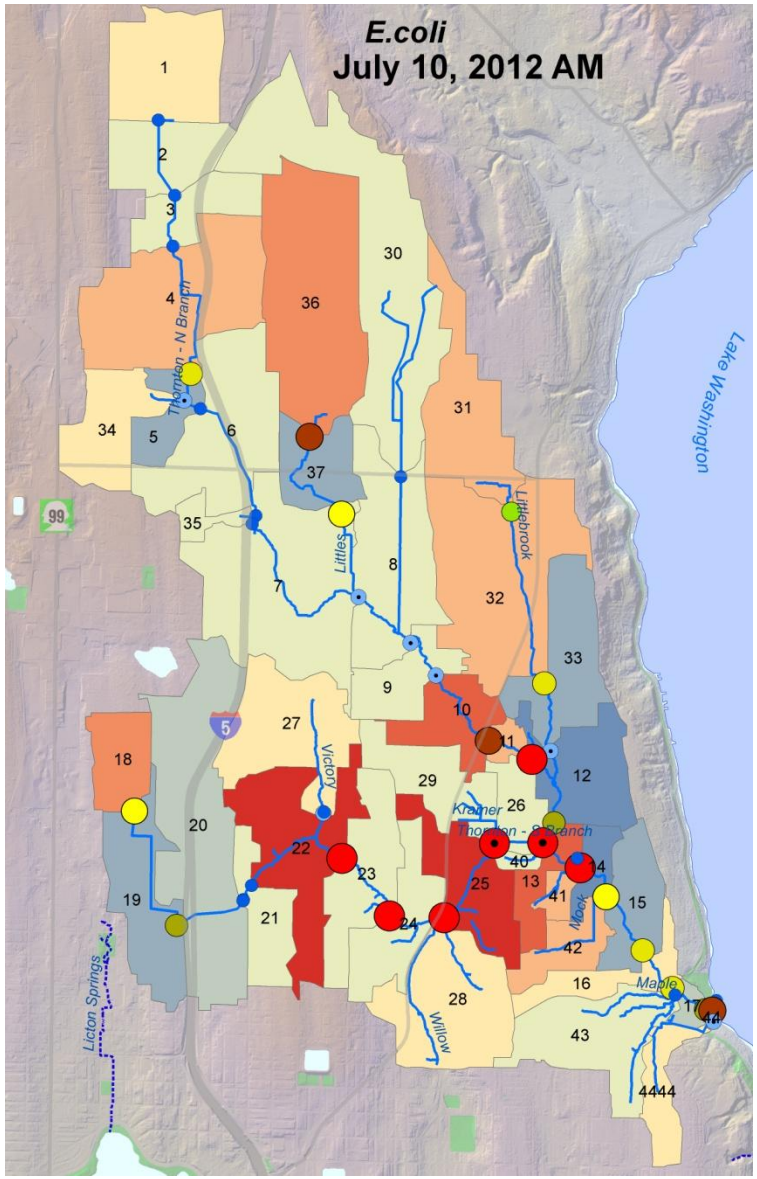
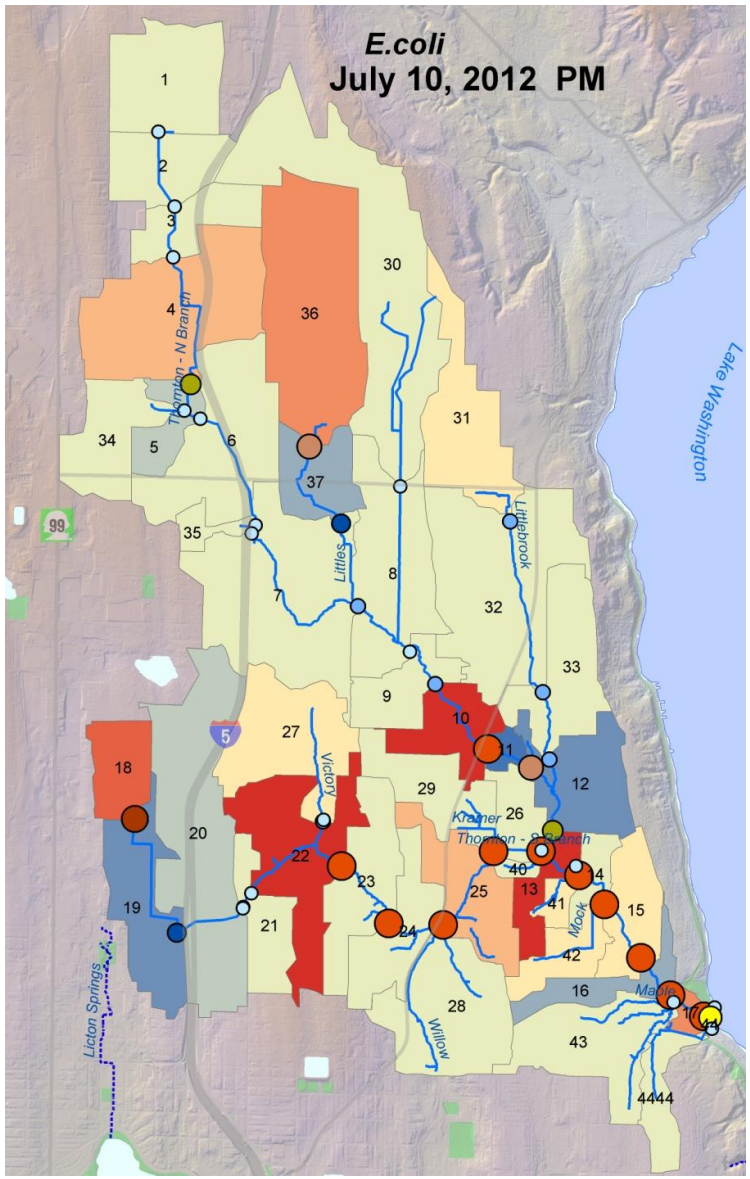


Figure 23. April 11, 2012 AM and PM E.coli counts at each sampling location. Sub basin polygons are colored according to *E.coli* differences calculated as downstream minus upstream from adjacent sampling locations. Darker red colors indicate sub basin suspected of contributing *E.coli* at the time of sampling.





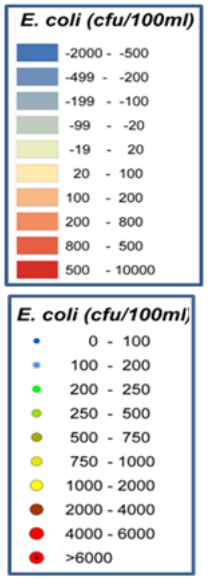


Figure 24. July 10, 2012 AM and PM E.coli counts at each sampling location. Sub basin polygons are colored according to *E.coli* differences calculated as downstream minus upstream from adjacent sampling locations. Darker red colors indicate sub basin suspected of contributing *E.coli* at the time of sampling.

Also in July 2012, large increases in *E.coli* counts were sampled in sub basins 10 and 25 (Figure 24 and 26). Portions of these sub basins drain the commercial areas along Lake City Way. Thornton Creek had consistently better water quality upstream of drainage from Lake City Way and degraded water quality downstream of this road (Table 2 figures 7-11). Recent SPU IDDE source investigations have identified water quality problems in this area. Soap suds were observed after any rains downstream of site 25 and there were fewer benthic invertebrates collected at this location during the New Zealand Mud Snail reconnaissance than at the site immediately upstream.

There is a persistent decrease in water quality and increase in *E.coli* counts between site 3 and site 4 on the upper mainstem of Thornton Creek (Table 2, figures 6, 9-11). The stream enters Twin Ponds just downstream of this sampling site. The change in water quality is not observed at the next site downstream (5) which is below the outflow from the ponds.

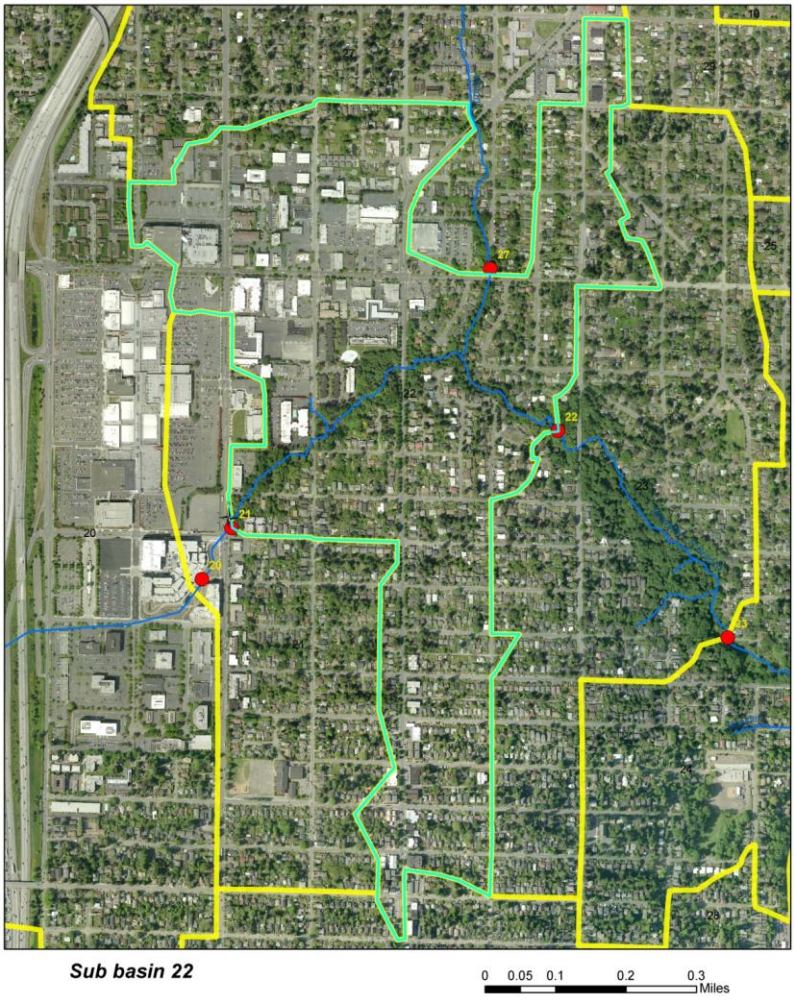


Figure 25. Sub basin 22 on the South Fork of Thornton Creek has mixed land cover of single family, multi-family, commercial and open space.

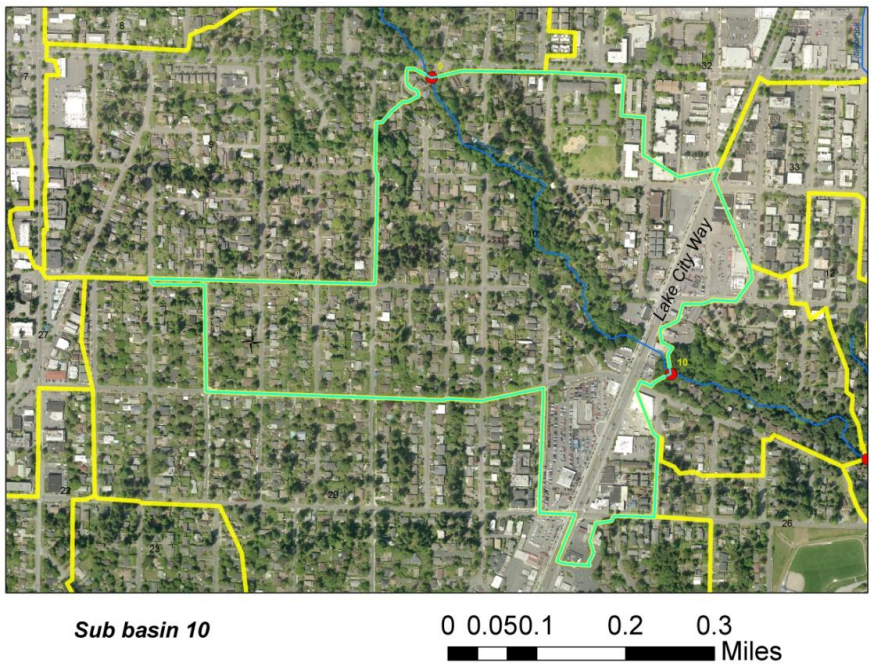


Figure 26. Sub basin 10 on the mainstem of Thornton Creek has mixed land cover of single family, commercial and open space. Site 10 is immediately downstream of drains from the Lake City Way road and commercial area.

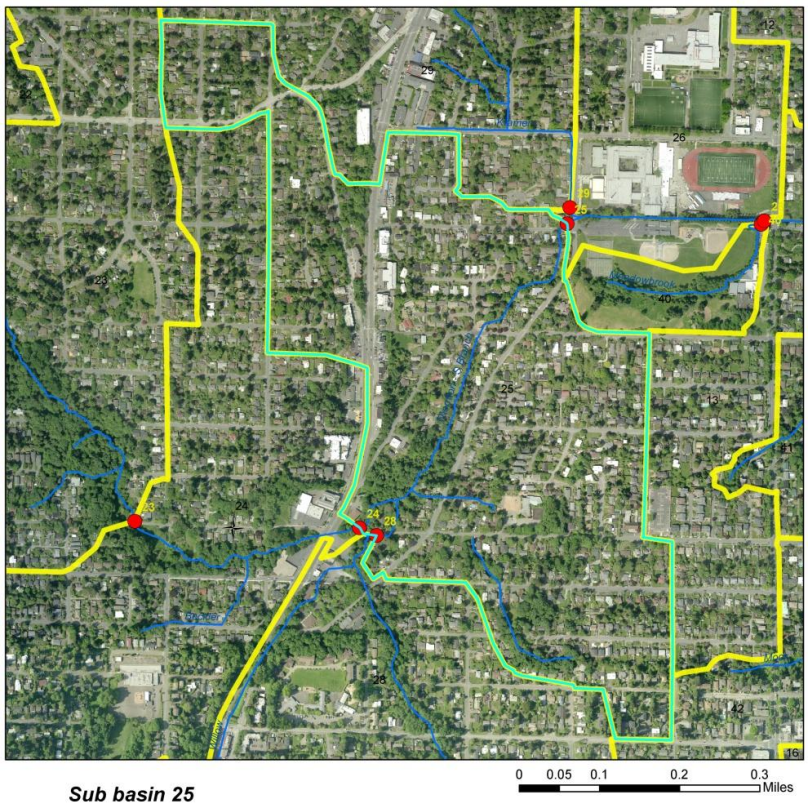


Figure 27. Sub basin 25 on the South Fork of Thornton Creek has mixed land cover of single family, commercial and open space and drains a portion of Lake City Way.

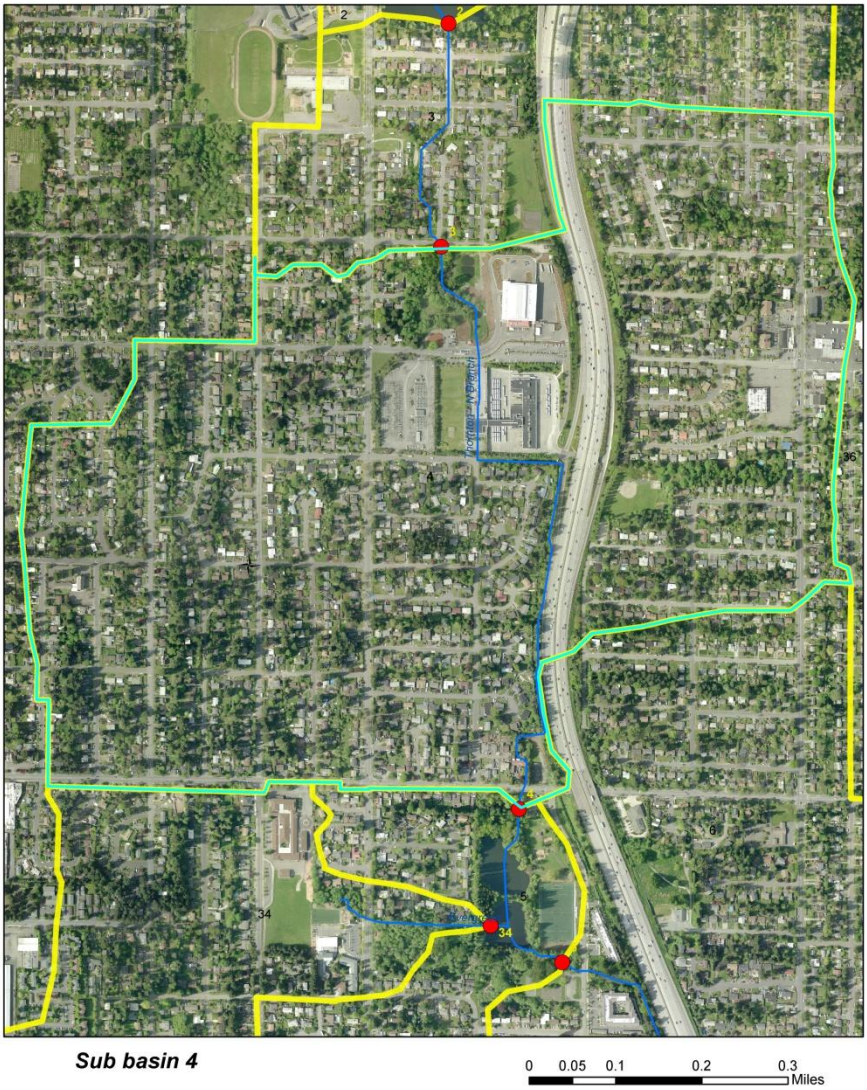


Figure 28. Sub basin 4 on the upper mainstem of Thornton Creek in Shoreline has mixed land cover of single family, highway runoff and the channel traverses the site of an old King County landfill and is adjacent to the King County Metro Transit Base.

Sub basins 13-17 in the lower mainstem had high *E.coli* geometric means (Table 5) above the ODEQ criteria. These high *E.coli* counts in the lower mainstem stream segments were less than upstream segments (Table 2; figures 20-23). While these lower mainstem sub basins may have local inputs of bacteria, the accumulated input of bacteria from upstream is so high these inputs are not currently detectible. The high bacteria counts in the lower part of Thornton Creek are consistent with the high bacteria counts sampled for several years at the King County ambient monitoring sites (0434). Any local inputs in this section of the stream will only be noticeable after the high upstream inputs are removed.

The sample sites in several of the smaller tributary streams had high *E.coli* geometric means (Table 5), and were the only sample sites in these smaller sub basins. The potential for locating the sources of bacteria in the small relatively uniform landcover Tributary E (41) and Mock Creek (42) sub basins should be higher and control of bacteria from the tributaries should reduce the overall counts of bacteria in the mainstem.

Littles Creek (36 and 37) also had high *E.coli* counts (Table 2). Both sites had high *E.coli* counts during the October 2012 rain event (3600, 7200 cfu/100ml) and site 37 is only about 3000 feet downstream of site 36 and most of that length is in the Jackson Golf Course. There appears to be inputs of *E.coli* in the section of Littles Creek between the two sampling sites as well as from above the upper site in North Crest Park. This sub basin should be investigated.

None of the three sites on Littlebrook Creek met criteria, and the headwaters sub basin 31 had *an E.coli very* high *E.coli* count (AM 6700 PM 1300 cfu/100ml) which implies an ephemeral bacteria source in this sub basin. This section of stream is in one of the few Seattle Parks in this section of the city.

Both of sub basins 36 and 37 have relatively small flows and their contribution to the bacteria counts in the mainstem are potentially marginal, but these basin should be looked at to discern the source of the high *E.coli* from these small sub basins of single family residences.

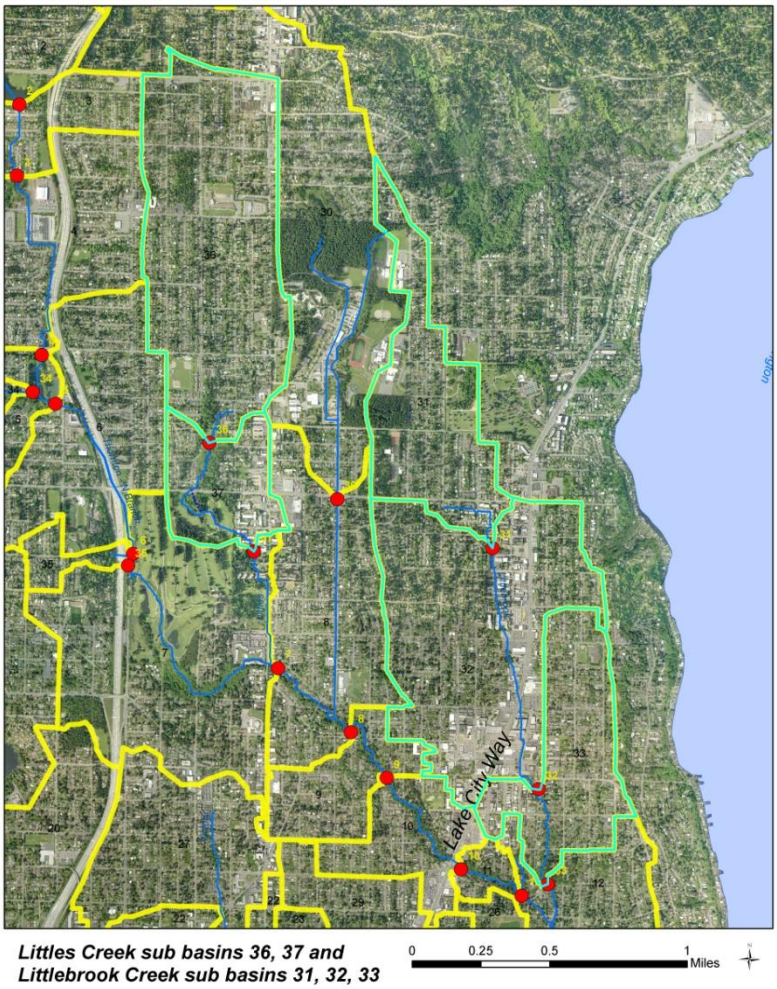


Figure 29. Littles Creek (36, 37) is primarily single family residences, with some mult-family, park and Jackson Golf Course. Littlebrook Creek (31, 32, 33) is primarily single family residences, with al large portion of commercial development along Lake City Way.

Conclusions

This study has identified where high counts of *E.coli* are probably entering portions of Thornton Creek, at least to the sub basin scale established for the current sampling design. The first priority sub basins to investigate for sources are 4, 10, 22, 25, 26 and 31, followed by 28, 32, 33, 36, 37, 44 and 4444. The *Bacteroides* data indicates that there is a high probability of frequent and widespread human component to the bacteria in the creek. Reduction of bacteria counts, whether to meet the WAC 173-201A fecal coliform criteria or the ODEQ *E.coli* criteria depends on the specific location and control of the sources of bacteria that impact Thornton Creek.

The *E.coli* geometric means for only 16 of the 46 Thornton Creek sampling sites met the Oregon Department of Environmental Quality (ODEQ) *E.coli* criteria of 126 cfu/100ml, and those sites tended to be higher in the basin or in some of the smaller tributary streams. Only 7 of the sampling sites met the WAC 173-201A water quality criteria of 50 cfu/100ml for extraordinary primary contact and only 8 met the 200 cfu/100 ml for secondary contact (Table 2). Similar to the *E.coli* counts, the sites that met criteria for fecal coliform tended to be in the upper watershed. The high fecal coliform bacteria counts that initiated this watershed analysis (Figure 2) were collected low in the basin at the USGS flow monitoring station near Sand Point Way (site 16 in this study) and sampled the accumulated bacteria loading from the entire watershed. It is undetermined whether the sites lower in the watershed contribute bacteria or exceed criteria because of upstream bacteria loads, or a combination of both, but all of these sites exceed the Washington fecal coliform bacteria criteria.

The mainstem of Thornton Creek above Lake City Way frequently met or slightly exceeded the ODEQ *E.coli* criteria. With the exceptions of site 4 above Twin Ponds and Littles Creek, samples collected in the mainstem and mainstem tributaries above Lake City Way either met the ODEQ *E.coli* criteria or only slightly exceeded them. Downstream of Lake City Way every *E.coli* sample collected on every sampling date exceed the ODEQ *E.coli* criteria and frequently by an order of magnitude or greater. Below Lake City Way there is degradation in water quality that impacts the bacterial load, aesthetics and the stream benthic community. Based on the bacteria increases the sub basin draining to this location is highly suspect for having undetected bacteria sources. Even though *E.coli* and fecal coliform counts in the lower mainstem of Thornton Creek are consistently above criteria, it may be more efficient to initially focus on locating and controlling the upstream and tributary sources which would decrease the overall background bacteria counts and potentially make it easier to discern the source from the background.

Herrera (2007) stated 'the low percentage (3 percent) of human bacteria sources observed in the Thornton Creek Microbial Source Tracking study is similar to that observed in other urban streams in Western Washington'. Based on *Bacteroides* collected in Thornton Creek it is probable that human sources of bacteria are much more prevalent than three percent of the isolates identified by ribotyping . Fecal coliform and *E.coli* bacteria counts in Thornton Creek are not similar to those observed in other Western Washington streams and are typically much higher. There may be several reasons for the discrepancy between the Herrera (2007) and current study. The amount of human source bacteria may be different between 2007 and 2012-13, although the overall bacteria counts from the long term ambient monitoring sites do not indicate a large change in either fecal coliform or *E.coli* bacteria counts making this an unlikely explination. There may be an absolute difference in the identification of human sources using the ribotyping approach versus the *Bacteroides* approach used in the current study. Ribotyping could either be less sensitive or *Bacteroides* overly sensitive in identifying human sources of bacteria. This discrepancy could most effectively be addressed by a synoptic study of the two techniques. The human *Bacteroides* technique provides peer reviewed information that human sources are present, but the lack of epidemiological studies or a correlation between human *Bacteroides* and total *E.coli* (Figure 20) make any percent source attribution impossible at this time. The overall *E.coli* counts are used to indicate the level of bacterial risk and positive *Bacteroides* results as corroboration of the high probability of human contribution to these bacteria loads.

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Appendix A

Quality Assurance Project Plan for
2011 Investigation of Fecal Coliform Sources in Thornton Creek Basin

Prepared by Jonathan Frodge
Prepared for Department of Ecology Water Quality Program

Approval Signatures:

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_____ Date: _____

Katherine Bourbonais, WQ Lab Project Manager, KCEL

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Background

Thornton Creek (Figure 1) is located in a highly urbanized basin with primarily single family residences and commercial landuse. The stream discharges adjacent to the popular public swimming beach at Matthews Beach Park on Lake Washington. Seattle Public Utilities and King County monitor the ecological health of Thornton Creek in a variety of ways including collecting and analyzing water, sediment and benthic invertebrate samples. Since 1971 water quality samples has been collected monthly in Thornton Creek; http://green.kingcounty.gov/WLR/Waterres/StreamsData/Bacteria.aspx?Locator=0434 . Station 0434 is located at the USGS gauging station north of Matthews Beach Park. The City of Seattle has monitored flows and fish passage along the mainstem of the creek and three of its tributaries at multiple locations from the mouth of the creek to the city limits .

Thornton Creek was designated a "Class AA" water body under the 1997 rules, Chapter 173-201A WAC. Under the 2003 rules, Thornton Creek is categorized as "Core Salmon Migration and Rearing Habitat" for aquatic life use and "Primary Contact - geometric mean <50 cfu/100ml and <10% of samples <200 cfu/100ml" for recreational use. As part of the updated water quality standards, the creek has been assigned an additional "Supplemental Spawning and Incubation Protection" temperature criterion of 13 ºC to be applied from September 15th through May 15th. Thornton Creek is on the 2004 Washington Department of Ecology's (Ecology) 303(d) list for violation of fecal coliform, dissolved oxygen and temperature standards. See Table 1 for a summary of water quality violations in the creek during the most recent water year. In 2008, Thornton Creek exceeded State Water Quality Standards for fecal coliform in 10 of the 15 samples collected by the routine monitoring program (Water Quality Monitoring of Northern Lake Washington Streams, King County. January 2002; http://green.kingcounty.gov/Lakes/reports/nlwsr.aspx)

Both routine King County sampling sites in Thornton Creek are listed on the 2004 Washington Department of Ecology's (Ecology) 303(d) list for violation of dissolved oxygen (DO), temperature and fecal coliform (FC) bacteria standards. For over thirty years, Thornton Creek has frequently exceeded state water quality standards for fecal coliform on an annual and seasonal basis and has bacterial counts among the highest of the streams routinely monitored by King County (Figure 2).

In August 1998, the USGS sampled several streams, including Thornton Creek, and rivers in the Puget Sound Basin as part of the National Water Quality Assessment Program (NAWQA) which looked at multiple indicators (bacterial, viral, chemical) of sewage pollution. The USGS documented high densities of *E. coli* and the presence of coliphages in water samples from Thornton Creek (Embrey, 2001). Impacts from sewage pollution were clearly indicated on the basis of chemical indicators.

Matthews Beach at the mouth of the creek also frequently exceeds state standards for fecal coliform (2005, 2004) most recently in 2005. 'The most likely source of bacteria that resulted in the closure of Matthews Beach was the high counts of bacteria that enter Lake Washington from Thornton Creek. Thornton Creek is currently being evaluated to identify and control the

chronically high bacteria in this stream. The bacteria counts at Matthew Beach are typically highest at the south end of the beach adjacent to the mouth of Thornton Creek and lowest at the north end, farthest from the stream. When it rains flows from Thornton Creek increase the bacteria counts at Matthews Beach (sometimes there is a one to two day time lag).' http://green.kingcounty.gov/swimbeach/matthews-closure.aspx.

The Thornton Creek watershed straddles Interstate Highway 5 (I-5) and drains approximately 10.9 square miles. The combined mainstem and tributary stream length is approximately 11.7 miles (Figure 1). The very upper portions of the watershed include a small area (2 percent) of unincorporated King County. About 30 percent of the watershed is in the City of Shoreline and 66 percent in the City of Seattle. The main stem of Thornton Creek originates west of I-5, and flows approximately five miles east and south entering Lake Washington on the south side of Matthews Beach Park. There are three main tributaries flowing into Thornton Creek. The entire watershed is within the Urban Growth Boundary (UGB).

The USGS maintains a stream flow gauge on Thornton Creek and the City of Seattle. Land use in the area has changed rapidly over the last 20 years. In 1981, only 40 percent of the basin was characterized as being "urban/suburban". Since then, much of the basin has been developed and the basin is now described as "highly developed" (Greater Lake Washington Technical Committee. August 22, 2001). Currently, the basin is primarily single family residences, with light industrial areas concentrated primarily near Interstate Highway 405 (I-405), and commercial areas along I-405 and near the swimming beach and Lake Washington. The basin is over 90% built-out according to current zoning, and approximately 48% of its area is covered in impervious surfaces.

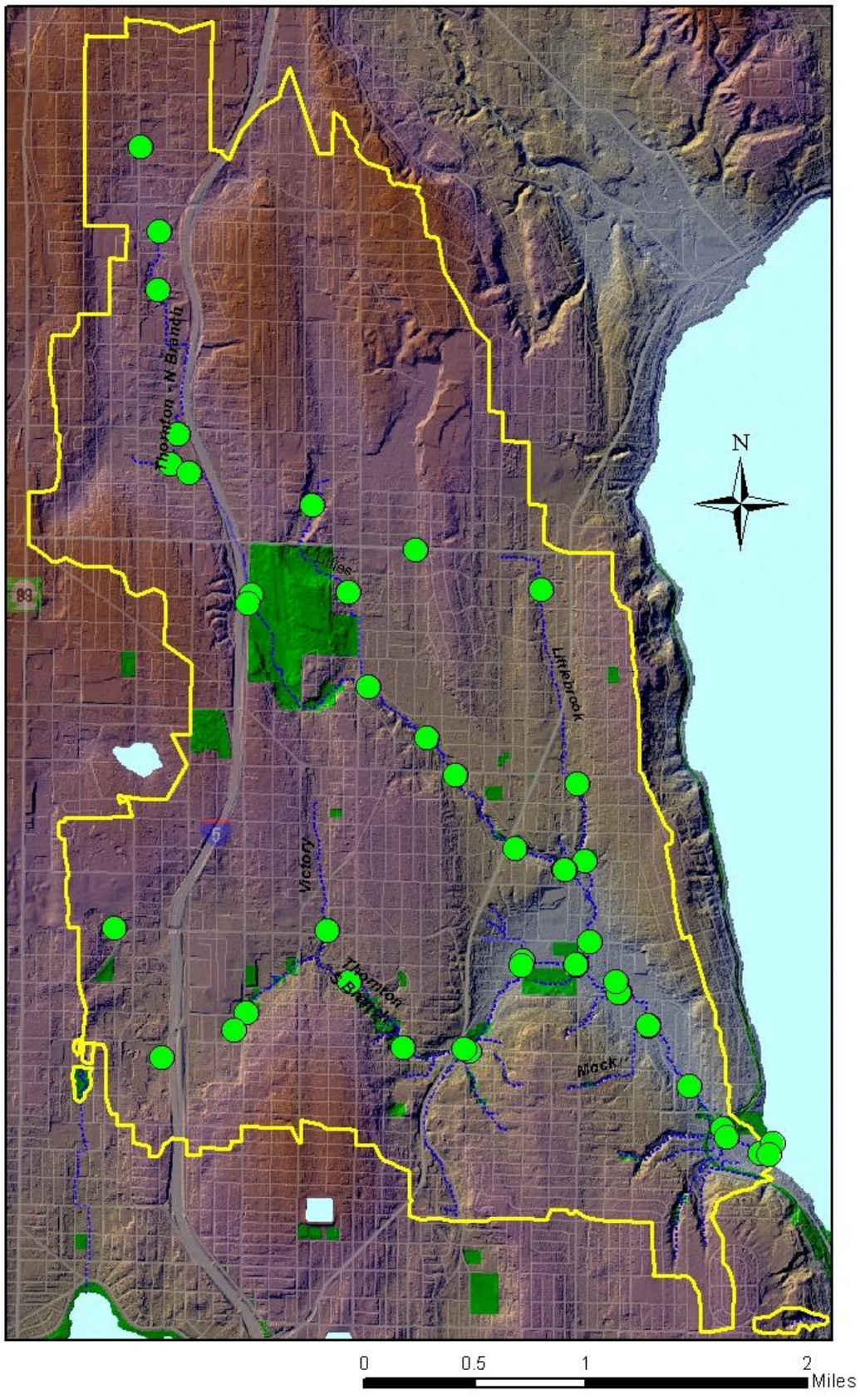

Figure 1. Thornton Creek watershed with bacteria monitoring locations.

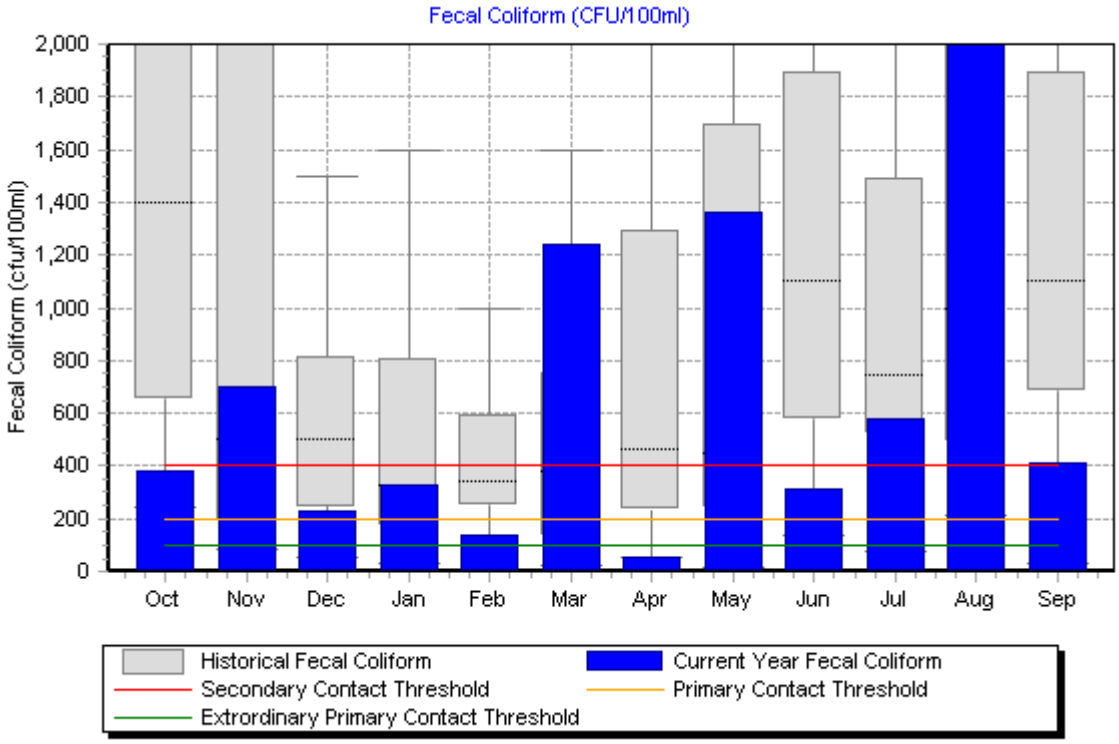

Figure 2. Current water year fecal coliform bacteria at locater 0434 for 2008-9 compared to water quality threshold values provided as an example of baseline data.

Project Description

Thornton Creek has high fecal coliform bacteria counts that routinely exceed the state water quality criteria for primary and secondary contact. Matthews Beach is often closed during the swimming season due to high bacteria counts. This study is designed to locate and preliminarily quantify sources of bacteria throughout the watershed that result in the stream being out of compliance with the State Water Quality Standards and that contribute to the 303(d) listing of Thornton Creek for fecal coliform bacteria and the periodic closing of the Matthews Beach.

This study is designed to sample for *E. coli* and fecal coliform bacteria throughout the Thornton Creek stream network at a sampling density sufficient to locate bacterial sources so the sources can be corrected (Figure 1 and Table 1). Sampling sites have been located as close as possible to the headwaters of the tributaries and at multiple locations downstream to the mouth of the creek. Differences between upstream and downstream bacteria counts will be used to locate potential sources along the stream segment between sampling locations. Selection of sampling locations is designed to isolate tributaries, stormwater pipes, retention/detention (RD) ponds, and short

stream segments in order to track potential bacterial sources to as small a geographic area as practicable.

The density of samples is constrained by the number of sampling locations that can be safely sampled within an approximately six hour period (to allow for two samplings of each location on each sampling day) and the analytical capacity of the King County Environmental Laboratory (KCEL). Selection of sampling locations was also constrained by safety concerns, time needed to access particular locations and ability to get permission from property owners to sample on private property.

Three sampling events are scheduled, two during the typical summer low flow period (August 11, and late August/early September), and one targeted at the first large rainfall event of the typical rainy season in autumn, i.e., the 'first flush' event that typically occurs in September/October. Data will be collected to provide an estimate of temporal variability by sampling each location twice each sampling day; the first round of samples collected beginning at 8 AM, and a second round of samples collected beginning after noon. We are attempting to evaluate variability both daily (by multiple sampling) and between sampling days.

If stream segments are identified that indicate a source of bacteria exists between the upstream and downstream sampling locations, additional efforts will be conducted to specifically locate that source of bacterial pollution. Visual surveys of the identified stream segment with an analysis of storm drains, septic fields, and sanitary sewer lines will be carried out to locate source(s) and begin corrective actions to eliminate them. All information on the bacteria counts and geographic extent of the suspect stream segments will be shared with PHS&KC for evaluation of potential human health risk.

Another goal of this study is to develop a data set that can potentially be used to design an effective sampling plan for urban watersheds with bacteria pollution issues. Post sampling analysis of the data will allow assessment of the power and sample size that would have been the most effective for evaluating the Thornton Creek watershed. This analysis will be available to optimize future sampling designs in other watersheds. Results from the Thornton Creek study will be compared to the results of the Juanita Creek Fecal Coliform Investigation (2008)

This project will constitute Phase I defined below:

> Phase I (covered under the current grant activity) - Investigate and identify reaches of concern along Thornton Creek through repeated intensive near synoptic E. coli and fecal coliform samplings during a minimum of two summer low flow sampling and an additional sampling event targeting the beginning of autumn higher precipitation. Investigations will also involve stream walks and windshield surveys to document potential sources. If identified sources warrant immediate required actions (e.g., sewer line breaks), then relevant partners, under their legal authority, will respond accordingly during Phase I.

Phase II - Correct identified bacteria sources by implementing on-the-ground best management practices and supporting local agency activities. Phase I investigation results can help guide implementation actions.

Expected water quality outcomes or deliverables from project:

Deliverables from this Phase I project will include a data summary report documenting findings from the field investigations and analysis, identifying follow-up implementation actions needed as part of Phase II (which is not addressed under this project).

Organization and Schedule

Project Manager Seattle Public Utilities

Jonathan Frodge, SPU- 206-684-8479, jonathan.frodge@seattle.gov . Cooperatively responsible for overall project design and implementation within the watershed. Responsible for coordination of data collection and sampling equipment, data analysis and final report.

Co-manager at King County Environmental Laboratory

Katherine Bourbonais, Laboratory Project Manager, KCEL. 206-684-2382, katherine.bourbonais@kingcounty.gov . Responsible for coordinating sample collection, SOP's, bottle kits and field sheets, login of bacteria samples.

Schedule

Target dates for:

Completion of Final Approved QA Project Plan:	August 15, 2011
Sampling Start/End:	August 2011, Sept-Nov 2011*
Draft Study Report:	March 2012
Final Study Report:	May 2012

Submittal of Data to the Environmental Information Management System (EIM):

December 30, 2011

*specific day will be determined by KCEL scheduling requirements. Scheduling of the 'first flush' autumn sample is dependant on rainfall

Table 1. Budget

a. Grant Proposal Total Project Budget and Time Frame

Task elements	Total Project Cost	Total Eligible Cost	Months needed to complete
1. **Project Administration/Management**	$5,000	$4,000	12
2. **Write QAPP**	$2,500	$1,000	2
3. **Conduct GIS analysis, stream walks and windshield surveys**	$5,000	$2,500	2
4. **Identify sampling sites**	$2,500	$2,500	2
5. **Generate GIS layers**	$10,000	$5,000	4
6. **Conduct field sampling and laboratory analysis QA/QC data**	$40,000	$55,000[b]	3.5
7. **Coordinate source control data with source control efforts**	$10,000	$0	
8. **Manage and Analyze data and write final report**	$15,000	$10,000	6
Total Costs and months needed to complete:	$90,000	$80,000	12

b. Cost breakdown based on current QAPP

Item	Costs of Material	Cost of Labor	Anticipated time to complete	Anticipated in-kind services	Total Item Cost
1. **Laboratory costs** (350+ bacteria samples)[1,2, 3]		$37,760	14 days Preparation and analysis		$27,305
2. **Design and implement study** , **produce final report**– City of Seattle staff time (150 hours)[4]		$10,000	35:65 design to implementation	$10,000[5]	$7,240
3. **Design and implement study**, **produce final report** – King County staff time[6] (125 hours)		$8,500	80:20 Design to implementation	$7,500	$8,500
4. Implement study, produce and review final report – Shoreline staff time (40 hours)		$3,000	50:50 Design to implementation	$2,500	$3,000
5. **Sampling equipment** (temperature hobos, sampling rods and cups, DO probe, gloves, etc.)	$3,500		rental of mult-probes		$3,500
6. Contingency[7]					$10,455
			Total Project Cost	$20,000	$60,000

1. Includes all QA/QC (blank and duplicate) samples and analysis
2. Collection and preparation of fecal coliform samples
3. Analytical breakdown of laboratory cost attached below
4. SPU task elements 1-8
5. SPU covering filtration cost for qPCR for first round of sampling w/ analysis dependant on addendum (see 7)
6. KC task elements 2, 6-8
7. Potential qPCR analysis dependant on approved addendum to this QAPP

c. Breakdown of laboratory costs at King County Environmental Laboratory

Item	Total
Fecal coliform analysis, up to 101 samples (cost is 'body of work' costing by KCEL)	$ 4,145
E. coli analysis, up to 350 samples (cost is 'body of work' costing by KCEL)	$21,520
20 Lab staff hours for design and implementation activities (cost is 'body of work' costing by KCEL)	$ 1,640
Total Not to Exceed Amount of MOA between KC SPU:	**$27,305**
Contingency cost breakdown	
QPCR filtration and archive, up to 350 samples (cost is 'body of work' costing by KCEL) $ 7,175	
QPCR analysis for *Bacteroides*, up to 40 samples (cost is 'body of work' costing by KCEL) $ 3,280	
Potential pPCR costs	**$10,455**[8]

8. If approved these costs will be added to item 1 Laboratory Costs in table 1b.

Quality Objectives

Accuracy of measurements can be assessed by evaluating both precision and bias. Precision is a measure of data scatter due to random error, while bias is a measure of differences between a parameter value and the true value due to systematic errors. Procedures used to evaluate the precision and bias of sample collection, field measurements and lab analysis are documented in the KCEL Standard Operating Procedures ((all SOP referenced in this QAPP will be provided electronically upon request; Katherine.bourbonais@kingcounty.gov) and Quality Assurance

Manual. Measurement quality objectives specific to the parameters to be reported for this project are summarized in the Quality Control section. It is expected that the quality objectives for this project will be achieved if the sampling plan and procedures in this document are followed and the frequency and acceptance limits in the Quality Control section are met.

Sampling Design and Rationale

This study is designed to sample for *E. coli* and fecal coliform bacteria throughout the Thornton Creek stream network at a sampling density designed to locate bacterial sources so the sources can be corrected (Figure 1; Table 2). All bacteria data will be evaluated under the criteria for Extraordinary Primary Contact as defined in WAC173-201A.

Sampling sites have been located as close as possible to the headwaters of the tributaries and at multiple locations downstream to the mouth of the creek. Differences between upstream and downstream bacteria counts will be used to locate potential sources along the stream segment between sampling locations. Selection of sampling locations is designed to isolate tributaries, stormwater pipes, RD ponds, and short stream segments in order to track potential bacterial sources to as small a geographic area as practicable.

The density of samples is constrained by the number of sampling locations that can be safely sampled within an approximately six hour period (to allow for two samplings of each location on each sampling day) and the analytical capacity of the Laboratory. Selection of sampling locations was also constrained by safety concerns, time needed to access particular locations, penetrate blackberry patches and ability to obtain permission from property owners to sample on private property. All samples will be collected from the shore of the stream if possible, in compliance with the draft decontamination protocols (WDFW, 2011) to minimize the spread of New Zealand mudsnails. If access to the stream is necessary for sample collection, all equipment will be inspected and cleaned according to the draft decontamination protocols.

Data will be collected to provide an estimate of temporal variability by sampling each sampling location twice each sampling day. We are attempting to evaluate variability both daily (by multiple sampling) and between days (by sampling low flows four weeks apart, and potentially estimate the first flush event (by targeting sampling of the first large rainfall event of the typical rainy season in autumn (first flush).

Table 2. Locations of bacteria sample site in the Thornton Creek Watershed.

sample	X_COORD	Y_COORD	CITY	address
1	1271145.328	280733.9572	Shoreline	NE corner N180th St & Meridian Ave N
2	1271584.23	278703.8648	Shoreline	outlet Ronald Bog at N end of Corliss Ave N
3	1271539.154	277336.9751	Shoreline	S side of N 167th St opposite of Corliss Pl N
4	1272014.363	273893.916	Shoreline	inflow Twin Ponds S of N 155th St SW of park lot
5	1272280.355	272955.7849	Shoreline	outflow of Twin Ponds immediately upstream of pedestrian bridge

6	1273751.118	270332.5999	Seattle	downstream culvert telephone pole 5th Ave NE next to Jackson GC
7	1276551.853	267875.2975	Seattle	downstream ped bridge at private res at 1519 NE 130th Pl
8	1277952.473	266640.5604	Seattle	Undeveloped ROW 22 Ave NE N of NE 127th St
9	1278638.746	265766.7996	Seattle	Lake City Baptist Church
10	1280063.393	264007.2759	Seattle	outfall downstream of Lake City Way
11	1281231.983	263501.701	Seattle	main upstream of 34th Ave NE
12	1281825.544	261796.1216	Seattle	upstream of 110th St W of 35th Ave NE
13	1282534.267	260578.2681	Seattle	mainstem E of 39th Ave NE N of NE 105th St
14	1283225.357	259798.4154	Seattle	upstream of outfall D235-026 N of 43rd PL Feguson
15	1284214.296	258350.2392	Seattle	downstream of 45th Ave NE bridge
16	1285013.138	257336.3289	Seattle	USGS gage downstream of Sand Pt Way
17	1285914.179	256759.2005	Seattle	pedestrian br. on 51st St NE near mouth
18	1270501.338	262109.4942	Seattle	pond N of end of ROW N Burke Ave and W Meridian Ave N
19	1271637.609	259030.0047	Seattle	outfall wetland NSCC W I-5
20	1273354.385	259673.2706	Seattle	downstream ped bridge in TCWQC
21	1273659.793	260101.7638	Seattle	downstream of outfall from TCWQC E 5th Ave NE
22	1276105.803	260831.6792	Seattle	S Branch downstream of Victory Ck
23	1277379.393	259281.0212	Seattle	ROW NE 102nd St W of 20th Ave NE
24	1278857.051	259237.7413	Seattle	E of LakeCity Way W of dead end of NE 100th St
25	1280224.087	261238.4624	Seattle	W of 30th Ave NE N of NE 107th St
26	1281521.246	261257.2261	Seattle	upstream of bridge at N end of Meadowbrook CC park lot
27	1275599.98	262047.7939	Seattle	mouth of Victory Creek W NE 107th St
28	1278971.155	259187.8961	Seattle	Willow above mainstem N NE 100th St W Ravenna NE
29	1280242.841	261345.3637	Seattle	Kramer Ck W 30th Ave NE across from NHHS
30	1277690.615	271122.3937	Seattle	S of NE 145th St W of 20th Ave NE
31	1280671.169	270180.3667	Seattle	Littlebrook W of Littlebrook Pk.
32	1281556.718	265550.6729	Seattle	immediately downstream RD pond 35th Ave NE

33	1281734.817	263726.35	Seattle	lower Littlebrook S of NE 155th St below outfall
34	1271842.114	273179.555	Shoreline	W inflow to Twin Ponds
35	1273673.507	269845.6607	Seattle	outfall D220-024 W side of 5th Ave E of I-5
36	1275229.635	272203.5282	Parks	park NE 147th St
37	1276089.286	270116.4426	Seattle	apt complex W of 15th Ave NE S of NE 143rd Ave
38	1281233.621	263518.8149	Seattle	33rd Ave NE trib.
39	1282451.197	260833.7183	Seattle	Meadowbrook Pond at glory hole
40	1281502.791	261233.8935	Seattle	Sm. stream below b. S end of Meadowbrook CC
41	1282544.084	260566.997	Seattle	drainage entering from S near Meadowbrook outfall
42	1283223.585	259778.6613	Seattle	outfall 43rd Pl and Ferguson
43	1285095.202	257143.8726	Seattle	sediment pond Sand Pt Way NE 93rd St
44	1286095.497	256731.5296	Seattle	outflow restoration pond
45	1286209.489	256995.8831	Seattle	LW N of Thornton Ck mouth

Sampling Locations and Frequencies at Each Location

Samples will be collected at the locations in Figure 1 and Table 1. Samples will be collected twice daily beginning at 8AM one day in mid-August 2011; late August/early September 2011; and late September/early October, 2011 (specific dates dependant on laboratory scheduling).

The first (AM) round of samples collected each sampling day will be dropped off by each sampling team at Matthews Beach Park for transportation back to the laboratory for analysis. A second (PM) round of sample collection will begin at approximately 1PM. This scheduling will allow all samples to be processed at laboratory within the 24 hour holding time for fecal coliform samples. All samples will be transferred by the sampling teams at Matthews Beach Park and transported from there to the laboratory.

Order of Sampling

The 45 sampling locations have been organized into three runs of 15 to facilitate collection within as short a time period as can be done safely and accurately. The order of the sampling runs (Table 3) reflects driving logistics and sampling from upstream to downstream rather than conforming to the sample site numbers, which are based on their upstream to downstream geographic organization. Sampling is from upstream to downstream in conformance with draft protocols to minimize the spread of New Zealand mudsnails.

Table 3. Sampling runs ordered according to driving directions.

Bottle set up will conform to the driving directions.

Shoreline	Thornton 1	Thornton 2
1	20	19
2	21	18
3	27	6
4	22	35
5	23	37
34	24	7
36	28	8
30	25	9
31	29	10
32	15	11
33	16	38
12	43	26
39	17	40
41	44	14
13	45	42

Number of Samples

See Table 2.

Assumptions Underlying the Design

The primary assumption of this design is that by sampling from the headwaters of the tributaries to the mouth of the stream, differences between upstream and downstream bacteria counts will identify short segments containing sources of bacterial pollution in the watershed. By identifying short stream segments that contain bacteria source(s), the probability of locating and subsequently correcting specific pollution sources is much higher than it would be without this density of sampling.

Bacterial sources are often temporally variable. By sampling twice each sampling day and conducting two sampling rounds during the low flow (summer) period, we assume we will increase the likelihood of detecting these potentially transitory sources. Transitory sources are

less likely to be non-point sources of bacterial pollution. If the bacteria source(s) are chronic (e.g. leaking sanitary pipe, overflow location), these sources should manifest in consistently elevated bacteria counts.

Site Map with Sampling Locations

Sampling locations are provided in Table 2 and Figure 1. Each location has been reconnoitered to maximize the number of accessible locations that can be safely sampled within a timeframe that will allow the lab to meet the holding time criteria of the fecal coliform samples. Sites have been marked and mapped, and permission has been obtained in writing at all sites that are on private property. Several sites have had blackberry brambles cut back to allow access to the stream.

All field decisions will be made by following established protocols. If unforeseen issues arise, sampling decisions will be made by Jonathan Frodge 206-478-6020.

Objectives for Comparability and Completeness of Data (quality objective related to sampling)

Comparability is a qualitative parameter expressing the confidence with which one data set can be compared to another. This goal will be achieved through use of standardized techniques to collect and analyze representative samples, along with standardized data validation and reporting procedures. All samples will be collected according to the sampling, handling and analytic protocols established in this document.

Every sample will be collected according to the protocols established in this document unless it is decided by the field crew on site that collection of the sample could not be accomplished safely. Completeness is defined as the total number of samples for which acceptable analytical data are generated, compared to the total number of samples submitted for analysis. The goal for this project is 100% completeness. If 100% completeness is not achieved, the Project Manager and Assistant Project Manager will evaluate whether Study Objectives can still be met or if additional samples may need to be collected and analyzed.

Sampling Procedures

Single grab samples for *E. coli* and fecal coliform bacteria will be collected at each sampling location for every designated sampling run, along with the requisite field replicates. If the selected stream segment has minimal flow or inaccessible flow from stream bank, a sampling pole with a 500 ml bottle holder will be used to collect the grab sample. If the selected stream segment is dry, samples will not be collected, and lack of flow will be noted on the field sheets. Field replicates will be collected at ten percent frequency from a randomly selected sub-set of the sampling sites that will be determined prior to the sampling events.

Conventional parameters (temperature, pH, dissolved oxygen, conductivity) will be measured at every sampling location using calibrated YSI or Hydrolab multiprobes. The KCEL SOP #205v4 *Field Measurements using an Attended Hydrolab* will be followed. A digital photograph will be

taken and referenced (tagged on the digital photo) at each sampling location, focusing on the wetted portion of the stream where the sample is collected. Each sampling location will have pre-established photo locations established and marked prior to sampling. All field water quality data collected with Hydrolabs will be written on field data sheets and referenced by sampling location and data collection date and times. Each field crew is responsible to verify at each location that the field data sheets and sample bottles have the same ID numbers, and that the ID number is correctly matched to the sample locations.

Sampling personnel will walk to the sites wearing all proper gear including gloves and hip boots or hip waders, and carrying all sample bottles. Prior to entering the stream when it is necessary, the sampler determines the safety of entry and if deemed safe, enters just downstream of sample site, wading in a manner to avoid disturbing the water with sediment disruption. If the sampling site cannot be reached safely by foot, a sampling pole with a 500 ml bottle holder will be used to collect the grab sample. Samples should be collected from the deepest, swiftest moving portion of the stream, especially during low flows. Facing upstream, the sampler removes the cap from the sample bottle, tips the sample container downward at a 45 degree angle and plunges the container so that the mouth is approximately 5 inches below the surface. In the same motion, the sample container is turned upward so it begins filling with ambient water. The container must remain below the surface until filled to the shoulder. A 1-inch headspace must be left in the container. Containers must not be pre-rinsed with sample prior to collection. Field replicates are to be collected using a separate container filled in the same manner and as soon as possible after the original sample is collected. Filled containers should be stored immediately in ice-filled coolers until, and during, transport to the lab. Equipment decontamination for bacterial samples is not necessary since all samples will be collected directly into the lab container. Each container has been sterilized prior to delivery to the field.

All personnel will follow the draft decontaminations protocols developed by Washington Department of Fish and Wildlife (WDFW), SPU, and KCDNRP to avoid the transfer of invasive species, particularly the recently identified New Zealand mudsnail (*Potamopyrgus antipodium*).

Containers, sample sizes and field preservation are listed below:

Parameter	**Container Type**	**Field Preservation**
E. coli, Fecal Coliforms,	500 ml Polypropylene, Sterile	Store on ice

10% of total samples per sampling event will be collected as field replicates

A 1 L sterilized polypropylene container will be collected at a randomly selected site during both the A.M and P.M runs during each sampling event to allow sufficient sample volume for lab QC.

Container labels will include:

- Lab Sample Number
- Sample Location ID (Locator)
- Date and Time of Collection
- Parameter

Responsibilities for Collecting and Shipping Samples.

Samples will be collected by a minimum of 3 sampling teams comprised of City of Shoreline, City of Seattle, King County and (possibly) Department of Ecology staff. The Project Manager, Jonathan Frodge will be responsible for team organization, work assignment and overseeing team efforts. KCEL staff will receive the morning round of samples at Matthews Beach Park for transport to the laboratory on ice for analysis. Sample transfer will occur as close to noon as possible. Additional ice and coolers for the second round of sampling will be provided for by the laboratory vehicle that arrives to transport the first round of samples. The second round of samples will be transferred to the primary sampling team, who will transport them to KCEL.

Chain of Custody Procedures: During sample collection, all sample bottles will be in the custody of sampling personnel. Field sheets generated by KCEL will be used to document all steps of the transfer of custody from the sampler to the laboratory. Sampling personnel who do not directly transport samples to laboratory will need to transfer custody to the courier by signing and dating the "relinquished by" section of each field sheet. Couriers will then transfer custody to the lab via a separate custody stamp on each field sheet.

Field Documentation: Sampling information, field measurements and observations will be documented using the methods noted below. Fieldsheets are created in LIMS/SIMS with the sample locators, sample numbers and collect dates, and are printed on 'Rite in the Rain' Paper. All entries are recorded in indelible ink. Unique sample numbers will be assigned to each sampling location for which surface water samples are collected. Sample numbers will be assigned prior to the sampling event and waterproof labels generated for each sample container. Each station has a set of field observation parameters that must be filled in by field personnel. Proper completion of fieldsheets will be demonstrated, and necessary completeness emphasized.

- Field sheets will include information:
    - sample ID number
    - station name
    - station description
    - date and time of sample collection
    - general site conditions
    - initials of all sampling personnel
    - field measurements (temperature, pH, dissolved oxygen and conductivity)
    - ID of replicate if appropriate
    - ID of photo documentation
    - Chain of Custody signatures, Dates and Time

Measurement Procedures

Field Measurements: In-situ temperature, pH, dissolved oxygen (DO) and conductivity are to be measured at each sampling location using YSI or Hydrolab sondes. The Hydrolab measurements will be made by sampling personnel synoptically with the collection of water samples. The

routine calibration, operation and maintenance of these devices are described in the KCEL SOP #205v4. These routines are summarized below:

Calibration: The sondes will be calibrated prior to the sampling run. Calibration is typically done in the lab in the following order; dissolved oxygen, conductivity, pH. Pre- and post-calibration values should be recorded on the Hydrolab QC sheet along with the lot numbers for all calibration and check standards used. Project information and the names of each instrument used should also be recorded. When the calibration is complete, the sonde is stored with the calibration cup filled with tap water until ready to use in the field. Post-calibration check standards are analyzed following the sample run.

Field Measurements: Enter the stream down-current from the sample site. Place the guard on the end of the sonde and place under the surface of the water in an area most representative of in-stream conditions, preferably in the thalweg. An equilibration time of approximately 1-3 minutes should be observed. Equilibration occurs when the instrument has stabilized enough so that the readings no longer change in a linear direction over the course of a short period of time, such as 20-30 seconds. The data is to be recorded on the fieldsheets. A cross check of the sample site location ID with the sample bottle ID and field datasheets will be done at each site to ensure that the location ID, sample bottle ID and field sheet ID are correct and consistent. One member of the crew should be delegated this task.

Lab Measurements: Samples will be collected for Fecal Coliform (FC) and *E. coli* (EC) analysis. This testing will be done at the KCEL, which is accredited by the Department of Ecology to perform FC and EC testing in nonpotable water samples. Information about the procedures is documented in KCEL SOP #506 *Fecal Coliforms in Environmental Waters by Membrane Filtration*, and KCEL SOP #526v1 *E. coli in Environmental Waters by Membrane Filtration (mTEC*; and shown in the table below.

Parameter	Reference Method and Technique	Reported Units	Lower Reporting Limit	Holding Time	Preservation
Fecal Coliform Bacteria	Standard Methods, 9222D	cfu/100 mL	1cfu/100 mL	24 hours	Cool to <10ºC
E. coli	Standard Methods 9213D	cfu/100 mL	1cfu/100 mL	24 hours	Cool to <10ºC

Quality Control

Field Measurements: A minimum of two field replicates will be collected per sampling run per probe, one near the beginning of the sampling run, and one near the end of the run. Following

collection of the first set of measurements, remove the probe momentarily from the water, then repeat the measurements from the same sampling location. A minimum of one check standard for both pH and conductivity is required per day per probe. These are typically analyzed immediately following the field replicate. End checks are check standards that are analyzed following the sample run. The purpose of these samples is to verify the quality of the Hydrolab data throughout the entire sampling run. The Relative Percent Different (RPD) or simple difference (SD) of each set of Hydrolab field replicates will be calculated. Percent recoveries will be calculated for check standards and end checks. The acceptance limits are as follows:

Field Parameter	Replicate RPD	Check Standard % Recovery	End Check % Recovery
Dissolved Oxygen	20%	N/A	96 – 104*
Conductivity	10%	90 – 100	90 – 110
pH	0.2 units	0.2 units	0.2 units
Temperature	0.3 units	N/A	N/A

*-calculation based on first sample

Lab Measurements: Routine QC analyses for fecal coliform bacteria monitor method performance of each sample analysis batch. A sample analysis batch should not exceed 20 samples of the same matrix which are all prepared together and analyzed using the same reagents, media equipment, and by the same analyst(s). The QC samples to be tested with this set of samples are described below:

Laboratory duplicates are prepared for each matrix type at a frequency of 1 per batch or 5%, whichever is more frequent. The duplicate must be processed through all preparation and incubation steps used for the original sample. The acceptance limits are based on a 95% confidence limit as described in the appropriate reference method.

A negative control is prepared each working day. Sample sets which arrive more than four hours apart will have an additional negative control run. The negative control should show an appropriate qualitative response for the test organism and should not be identified as containing the target organism. For Fecal Coliform, the negative control organism is Proteus sp. or Enterobacter sp.

-A positive control is prepared each working day. Sample sets which arrive more than four hours apart will have an additional positive control run. The positive control should show an appropriate qualitative response for the test organism. For Fecal Coliform, the positive control organism is E. coli.

Pre-filtration and post-filtration blanks are prepared each working day to evaluate the sterility of the dilution water and filtration equipment. These sterility controls are considered acceptable if no growth is detected.

Sample Collection: Routine QC for sample collection consists of collection and analysis of replicate field samples for laboratory analysis. At a minimum, one replicate should be collected per sampling event and will be analyzed and reported as a separate sample ID #. The field replicate will have the same location information as the original but will have a separate sample ID #.

The focus of this survey is to identify potential bacterial sources in short segments of the creek or specific outfall pipes, and once located, to initiate corrective actions. While the design has inherent variability issues, it is assumed that with sequential sampling upstream, any contributors to the bacterial count variability will be similar at adjacent sites and that the absolute difference will not be significantly influenced by local variability. This study is neither a loading study nor a TMDL and quantification of the absolute counts is secondary to the absolute differences between adjacent sampling locations. There are no established acceptance limits for replicate samples analyzed for fecal coliforms but it is expected the RPD should be less than 50 percent in order for the evaluation of the spatial and temporal bacterial levels to be meaningful.

Higher variability with low results is especially noticeable for bacteria. Therefore, the precision MQO for bacteria parameters requires that replicate pairs be divided initially into two categories: (1) those pairs with a mean less than or equal to 20 colonies/100 mL and (2) those pairs with a mean greater than 20 colonies. For the second category, the mean RSD of replicate pairs will be evaluated by a cumulative frequency distribution. The project manager will review replicate pairs in the first category, as well as sample sets with less than 10 replicate pairs, to determine the usability of the data.

Data Management Procedures

Data review, verification and validation requirements

Data reported by the lab, including field measurements, must pass a review process before final results are available for use. A "Peer Review" process for laboratory data is used wherein a second analyst or individual proficient at the method reviews the data set. The reviewer will complete a data review checklist which will document the completeness of the data package and if any QC failures exist.

Once data review is complete and all data quality issues have been resolved or corrected, the status of the data in LIMS will be changed to "approved". Once a data set has been approved, it is "posted" or transferred to the portion of the LIMS database known as the Environmental Data System (EDS) where all historical LIMS data are maintained. Signatures or initials of the lab lead and reviewer(s) indicate formal approval of hardcopy data or reports (non-LIMS), typically on the review checklist. A copy of this approved checklist should be stored with the final hardcopy data package.

Data Storage

Once raw data has been generated by an analytical procedure or from field measurements, the data must be transformed into a format appropriate for use. For microbiological parameters, numerical results are entered into LIMS where additional calculations may take place such as conversion of instrumental concentrations to final sample results.

Data is not to be distributed outside lab units until it has met the full definition of final data. "Final Data" is defined as approved data posted to the historical database (EDS) or is otherwise in its final reportable and stored format (if not a LIMS parameter). This implies the data has been appropriately peer reviewed, properly qualified and is in its final format in terms of units and significant figures. Not only is final data assured of a higher level of quality through peer reviewing and qualification, but it will also match any future reports since it has come from the final storage location.

The standard methods for data users to access final data is either through direct electronic access to LIMS (EDS database) or through hard-copy reports and/or electronic files provided by the Laboratory Project Manager (LPM) or their equivalent. Direct access to the EDS database is controlled by access privileges provided by the Information Systems and Data Analysis unit of the KCEL for individual users. Data reporting via hardcopy through LPMs must follow the guidelines in KCEL SOP# 11-03-001-001 (Project Report Review Guidelines) before being delivered to the data user. Electronic file deliverables must follow KCEL SOP # 08-01-001-000 (Guidelines for Delivering Electronic Lab Data to Customers).

Data reduction, review, and reporting:

All lab and field measurements will follow the procedures outlined in the KCEL's SOPs and QA Manual. Laboratory staff will be responsible for internal quality control verification, proper data transfer, and reporting of microbiological data to the Project Manager via the Laboratory Information Management System (LIMS). The following table summarizes the information entered to LIMS for the data to be collected for this project:

LIMS Parameter Name	Units	Method Detection Limit (MDL)	Reporting Detection Limit (RDL)
Dissolved Oxygen, Field	mg/L	0.5	1.0
Conductivity, field	umhos/cm	0.5	10
pH, Field	pH units	-	-
Sample Temperature, Field	deg C	-	-
Fecal Coliform	CFU/ 100 mL	- 1 CFU/100 mL	1
E. coli	CFU/100 mL	- 1 CFU/100 mL	1

Fecal coliform and *E. coli* results for samples with no detectable colonies are reported in LIMS as <1 CFU/100 mL.

Data Qualifiers: If it is determined in the review process that the quality objectives were not met or an analysis anomaly has occurred, the affected data will be flagged and the project manager notified. Data qualification flags, which may be entered to LIMS, are presented in the table below:

Qualifier	Description
H	indicates that a holding time criterion was not met prior to analysis.
R	Indicates that the data are judged unusable by the data reviewer. The qualifier is applied based on the professional judgment of the data reviewer rather than any specific set of QC parameters and is applied when the reviewer feels that the data may not or will not provide any useful information to the data user. This qualifier may or may not be analyte-specific.
TA	Applied to a sample result when additional narrative information is available in the text field. The additional information may help to qualify the sample result but is not necessarily covered by any of the standard qualifiers.
C	Applied to fecal coliform data when the sample analysis exhibits confluent growth of organisms. The value reported can be reliably used as an indicator of relative abundance; however, it can not be used as an accurate count of the associated organism.
J	Applied to a parameter result when the reported value is an estimated value
SH	Indicates that a sample handling criterion was not met in some manner prior to analysis. The sample may have been compromised during the sampling procedure or may not comply with storage conditions or preservation requirements.
PASS	**PASS** is applied for Microbiology QC samples (positive and negative controls), **PASS** is applied when the results are acceptable (Passing).
FAIL	FAIL is applied to Microbiology QC samples (positive and negative controls), the **FAIL** is applied when the results are unacceptable (Failing).
>#####	Applied in to fecal coliform, and *E coli* data when the population count exceeds the procedural capacity to measure quantitatively. The number in the qualifier is the highest procedural count or concentration possible for the sample dilutions analyzed. A value is not entered into the numvalue field. The actual population count is at least as great as or greater than the value reported in the qualifier.
<MDL	Applied when a target analyte is not detected or detected at a concentration less than the associated method detection limit (MDL). MDL is defined as the lowest concentration at which an analyte can be detected. The MDL is the lowest

Qualifier	Description
	concentration at which a sample result will be reported.
<RDL	Applied when a target analyte is detected at a concentration greater than or equal to the associated MDL but less than the associated reporting detection limit (RDL). RDL is defined as the lowest concentration at which an analyte can reliably be quantified. The RDL represents the minimum concentration at which method performance becomes quantitative and is not subject to the degree of variation observed at concentrations between the MDL and RDL.

Data Storage: All field and sampling records, custody documents, raw lab data, and summaries and narratives will be archived according to KCEL policy. All data will be entered into Ecology's EIM database by the Data Management section at the King County Environmental Laboratory.

Audits and Reports and Data Quality (Usability) Assesment

An interim report will be produced by J. Frodge after each sampling event. This report will be produced soon after data is reported by the KCEL. It will included the number of locations sampled, a brief description of the timing of the sampling, and description of any sites that could not be sampled. The report will be emailed to everyone on the contact list in this document.

Final Report

Data will be collected to provide an estimate of temporal variability by sampling each sampling location twice each sampling day. The report will provide an estimate of variability both daily (by multiple sampling) and between days (by sampling low flows one month apart), and estimate the first flush event (by targeting sampling of the first large rainfall event of the typical rainy season in autumn – the first flush).

If stream segments are identified that indicate a source of bacteria exists between the upstream and downstream sampling location, additional efforts will be conducted to specifically locate the source of the bacterial pollution. Visual surveys of the identified stream segment with an analysis of storm drains, septic fields, and sanitary sewer lines will be carried out to locate sources and begin corrective actions to eliminate the bacterial source. All information on the bacteria counts and geographic extent of the suspect stream segments will be shared with PHS&KC for evaluation of potential human health risk.

The data set will be analyzed *post-facto* to evaluate potential sampling design for urban watersheds with bacteria pollution issues. Post sampling analysis of the data will analyze the power and sample size that would have been the most effective design to evaluate the Thornton watershed, or provide insight to the feasibility of this approach. This analysis will be available to optimize future sampling designs in other watersheds.

Bacterial counts of all stream segments will be represented on a GIS coverage and used to focus source identification and control efforts.

The final report will be produced by the City of Seattle with support from King County Department of Natural Resources and delivered to Ecology for final review and approval.

Data Verification and Validation

Data will not be distributed outside the lab unit until it has met the full definition of final data. "Final Data" is defined as approved data posted to the historical database (EDS) or is otherwise in its final reportable and stored format (if not a LIMS parameter). This implies the data has been appropriately peer reviewed, properly qualified and is in its final format in terms of units and significant figures. Not only is final data assured of a higher level of quality through peer reviewing and qualification, but it will also match any future reports since it has come from the final storage location.

The standard methods for data users to access final data are either through direct electronic access to LIMS (EDS database) or through hard-copy reports and/or electronic files provided by the LPM or their equivalent. Direct access to the EDS database is controlled by access privileges provided by the KCEL's Information Systems and Data Analysis unit for individual users. Data reporting via hardcopy through LPMs must follow the guidelines in KCEL SOP# 11-03-001-001 (Project Report Review Guidelines) before being delivered to the data user. Electronic file deliverables must follow KCEL SOP # 08-01-001-000 (Guidelines for Delivering Electronic Lab Data to Customers). KCEL staff will be responsible for internal quality control verification per SOPs referenced above.

References

Embrey, Sandra S. 2001. Microbiological quality of Puget Sound basin streams and identification of contaminant sources. JAWRA, vol 37, issue 2. pp: 407-421.

King County 2005. *Standard Operating Procedure for Analysis of Fecal Coliforms in Environmental Waters by Membrane Filtration*, SOP #506. King County Environmental Laboratory. Seattle, Washington.

King County 2006. *Standard Operating Procedure for Field Measurements using an Attended Hydrolab*, SOP #205v4. King County Environmental Laboratory. Seattle, Washington.

King County 2006. *Quality Assurance Manual, Revision 2*. King County Environmental Laboratory. Seattle, Washington.

WDFW Invasive Species Management Committee: Bill Tweit, Allen Pleus, Dave Heimer, John Kerwin, Marc Hayes, Carl Klein, Stacie Kelsey, Mike Schmuck, Larry Phillips, Bill Hebner 2011. Invasive Species Management Protocols

Appendix B. Conventional Water Quality Data

Temperature °C								
sample	*August 28, 2011*		*September 27, 2011*		*April 11, 2012*		*July 10, 2012*	
number	AM	PM	AM	PM	AM	PM	AM	PM
1	16.2	16.9	14.8	nd	12.3	12.1	17.0	19.2
2	21.2	23.1	17.9	18.1	14.0	13.8	20.0	22.7
3	15.8	16.1	17.2	17.4	12.3	12.2	17.5	17.9
4	14.0	15.6	14.9	15.3	10.7	10.7	13.6	14.9
5	18.8	19.1	16.4	16.4	12.4	12.2	18.8	19.7
6	13.2	13.5	14.1	nd	10.5	10.6	13.0	13.5
7	14.8	16.8	14.5	14.8	10.2	10.3	13.3	15.1
8	14.9	16.2	14.4	14.8	10.2	10.3	15.3	14.8
9	14.8	15.9	14.4	14.7	10.1	10.2	13.4	14.5
10	15.1	16.0	14.4	14.7	10.2	10.4	13.5	14.7
11	15.2	16.3	14.4	14.7	10.3	10.3	13.6	14.8
12	15.6	16.8	14.6	14.9	10.5	10.5	14.2	15.4
13	16.6	17.9	15.0	16.4	10.8	10.8	14.6	16.2
14	16.8	17.3	14.9	15.2	10.7	10.7	14.3	15.8
15	16.0	17.7	14.8	15.1	10.7	10.7	14.5	16.0
16	16.0	17.6	14.8	15.3	10.7	10.7	14.5	15.9
17	16.0	17.4	14.7	15.1	10.7	10.8	14.5	15.9
18	16.3	17.0	14.6	15.1	10.5	10.5	14.5	14.8
19	19.4	23.9	14.7	17.5	10.6	10.4	17.3	16.2
20	15.6	16.9	15.1	15.4	12.2	12.2	15.1	16.1
21	15.5	16.6	15.1	15.2	11.9	12.0	14.9	15.6
22	15.6	16.5	14.8	15.1	11.2	11.2	14.4	15.5
23	15.7	16.9	14.7	15.0	11.0	11.0	14.5	15.5
24	15.7	16.9	14.6	15.0	10.9	11.0	14.4	15.5
25	15.6	17.1	14.5	14.8	10.8	10.8	14.3	15.5
26	16.4	17.4	14.6	15.0	10.8	10.9	13.5	15.1
27	16.0	17.2	14.8	15.3	9.7	9.9	14.1	15.3
28	14.2	15.3	13.8	14.0	10.4	nd	13.2	14.0
29	18.2	20.4	15.6	16.7	10.7	11.0	15.1	17.0
30	18.8	19.0	16.9	17.1	10.9	11.1	15.6	15.6
31	17.0	17.9	16.0	16.2	10.5	10.6	15.4	16.2
32	17.0	17.9	16.1	16.4	10.7	10.8	15.3	16.1
33	15.4	16.2	15.1	15.3	10.4	10.6	14.2	15.2
34	14.3	14.4	14.6	14.6	9.2	9.3	13.6	14.0
35	11.9	12.1	11.9	12.0	10.2	10.2	11.3	11.4
36	13.9	15.2	13.4	13.9	10.0	nd	12.7	13.7
37	16.7	17.4	14.5	14.7	10.7	10.5	15.2	15.8
39	21.5	22.4	15.0	16.2	14.3	14.2	21.9	23.9
40	17.3	18.4	13.7	14.4	10.3	10.4	14.3	15.5
41	nd	nd	16.4	15.6	10.3	11.3	16.8	18.1
42	15.2	15.7	14.3	14.4	10.1	11.4	13.7	14.6
43	14.4	15.1	13.3	13.6	10.9	11.0	13.1	14.6
44	18.0	18.7	14.0	15.7	9.9	10.3	15.5	16.5
45	24.0	24.4	17.5	16.8	9.0	9.2	19.3	21.3
4444	nd	nd	nd	nd	9.7	10.5	12.6	12.9

pH								
sample	August 28, 2011		September 27, 2011		April 11, 2012		July 10, 2012	
number	AM	PM	AM	PM	AM	PM	AM	PM
1	nd	nd	nd	nd	7.36	7.90	nd	nd
2	8.18	7.84	7.52	7.79	7.19	7.76	nd	nd
3	7.19	7.36	6.93	7.72	7.14	7.56	nd	nd
4	7.64	7.99	7.25	7.85	7.23	7.63	nd	nd
5	7.08	7.14	6.90	7.38	7.26	7.61	nd	nd
6	7.29	7.30	7.27	nd	6.79	6.96	7.31	7.39
7	7.69	7.32	7.64	7.67	7.11	7.09	7.71	8.15
8	7.86	7.95	7.88	7.89	7.29	7.28	7.87	8.22
9	7.82	7.87	7.87	7.90	7.22	7.22	7.78	8.25
10	7.34	7.91	7.88	7.90	7.30	7.28	7.86	7.93
11	7.90	7.98	7.91	7.93	7.34	7.32	7.88	7.99
12	8.09	8.14	7.89	8.04	7.99	8.02	nd	nd
13	8.16	8.13	7.91	7.91	7.99	7.88	nd	nd
14	7.36	7.88	7.51	7.54	7.22	7.24	7.78	7.92
15	7.94	8.01	7.47	7.47	7.31	7.32	7.30	7.38
16	7.92	7.99	7.53	7.51	7.29	7.28	7.30	7.36
17	7.94	8.03	7.58	7.60	7.38	7.25	7.35	7.41
18	6.48	6.60	6.66	6.65	6.05	6.26	6.46	6.85
19	7.03	7.37	6.66	6.90	5.68	6.87	5.94	6.59
20	7.19	7.21	6.95	6.67	6.80	6.89	6.62	6.79
21	7.39	7.39	6.98	6.99	6.94	6.98	6.76	6.82
22	7.86	7.74	7.47	7.55	7.38	7.46	7.18	7.27
23	8.05	8.02	7.71	7.80	7.60	7.70	7.39	7.46
24	8.09	8.10	7.79	7.34	7.64	7.71	7.50	7.50
25	8.11	8.16	7.78	7.85	7.55	7.63	7.46	7.50
26	7.75	7.37	7.60	7.71	7.32	7.37	7.60	7.80
27	7.71	7.66	7.38	7.46	7.04	7.11	7.15	7.17
28	7.99	7.99	7.36	7.38	7.40	10.60	7.43	7.41
29	7.74	7.80	7.42	7.47	6.87	7.02	6.84	6.86
30	7.80	7.85	7.33	7.73	7.64	7.71	nd	nd
31	7.84	7.95	7.42	7.78	7.71	7.77	nd	nd
32	7.48	7.53	7.11	7.38	7.65	7.80	nd	nd
33	7.75	7.79	7.38	7.75	7.80	7.88	nd	nd
34	6.78	6.95	6.50	7.18	7.27	7.63	nd	nd
35	7.18	7.28	7.25	7.24	6.79	6.88	7.17	7.26
36	7.55	7.39	7.14	7.52	7.33	10.20	nd	nd
37	7.91	7.46	7.29	7.30	6.95	7.01	7.30	7.40
40	7.79	7.81	7.62	7.69	7.14	7.23	7.74	7.79
41	nd	nd	7.86	7.96	8.05	7.77	nd	nd
42	7.66	7.68	7.84	7.63	6.86	7.12	7.61	7.67
43	8.08	8.06	7.92	7.90	7.43	7.29	7.47	7.43
44	7.70	8.23	7.25	7.52	7.22	7.08	6.86	7.30
45	8.86	8.91	8.11	7.81	7.38	7.71	7.66	8.58
4444	nd	nd	nd	nd	7.15	6.95	7.11	7.12

dissolved oxygen (mg/l)								
sample	August 28, 2011		September 27, 2011		April 11, 2012		July 10, 2012	
number	AM	PM	AM	PM	AM	PM	AM	PM
1	10.1	9.8	5.3	nd	7.7	8.1	3.7	4.4
2	6.8	8.2	4.9	4.7	7.1	8.5	5.1	5.9
3	4	4.2	4.4	5.3	6.3	7	2.1	3.5
4	8.7	9.8	8.2	8.5	9.7	10.6	7.6	8
5	0.61	0.58	3	3.1	4.5	4.5	1.5	2.2
6	8.5	8.5	8.1	nd	9.4	9.5	8.4	8.4
7	9.7	8.9	8.4	9.8	10.3	11.2	10.3	10.7
8	9.6	8.6	9.6	9.7	11.1	11.2	10.2	10
9	10.1	9.8	10.2	9.9	11	11.1	10.3	10.1
10	9	9.2	9.4	9.3	11	10.6	10.3	9.9
11	9.2	9.5	9.6	9.8	10.8	9.6	10.2	9.8
12	9.5	9	9.3	9.3	12.1	11.5	7.8	9
13	9.4	9	8	7.3	11.3	11.7	7.9	8.2
14	9.1	8.6	7.4	7.9	10.8	9.7	9.9	9.6
15	9.1	9.3	9	8.6	10.8	10.4	9.8	9.9
16	7.9	8.4	7	7.1	9.5	9.7	8.6	9.3
17	8.1	8.5	8.8	8.8	10.3	10	9.3	9.6
18	1.1	2.7	3.2	2.6	4.9	6.3	4.4	4
19	4.5	7.3	4.5	5.7	7.8	8.3	6.3	6.4
20	5.5	6.6	6	5.7	7.8	8.7	6.2	7.5
21	7.1	7.2	6	6.2	8	8.4	7.1	7.1
22	8.6	8.6	8.9	9.3	10.7	11.4	9.1	9.3
23	9.2	9.1	9.7	9.7	10.7	11	9.8	9.8
24	7.7	8.5	8.5	7.7	11.3	10.6	9.6	9.6
25	9.2	9.1	9.5	9.5	10.3	11	9.9	9.6
26	9	8.4	9.2	9.4	11.2	10.2	9.1	8.6
27	7.7	6.7	8.1	8.3	10.4	10.2	9.1	9.3
28	9.2	8.8	10.2	8	10.5	10.7	10.6	10
29	8.8	8.5	9.1	8.3	9.7	8.9	8.3	7.4
30	9.2	6.8	8.5	8.6	11	11	7.5	7.9
31	7.4	7.6	6.5	6.6	10.3	10.2	6.7	6.7
32	0.92	1	1.7	1.3	8.1	9.1	4.7	4.9
33	7.8	7.2	7.9	7.6	10.5	10.1	7.1	7.3
34	0.1	0.1	1.9	1.8	6	6.7	2.1	2.7
35	8.7	8.7	8.3	8.4	8.2	8.7	7.9	7.9
36	7	6.4	5.5	5.7	7.7	nd	6	6
37	8.1	7.8	7.7	8	10.1	10.7	8.7	9.1
39	2.3	2.1	7.7	7.9	6.8	7.7	4.8	6.8
40	8.3	8	8.7	8.4	9.8	8.2	9.8	9.4
41	nd	nd	7.5	8.1	11.1	11.3	6.5	6.8
42	9.5	9.6	9.8	9.9	10.8	9.7	10.1	9.7
43	6.7	9.9	9.7	10.1	10.5	10.3	10.5	10.4
44	8.8	11.4	6	9	9.7	10.1	6.7	11
45	9.9	9.4	9.4	9.8	10.9	11.8	9.5	12.8
4444	nd	nd	nd	nd	10.8	10.3	10	10.1

Conductivity (μsiemens/cm)								
sample	August 28, 2011		September 27, 2011		April 11, 2012		July 10, 2012	
number	AM	PM	AM	PM	AM	PM	AM	PM
1	171	173	238	nd	95.5	96.1	97.3	104
2	156	157	174	176	145	144	216	125
3	233	242	171	174	181	182	171	173
4	164	195	187	188	209	209	212	184
5	174	174	202	187	172	171	149	146
6	256	256	243	nd	265	263	225	224
7	231	232	234	236	245	241	209	213
8	230	230	231	234	244	241	208	207
9	228	229	228	233	212	247	205	206
10	227	219	225	229	239	215	205	205
11	226	226	223	228	238	234	204	204
12	182	187	205	211	216	212	217	217
13	193	200	163	244	231	225	228	230
14	235	235	168	173	255	250	215	216
15	244	244	172	178	245	226	247	249
16	245	245	171	176	246	230	247	248
17	240	242	176	181	244	219	245	247
18	353	305	163	166	445	452	220	226
19	297	226	100	113	90.9	86	66.9	68.5
20	315	309	168	171	341	345	311	319
21	313	314	170	177	341	345	312	318
22	276	279	172	190	389	289	286	282
23	265	271	170	186	276	274	276	275
24	262	264	180	184	271	259	271	269
25	257	259	178	191	267	258	266	267
26	243	245	177	188	275	267	192	192
27	192	193	134	133	206	205	200	195
28	245	244	242	244	262	7.4	257	260
29	219	240	227	235	247	239	250	255
30	216	236	122	137	284	210	264	255
31	191	197	138	173	237	227	231	231
32	238	244	140	156	280	258	276	200
33	192	196	117	130	240	220	241	239
34	320	328	93.2	101	198	200	166	167
35	243	244	249	250	273	272	230	229
36	161	167	187	196	166	nd	199	199
37	205	205	164	168	210	208	185	186
39	218	228	159	167	227	226	186	188
40	208	210	211	213	220	214	228	230
41	nd	nd	238	170	265	118	257	259
42	112	232	241	241	252	89.2	220	219
43	230	232	233	233	233	185	239	240
44	321	329	291	295	275	192	299	295
45	100	101	126	176	139	126	109	111
4444	nd	nd	nd	nd	275	112	284	297