2016

Water Quality in False Creek

For Policy Makers

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CITY OF VANCOUVER | GREENEST CITY | UBC sustainability

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Executive Summary

This report was created as part of the Greenest City Scholar program, a coordinated effort between the University of British Columbia and the City of Vancouver to help the city reach its goals laid out in the Greenest City 2020 Action Plan, while providing invaluable opportunities for UBC students. This project, entitled “Understanding patterns of water quality and environmental health in False Creek”, relates to the Greenest City 2020 goal #6, “Access to Nature”.

This project was broken down into 5 objectives:

1) Determine the long-term spatial and temporal patterns of *E. coli* and fecal coliform concentrations in False Creek.
2) Analyse environmental variables, and determine if any are correlated to *E. coli* or fecal coliform levels.
3) Improve our understanding of the sources of *E. coli* in False Creek.
4) Further our understanding of the relationship between the mid-channel and shoreline of False Creek.
5) Collect water chemistry variables; therefore, increasing knowledge of False Creek and determining correlations to *E. coli* concentrations.

Two approaches were undertaken to address these objectives. The first was to take a long-term perspective and examine patterns in data on *E. coli* and fecal coliform concentrations collected from shoreline sites by Metro Vancouver from 1993-2016, and examine possible correlations to environmental data. The second approach was first-hand research, with *E. coli* samples collected from False Creek, and water chemistry variables measured on site in July 2016.

Results

Spatial and temporal patterns of *E. coli* in False Creek

From 2013-2016, *E. coli* concentrations increased west to east, with the highest concentrations along the eastern shoreline. Shoreline values in east False Creek are consistently higher than mid-channel values, suggesting *E. coli* are either originating from, or getting caught along, the shoreline. Fecal coliform trends from 1993-2012 were similar, increasing west to east. Fecal coliform concentrations were higher in the winter, often exceeding secondary contact guidelines. There are not currently enough winter *E. coli* samples from 2013-2015 to discern a seasonal pattern. There is no consistent timing to summer peaks in *E. coli* concentrations from 2013-2016.

Correlations between E. coli or fecal coliform and environmental variables

There is a significant positive correlation between temperature in Vancouver Harbour and *E. coli* from 2013-2015 in False Creek at temperatures above 11°C. This suggests that in summer months, as temperatures rise, either *E. coli* survival increases or there are higher inputs of *E. coli*. Higher fecal coliform counts were found in the colder, winter months than in the summer months from 1993-2012. This could be due to changing sources of *E. coli* in False Creek over time, as all but one CSO outfall have been separated in False Creek. More CSOs combined with high winter precipitation may have meant more fecal coliform inputs in the winter. A positive correlation was found between the preceding 24 hours of precipitation and fecal coliform from 1993-2012 in all three basins, and at all sites, further supporting this theory. Only two sites had *E. coli* concentrations significantly positively correlated precipitation from 2013-2015, both of which were near the CSO. This suggests precipitation had a more significant effect on fecal coliform concentrations in the past then it currently does on *E. coli*.

Salinity data were conflicting, with both positive and negative correlations with *E. coli* and fecal coliforms over time and space. This could be due to its brackish waters, as salinities are lower in False Creek than in open oceans. It is also possible that the salinity and fecal coliform concentrations are responding to a confounding variable that influences both. Solar, tide, and wind speed and direction were not found to have a significant correlation with the average 30-day geometric mean *E. coli* concentration from 2013-2015 in False Creek.

Sources of *E. coli* in False Creek

Temporal and spatial patterns suggest the sources of *E. coli* are likely localized and are not solely dependent on the time of year. Bacterial Source Tracking (BST) analysis revealed that elk, pig, horse, gull and ruminant animal strains were not found. The lack of ruminant animal *E. coli* strains suggests *E. coli* is not coming from manure, making contamination from urban farming unlikely. Dog strains were found at 3 of the 4 sites, suggesting stormwater runoff is collecting and carrying *E. coli* from dog waste. The rest of the *E. coli* in False Creek were from human or general strains. Possible human sources of contamination need to be narrowed down, but could include: combined sewer overflows, crossed connections, marinas and recreational vessels (i.e. illegal liveaboards, fishing boats, evening cruises, pleasure crafts), unauthorized inputs into the stormwater system, etc. Unfortunately, geese could not be directly tested for.

Relationship between mid-channel and shoreline of False Creek

Shoreline values provide an indication of mid-channel *E. coli* concentrations for most of False Creek. Only at sites BFC-04-03 (under Cambie St. Bridge) and BFC-04-04 (above Heather St. CSO) in central False Creek did shoreline values underestimate the mid-channel concentrations.

Physical and chemical properties of False Creek, and their relationship to *E. coli*

False Creek stratifies both chemically and thermally around 3-6 m. A warmer, lower salinity layer is found in the first 3-6 meters, with a cooler, higher salinity layer below. There is not a lot of variation among sample sites for most chemical variables. However, mid-channel sites tend to have slightly higher salinity and total dissolved solids. BFC-02-22 (behind Plaza of Nations) was the only site experiencing elevated nitrate and phosphorus concentrations, suggesting there may be local nutrient inputs. This could be from its resident goose population, from Sole foods urban farm, or from nearby stormwater outfalls. Mean air temperature in Vancouver Harbour is strongly correlated to water temperatures in False Creek. This suggests that as air temperature can be used as a proxy for water temperature when water temperature data is absent.

The concentrations of *E. coli* continue to increase west to east in False Creek, with the highest concentrations near Plaza of Nations or Science World. Since 2013, concentrations are often high at the start of the summer in April and May, so sampling should start a little earlier in the year. Negative correlations were found between *E. coli* concentrations and: conductivity, total dissolved solids, salinity, pH, and oxidation-reduction potential. There were not significant correlations between *E. coli* concentrations and temperature, oxygen, or turbidity. There may be another, over-riding correlation that may be masking or counter-acting the expected positive effects of temperature on *E. coli* concentrations. *E. coli* are able to survive in both aerobic and anaerobic environments, which is likely why oxygen was not correlated to *E. coli*. Nutrients do not appear to be supporting or limiting *E. coli* growth in False Creek. Turbidity and *E. coli* concentrations exhibited a positive relationship, but it was not statistically significant. This could be due to turbidity concentrations too low to have a large enough influence on *E. coli* survival to be statistically significant.

Primary and secondary guideline exceedances, 1993-2016

From 2013 to 2015, 43% of mean *E. coli* concentrations in central and 15% in west False Creek exceeded Canadian primary contact guidelines. In east False Creek, 77% of means exceeded primary and 27% exceeded secondary contact guidelines. With one exception, fecal coliform means for west, central and east False Creek were under the secondary contact guideline April-September, 1993 to 2012. The magnitude of *E. coli* concentrations in 2016 is lower than in 2014 or 2015. While east False Creek still regularly exceeds primary contact guidelines, secondary contact guidelines were not exceeded. Between 65% and 82% of the calculated geometric means of each of the 4 sites in east False Creek exceeded primary contact guidelines from 2013-2015, occasionally exceeded secondary contact guidelines and single-sample maximums.

Recommendations and Future Directions

1. **Health Canada's primary contact guidelines are regularly exceeded in False Creek; secondary contact guidelines are occasionally exceeded.** Water quality in 2016 has improved compared to 2014 and 2015; however, primary contact guidelines are still regularly exceeded, particularly in east False Creek. According to Vancouver Coastal Health, False Creek is not classified as a Primary Contact Recreational Water Body; therefore, it is not currently a swimming/bathing beach. For up to date *E. coli* concentrations in False Creek and all lower mainland beaches go to www.vch.ca.

2. **Collect more data to narrow down sources of *E. coli* from human waste**. BST analysis suggests that the majority of *E. coli* contamination in False Creek is human. Possible human-based sources of *E. coli* in False Creek are many, including: wastewater from boats, CSOs, crossed sewer connections, inputs to the stormwater system, etc. Sources of human-based *E. coli* contamination need to be uncovered, then reduced or eliminated.

3. **Understand the amount and spatial distribution of contamination through the stormwater system, and work to reduce it**. The presence of dog *E. coli* at 3 of the 4 tested sites, combined with 2 of the shoreline sites being correlated to precipitation, suggests some contamination is coming through the stormwater system. Samples from stormwater outfalls should be tested for *E. coli* to gain an understanding of amount and spatial distribution of *E. coli* in the stormwater system. The use of green stormwater infrastructure combined with a decrease in impervious surfaces should be supported.

4. **Shoreline sample sites are likely sufficient in False Creek**. Preliminary results from this study suggest that shoreline samples over-estimate the concentration of *E. coli* in the open water throughout most of False Creek, except under Cambie St. Bridge and over the Heather St. CSO. Further samples should be collected and analyzed to confirm shoreline sampling is consistently estimating the concentration of *E. coli*.

5. **Remove or improve dispersal of *E. coli* throughout False Creek**. *E. coli* is locally sourced or gets trapped along the edges of east False Creek. Changing the shape or improving water circulation would dilute high concentrations by dispersing *E. coli* throughout False Creek. Another option is to use bivalves, which filter large volumes of water, removing particulate matter including chemical contaminants, bacteria, and phytoplankton, which then accumulate in mussel tissues or settle out as excrement. Native species of mussels could be placed targeted locations around False Creek, restoring ecological functions while removing both biological and chemical contaminants.

6. ***E. coli* sampling such as sediment testing, winter samples, BST analysis and ecosystem interactions could provide insight into *E. coli* sources and patterns in False Creek**.

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Introduction

Greenest City Scholar Project

In July of 2011, Vancouver committed to a vision of becoming the greenest city in the world by 2020. To do so, they set 10 overarching goals, each with their own targets and strategies laid out in their Greenest City 2020 Action Plan (COV, 2011). The Greenest City 2020 vision is threefold, to create opportunities while building: a strong local economy; vibrant and inclusive neighbourhoods; and an internationally recognized city that meets the needs of generations to come (COV, 2011). To help achieve these goals, they partnered with the University of British Columbia (UBC), creating the Greenest City Scholar program. This program gives UBC graduate students the opportunity to take on interesting research projects related to the Greenest City 2020 goals. This project, entitled "Understanding patterns of water quality and environmental health in False Creek", relates to the Greenest City 2020 goal #6, "Access to Nature".

False Creek

False Creek is an inlet off English Bay that runs through the centre of the city, separating the downtown peninsula and the rest of Vancouver. It is currently used for numerous recreational activities including dragon boating, canoeing, kayaking, paddle boarding, dinner cruises, and pleasure crafts. Its user traffic will likely continue to increase, as developments continue to go up around False Creek, increasing the coastal population as well as growing tourism.

Much of the appeal of coastlines is the access to water; however, human development along coastlines can have significant human health and environmental consequences, and natural ecosystem functions can become compromised (Mallin et al., 2000). In False Creek, water activities are restricted. Signs are posted stating "Water Not Suitable for Swimming", and secondary contact activities proceed with caution. This is due to high levels of *E. coli*, which can signal high levels of associated fecal coliforms, bacteria, protozoa, and viruses (Health Canada, 2012). Health Canada has set the Canadian Recreational Water Quality Guidelines (referred to as "guidelines" going forward), splitting them into primary and secondary contact guidelines. False Creek is regularly above the primary contact guideline of a 30-day geometric mean of 200 *E. coli*/100 mL, and a single sample maximum of 400 *E. coli*/100mL (Health Canada, 2012). Even the secondary contact guidelines of a 30-day geometric mean of 1000 *E. coli*/100 mL can occasionally be exceeded.

Background Information

The waters of False Creek were used industrially for over a century, starting late in the 19th century. This led to severe contamination of the water and its sediments with high fecal coliform counts, heavy metals, and other toxins exceeding acceptable levels (COV, 1974). Plans began in the 1970s to convert lands adjacent to False Creek from industrial uses to recreational, residential, and commercial uses (COV, 1974). With these intentions to change the use of land around False Creek, plans to improve the quality of the water and remediate the soil began to occur in earnest. Millions of dollars were spent to improve the sewer system in False Creek beginning in the 70s, with the intention of eliminating further pollution to the creek from sewers. Creek bottom deposits containing toxic elements detrimental to sea bottom life and shore side life were removed.

By 1990, Metro Vancouver was regularly collecting water samples and measuring fecal coliform concentrations throughout False Creek. In 1995, fecal coliform concentrations were examined in relation to combined sewer overflows (CSOs), rainfall, tides, salinity, and Fraser River flows (Sea Science, 1997). It was found that fecal coliform was better correlated with rainfall than with CSO discharge events, and fecal coliform geometric means were positively correlated with peak flows in the Fraser River.

As of 2002, more westerly sites in False Creek showed significantly higher concentrations of fecal coliforms during the winter season (October to March) than in the summer season (April to September); however, this relationship did not extend to the easterly sites (BC MOE, 2006). Precipitation, salinity, and CSO discharges were not strongly correlated with fecal coliform, though precipitation was weakly positively correlated (BC MOE, 2006). Rain events could be used to predict elevated fecal coliform concentrations associated with CSO discharges, as the two were found to have a strong correlation; however, there were also periods during which elevated fecal coliform levels did not appear to be directly related to environmental conditions (BC MOE, 2006).

In 2006, water use designations were updated, and water quality objectives set, for many of the largest and most heavily used waters in B.C. False Creek was designated for aquatic life and wildlife, and secondary contact recreation, but was deemed not acceptable for primary contact (BC MOE, 2006). Water quality parameters were measured for some of the waterbodies, but False Creek was not among them (BC MOE, 2006). In 2013, Metro Vancouver changed from measuring fecal coliforms to *E. coli*, with new research and water quality guidelines suggesting that *E. coli* are a better indicator of the likelihood of dangerous pathogens than fecal coliforms (Health Canada, 2012).

In recent years False Creek has been in the news for its abnormally high *E. coli* concentrations during the summer months. In light of this, several directors of the Vancouver Board of Parks and Recreation have stated the problem of high *E. coli* concentrations in False Creek needs to be addressed. They called for a better understanding of the sources of *E. coli*, and to determine the most pressing and addressable issues and their corresponding remedies (Evans and Wiebe, 2015). In order to address these issues, they started a campaign with three slogans to address some of the possible sources of *E. coli* contamination. They include: “Scoop the poop,” “Put waste in its place,” and “Pump, don’t dump.”

In May of 2015, the City of Vancouver passed a motion to: *"Direct staff to address the Park Board objective (to work with interested government agencies and departments, non-government organizations and individuals to achieve a goal of zero beach closures), in staff's ongoing work on the Integrated Stormwater Management Plan."* Part of this involved creating a working group to bring together the different stakeholders involved in water quality in False Creek. This includes various departments of the City of Vancouver, Metro Vancouver, Vancouver Coastal Health, Vancouver Fraser Port Authority, Vancouver Board of Parks and Recreation, B.C. Ministry of the Environment, and Transport Canada. They met several times throughout 2015 and 2016, and are working collaboratively to improve the situation in False Creek. All agencies agree that the issue is complex and sometimes perplexing, and ongoing inter-agency work is required to consistently achieve zero beach closures and improve False Creek water quality.

Possible Sources of Contamination

The exact sources of *E. coli* contamination in False Creek are unknown. Determining the sources of contamination in urban areas is difficult, as stormwater infrastructure is complex and pollutant sources of *E. coli* are variable (Chen and Chang, 2014). The following list is not comprehensive, but discusses some of the suspected sources of contamination in False Creek.

Combined sewer overflow (CSO)

The original system of stormwater management in Vancouver was to combine sanitary sewage with stormwater in a system called a combined sewer system. Stormwater was piped with the wastewater and sent to water treatment plants. The systems were built to handle existing and future sanitary flows, but only a portion of the stormwater runoff (Sea Science, 1997). Unfortunately, this means that during heavy precipitation events the capacity of the system is exceeded, and any extra sewage stormwater mix that cannot be handled overflows through a combined sewer overflow outfall into local waterbodies. In the 1950's, people began to realize that False Creek had a severe fecal coliform contamination problem, and by 1960 they started to work on improving it (Crowe, 2014). By 2000, direct sewage discharge into False Creek had decreased by over 95% (Crowe, 2014).

By 2010, all but 2 combined sewer overflow (CSO) outfalls in False Creek had been separated (BES, 2010). The first, at the foot of Crowe St. East, had an annual overflow volume of 92,300 m^3, and a yearly duration of 35 hours (BES, 2010). The other is at the foot of Heather St., with an annual overflow volume of 3,652,000 m^3 over a total of 495 hours (BES, 2010). The Crowe Street CSO was separated in 2013, and should have resulted in a 50% reduction in discharges (BC MOE, 2006). The Heather St. CSO is currently active, and is likely a source of *E. coli* during heavy precipitation events.

While the City of Vancouver is currently working on the separation of all sewers, it is a time intensive and expensive project (Crowe, 2014). Therefore, they have been working on a replacement rate of approximately 1% a year since the mid 1900s. They plan to have the Heather CSO separated by 2040 (BC MOE, 2006), with all CSOs separated by 2050 (Crowe, 2014).

Stormwater outfalls and runoff

In addition to the CSOs, False Creek has 17 stormwater discharge points owned by the City of Vancouver. While these are unlikely to be a source of household waste contamination, they can still pick up any overland sources of *E. coli*, such as animal waste (dogs, birds, etc.), as well as any illegal deposits into the stormwater system. Illegal discharges into the system could include: water waste from food trucks; water runoff from urban farm operations; recreational vehicles releasing their waste over storm drains, etc.

Crossed sewer connections and system failures

Another possible source could be cross-connections between sewers and stormwater drains for one or more of the stormwater discharges located in the east basin of False Creek. (BC MOE, 2006). A clogged pipe was found by the City of Vancouver in 2015 at the end of Terminal Ave., and has since been fixed, resulting in a decline in effluent discharge into False Creek and a corresponding drop in *E. coli* concentrations.

Discharges from marinas and recreational vessels

In Canadian waters, it is illegal to discharge human waste from a pleasure craft less than 3 nautical miles offshore. However, studies have shown that the use of pump out facilities are low (Sea Science, 1997), and recreational vessels often ignore this law, discharging human waste closer to shore than legally allowed. Anecdotal evidence has suggested that *E. coli* concentrations can peak after major events in nearby waters that draw boats, such as the Festival of Lights. In addition, marinas often unknowingly harbour illegal liveaboards that are not properly hooked up to the city's waste treatment facilities, as legal liveaboards would be.

Vancouver has attempted to reduce the release of sewage from pleasure crafts in False Creek through regulations. The federal government gave Vancouver special permission to require permits to anchor in False Creek. Permits are free, and allow boaters to anchor a maximum of 14 of 30 days during high season (April 1 – September 30) and 21 of 40 days in low season (October 1 – March 31) (BC MOE, 2006). In the summer of 2015, the Vancouver Board of Parks and Recreation made the 2 city-owned pump out stations in False Creek free in an attempt to increase the use of pump out facilities and reduce the direct dumping of effluent.

Other possible marine-based sources of *E. coli* include fishing boats and evening cruises. As of 2006, 65% of the boats moored at the False Creek Harbour Authority (Fisherman's Wharf) were commercial fishing boats, which generally do not have holding tanks (BC MOE, 2006). There are also a number of evening cruises that take place in False Creek, primarily in the summer months, from the Plaza of Nations Marina. It is not known if these cruise boats have holding tanks, or if the tanks are emptied within False Creek (BC MOE, 2006).

Gulls and geese

Local populations of birds, including gulls and geese, exist throughout False Creek. They may contribute droppings directly into receiving waters, or they may be present on the beach and adjacent green areas and washed into receiving waters during rainfall (Sea Science, 1997).

Urban farming

Some suspect that runoff from urban farming operations around False Creek may contribute to the elevated *E. coli* concentrations. These farming operations often use manure to provide nutrients to plants. It is possible that water runoff from the farm contains *E. coli* if the manure is not properly treated, and could end up in storm drains.

Objectives

This project aims to improve our understanding of temporal and spatial patterns of *E. coli* in False Creek, as well as what environmental variables are correlated to *E. coli* concentrations. This is done with the intention of improving access to the waters of False Creek for current and future generations, contributing to the goal of improving citizen access to nature.

This goal can be broken down into the following main objectives:

1) **Determine the long-term spatial and temporal patterns of *E. coli* and fecal coliform concentrations in False Creek**. *E. coli* sample collection data available for False Creek goes back to 2013, while fecal coliform concentration data goes back to 1992. The data will be explored for spatial and temporal patterns in False Creek.
2) **Analyse environmental variables, and determine if any are correlated to *E. coli* or fecal coliform levels**. Examining the relationships between *E. coli* and fecal coliform concentrations and environmental variables such as air temperature, wind, tide, and precipitation will improve our understanding of what environmental conditions are correlated to *E. coli* or fecal coliform concentrations.
3) **Improve our understanding of the sources of *E. coli* in False Creek**. This will be accomplished through a technique called Bacterial Source Tracking (BST) that will aid in understanding which animals *E. coli* pollution is coming from.
4) **Further our understanding of the relationship between the mid-channel and shoreline of False Creek**. Collection of *E. coli* samples from the mid-channel of False Creek will improve our understanding of the representativeness of shoreline collection samples.
5) **Collect water chemistry variables, increasing knowledge of False Creek and determining correlations to *E. coli* concentrations**. Temperature and salinity profiles will be determined to understand the stratification of False Creek, as well as surface oxygen, turbidity, salinity, pH, nitrate, etc. The relationships between *E. coli* concentrations and the collected water chemistry variables will then be explored.

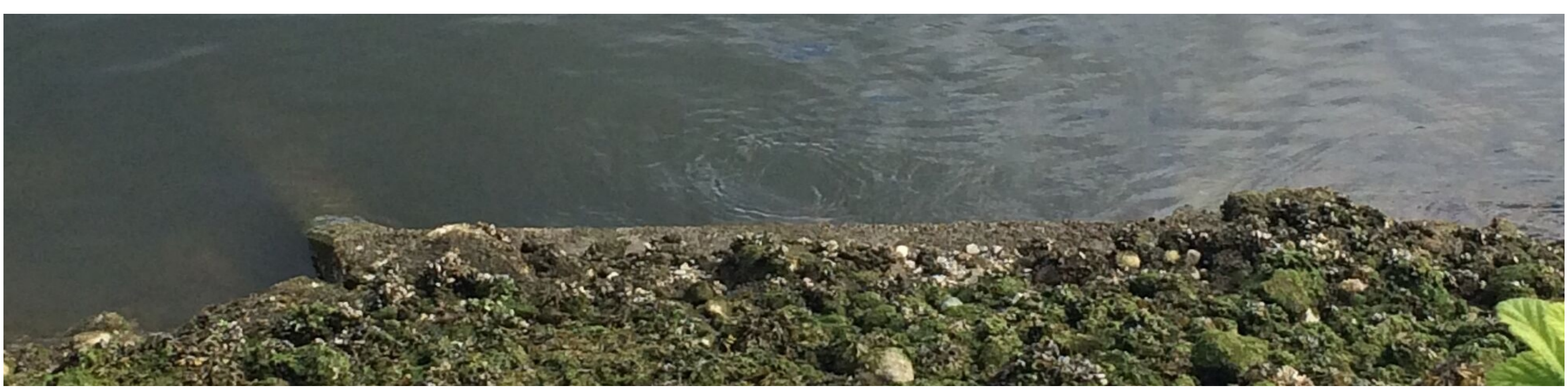
Literature Review

E. coli Growth and Survival

E. coli primarily exist in the intestinal tracts of mammals, and are released into the environment through the excretion of waste, with each individual human excreting up to billions of bacteria a day. *E. coli* can find their way to local waterways, soils, and beaches through combined sewer systems, stormwater runoff, misconnected sewer systems, and others (Williams et al., 2007). While some species of *E. coli* are safe for humans, others can be pathogenic and can lead to severe health impacts (Health Canada, 2012). *E. coli* are considered an indicator species, as they can indicate the presence of other, more pathogenic species of bacteria, viruses, and protozoa that can be dangerous to human health (Health Canada, 2012). As such, they are used as a proxy for water quality, with guidelines developed based on the relationship between concentrations of *E. coli* and the incidence of swimming-associated gastrointestinal illness observed among swimmers (Health Canada, 2012). In general, the higher the concentration of *E. coli* in water bodies, the greater the possibility that the water has been polluted by feces associated with pathogens (Chen and Chang, 2014).

E. coli can survive in different types of open environments including manure, soil, water, and sediments, and can migrate between these different environments (van Elsas et al., 2011). It has been found that some *E. coli* colonies can survive in excrement for up to 21 months, but individual bacteria usually survive 24 hrs to 40 days (Kudva et al., 1998). Their survival declines in soil, but colonies can still survive past 200 days at room temperature (Jiang et al., 2002). In open water, the combination of abiotic (water temperature, nutrients, pH, salinity, etc.) and biotic factors will influence the survival of *E. coli* (van Elsas et al., 2011), with most fecal coliform bacteria surviving only days in seawater (Šolić and Krstulović, 1992). Beach sands may provide a favourable environment for *E. coli*, permitting them to survive for longer periods than in the adjacent waters. Waves, storm surges, tidal activity and higher swimmer loads can transfer *E. coli* from the sands into the water body (Health Canada, 2012). Pathogens can still be recovered 5 days later from sand infected with *E. coli*, though tidal action can reduce the concentration of pathogens in the sand (Williams et al., 2007).

Various studies have shown that *E. coli* concentrations are related to water chemistry, physical characteristics of the water body, as well as the pre-existing biological community (Chen and Chang, 2014). This section attempts to break these down further, examining the effects of specific chemical, physical and biological characteristics to improve our understanding of what could be affecting *E. coli* survival in False Creek.



Chemical Factors

Nutrients (Nitrates and Phosphates)

E. coli are able to obtain diverse nutrients in open environments, but are still dependent on a minimal concentration of nutrients (van Elsas et al., 2011). Nutrient scarcity will reduce *E. coli* survival (van Elsas et al., 2011), while higher nutritional conditions can significantly prolong survival (Wcisło and Chróst, 2000, Williams et al., 2007). Nitrates in particular have been found to be strongly correlated to *E. coli* growth and survival (Mallin et al., 2000); nitrate concentrations above natural seawater levels (> 1 ppm) can improve survival rates of *E. coli* while limiting survival at unnaturally low levels (<.1 ppm) (Carlucci and Pramer, 1959). Higher phosphorus concentrations can prolong the survival of *E. coli* in water (Juhna et al., 2007), but they are only weakly correlated with abundance (Mallin et al., 2000). It is unlikely nutrients will have a strong effect on *E. coli* concentrations in False Creek, as winter nitrate levels are within the normal survival range, around 0.5 mg/L (Anony et al., 2015).

Salinity

Salinity influences the survival of *E. coli* to such a strong degree that *Enterococci* are considered the fecal coliform bacterial indicator of choice in open ocean waters (Health Canada, 2012). Increased salinity is generally associated with declines in *E. coli* survival (Šolić and Krstulović, 1992; Williams et al., 2007). However, this effect is more pronounced at high salinities, and has less of an impact on concentrations at low salinities (Mallin et al., 2000). The water in False Creek is considered brackish, as it has significant inputs of freshwater. Therefore, salinity may not have a large effect on *E. coli* in False Creek.

pH

E. coli in open environments have an optimum pH between 6 and 7, with their survival declining above and below these values (Šolić and Krstulović, 1992). One study conducted in the winter of 2015 found pH in False Creek to be ~7.7 fairly consistently over a 4-month period (Anony et al., 2015); therefore, pH is unlikely to have a large impact on *E. coli* concentrations.

Oxygen

E. coli can function in environments with or without oxygen, even surviving oxygen levels 3x saturation level (Baez and Shiloach, 2013). There is generally a weak relationship between oxygen and *E. coli*, though it can be important for replication (Carlucci and Pramer, 1959). Oxygen is unlikely to affect *E. coli* concentrations in False Creek, as winter oxygen levels are within the normal range at ~10 mg/L (Anony et al., 2015).

Total Suspended Solids (TSS), Total Dissolved Solids (TDS), and Turbidity

Total suspended solids (TSS) and total dissolved solids (TDS) are similar measures that are both related to turbidity. The effect of TSS and TDS on the survival of *E. coli* can be counteracting. Sediments in the water column can bind to bacteria and remove them from the water column and trap them in sediments (Carlucci and Pramer, 1959). However, in urbanized environments *E. coli* concentrations may be correlated positively with TSS (Chen and Chang, 2014) and turbidity (Mallin et al., 2000). *E. coli* can be transported to streams bound to particulate matter, adsorbed onto resuspended stream bed particles (Chen and Chang, 2014), and can be protected from solar radiation by suspended sediments (Carlucci and Pramer, 1959). Therefore, it is possible that turbidity and TDS may have a weak positive or negative correlation with *E. coli* in False Creek.

Biological Factors

Urban Development

Urban development can have a significant impact on local waterways. Fecal coliform abundance has been positively correlated with watershed population; the percentage of land developed in a watershed; and the percentage of impervious surface coverage such as roofs, roads, driveways, sidewalks, parking lots, etc. (Mallin et al., 2000). These impervious surfaces can concentrate and convey storm water borne pollutants to downstream receiving waters (Mallin et al., 2000). By minimizing these impervious surfaces in urbanizing coastal areas, and increasing porous surfaces, waterborne health risks can be reduced (Mallin et al., 2000). Vancouver City Council recently passed a Rainwater Management Plan and Green Infrastructure Strategy, which aims to capture and treat 90% of Vancouver's average annual rainfall through the implementation of green infrastructure such as rain gardens, swales, and permeable pavements (COV, 2016). Upon implementation of these strategies, green infrastructure could reduce the concentrations of *E. coli* found in the urban runoff that reaches False Creek.

Ecosystem Interactions

Bacterial survival is dependent on what else exists in the environment with them. Ecosystems with a higher level of biodiversity are more resistant to disturbances such as *E. coli* than those with lower diversity (van Elsas et al., 2011). Microflagellates can increase the mortality of *E. coli* through grazing (Wcisło and Chróst, 2000), while protozoa have been known to either increase *E. coli* survival, or decrease due to predation and substrate competition (van Elsas et al., 2011). Ecosystem interactions such as predation and resource competition will not be looked at in this project. Future studies should consider looking into algal and zooplankton communities to gain a more thorough understanding of how they are interacting in False Creek.

Physical Factors

Temperature and Solar Radiation

Evidence for the relationship between *E. coli* and temperature is conflicting. Several studies have shown that die off rates for *E. coli* are higher as temperature increases in both field and lab experiments; however, this could be partially attributed to stronger sunlight radiation in warmer seasons as the effect is often more pronounced in the field than in the lab (Chen and Change, 2014; Ki et al., 2007; Šolić and Krstulović, 1992). Fecal coliform survival is known to decline with increased exposure to solar radiation (Šolić and Krstulović, 1992); however, the lethal effect of sunlight appears to decline past 20 cm of depth in the water column (Carlucci and Pramer, 1959). *E. coli* are also more likely to persist and grow in a warmer environment when sunlight exposure is limited (Chen and Chang, 2014).

Precipitation

E. coli concentrations can increase in response to storm events, as runoff can introduce new sources of *E. coli* into the waterbody (Chen and Chang, 2014). A significant correlation has been observed between *E. coli* and preceding rainfall events, which suggests that the antecedent rainfall conditions are likely to impact both the amount of water and energy available for *E. coli* transport and the amount of moisture present in a watershed that is critical for *E. coli* survival (Chen and Chang, 2014). Alternatively, if the main sources of *E. coli* in a waterbody are not due to runoff, then rainfall and higher flows can help to washout bacteria and dilute *E. coli* concentrations (Chen and Chang, 2014). Therefore, precipitation may be positively or negatively correlated to *E. coli* concentrations in False Creek.

Seasonality

E. coli concentrations often increase in the summer months and decrease in the winter months (Chen and Chang, 2014). Temperatures are warmer in the summer season, which corresponds to higher growth and survival rates of *E. coli* bacteria (Chen and Chang, 2014). Additionally, there is an increase in human and animal activities in the summer. This could lead to elevated *E. coli* levels in urban watersheds if, for example, domestic pet waste is a source of *E. coli* and there are more dog droppings around the city (Chen and Chang, 2014)

As *E. coli* bacteria are thermotolerant, the lower water temperatures during the winter season may inhibit the growth and survival of *E. coli* bacteria (Chen and Chang, 2014). Additionally, precipitation generally increases in winter months, which can effect *E. coli* concentrations (Chen and Chang, 2014). Previous reports suggest that fecal coliform concentrations in False Creek are high during the summer months, as well as in the winter months (BC MOE, 2006).

Tides

A weak positive correlation between tides and *E. coli* concentration and survival has been reported, but *E. coli* concentrations are often dominated by other processes (Ki et al., 2007). It is possible tides will have an influence on *E. coli* concentrations in False Creek.

Stratification

In the summer in temperate latitudes, stratification of water bodies can occur. The top layer receives more heat energy than can be transmitted through the entire water column, essentially creating two layers. The top become a warmer, less dense layer with colder, denser water below. Stratification can also be chemical in nature with a less dense, lower salinity layer on top of a denser, higher salinity layer. This stratification limits mixing in the water column, essentially decreasing the volume of water available to dilute the concentration of *E. coli*. Furthermore, *E. coli* distributions can be different laterally within a waterbody depending on the source(s) of the *E. coli* (Quilliam, et al., 2011). Therefore, it is likely that in False Creek *E. coli* concentrations will vary across the shoreline, and may have higher concentrations during times of the year when False Creek stratifies.

Size and Shape of False Creek

False Creek is long and narrow, with relatively low inflows of freshwater (BC MOE, 2006). The channel widths range from 100 to 400 m, with an average depth of 5 m, and a curved u shape (Sea Science, 1997). At Cambie Street Bridge, the mean depth is further reduced, which reduces the circulation between the east and west basins (BC MOE, 2006). This configuration can prevent flushing of the water in False Creek, resulting in little water circulation and promoting stagnation (COV, 1974; Sea Science, 1997, BC MOE, 2006). By the mid-20th century, False Creek was not receiving any tributary streams (BES, 2010). These factors combined with the restrictive nature of False Creek and its artificial constraints can reduce the speed at which *E. coli* and associated fecal coliforms are removed from the water (COV, 1974). Studies have suggested improving the flushing of False Creek to remove contaminates and pollutants, including fecal coliforms (COV, 1974; Sea Science 1997).

Methodology

Data Sources

Data received from external sources was integral to the project's success. Data was provided as outlined in Table 1. Air temperature and precipitation for Vancouver Harbour was selected over Vancouver International Airport for its proximity to False Creek. Wind speed and direction for Vancouver International Airport were used as Vancouver Harbour did not record it. Solar incidence was found online through NASA, but is not very detailed at 1-degree coverage.

Table 1: Sources, and a brief description, of data used in this report.

Data Description	Data Source
Fecal coliform concentrations in False Creek, from 1992 to 2012. Data were provided in raw counts, and as calculated 30-day geometric means.	Metro Vancouver
E. coli concentrations in False Creek, from 2013-2015. Data were provided in raw counts, and as calculated 30-day geometric means.	Metro Vancouver
Long-term salinity in False Creek, from 1992 to 2015.	Metro Vancouver
Temperature, precipitation, wind, tide	Government of Canada, climate.weather.gc.ca
Solar incidence	NASA

Data Collection

Another vital component of this project was first-hand data collection. While long-term *E. coli* and fecal coliform counts existed, as well as weather data, information about the water itself was largely absent. Little data existed around water temperature, water chemistry, mid-channel *E. coli* counts, and sources of *E. coli* in False Creek. The following sampling approaches were undertaken to attempt to address data gaps:

1. **Continuous temperature profiles**: Metro Vancouver has started to collect and report water temperature readings with their water sample collections for the 2016 sampling season. However, it is useful to have an understanding of water temperatures prior to *E. coli* sampling to better understand the conditions *E. coli* would exist under. HOBO TidbiT v2 temperature probes were installed 1 m below surface attached to a dock at Burrard and Heather Civic marinas in False Creek to collect detailed water temperature data. These probes measured water temperature every 30 minutes from June 9^{th} until July 27^{th}.

2. ***E. coli* sample collection from mid-channel**: Currently, Metro Vancouver collects *E. coli* samples from 12 locations around the shoreline of False Creek (Figure 1). This approach is sufficient on beach front areas in Vancouver; however, since False Creek is largely used by recreational boaters their use of False Creek is not confined to the shoreline. Therefore, it is useful to have an understanding of mid-channel *E. coli* levels, and how they relate to shoreline levels. Mid-channel samples were collected 5 times from 8 points across the East, Central, and West basins of False Creek in July 2016 (Figure 2). *E. coli* samples were mostly enumerated by Metro Vancouver, with one event analysed by ALS Environmental.

3. **Temperature and water chemistry profiles**: Minimal data are available for water quality parameters for False Creek. By taking water chemistry data using a YSI 6920 v2 probe, variables related to *E. coli* growth and survival can be monitored along current Metro Vancouver and mid-channel *E. coli* collection points. Metro Vancouver generously provided transportation to its 12 sites on their regular data collection days (Figure 1), with the 8 mid-channel collection points accessed by boat (Figure 2). Heather Civic Marina provided transportation to the boat sample collection points twice, while the final three were collected by rented boats from Granville Island Boat Rentals. Data collected includes: temperature, turbidity, dissolved oxygen (DO), pH, conductivity, oxidation reduction potential (ORP), total dissolved solids (TDS), and conductivity. In addition, water samples were collected from the shoreline and mid-channel once on July 19th, 2016 to determine total phosphorus (TP) and nitrate concentrations. Nutrient samples were analyzed by ALS Environmental. Temperature and salinity profiles were collected in 1 m intervals from mid-channel locations to determine if stratification occurs in False Creek. Depth profiles were collected on July 11th, 2016 to a depth of ~8m to avoid damage to equipment.

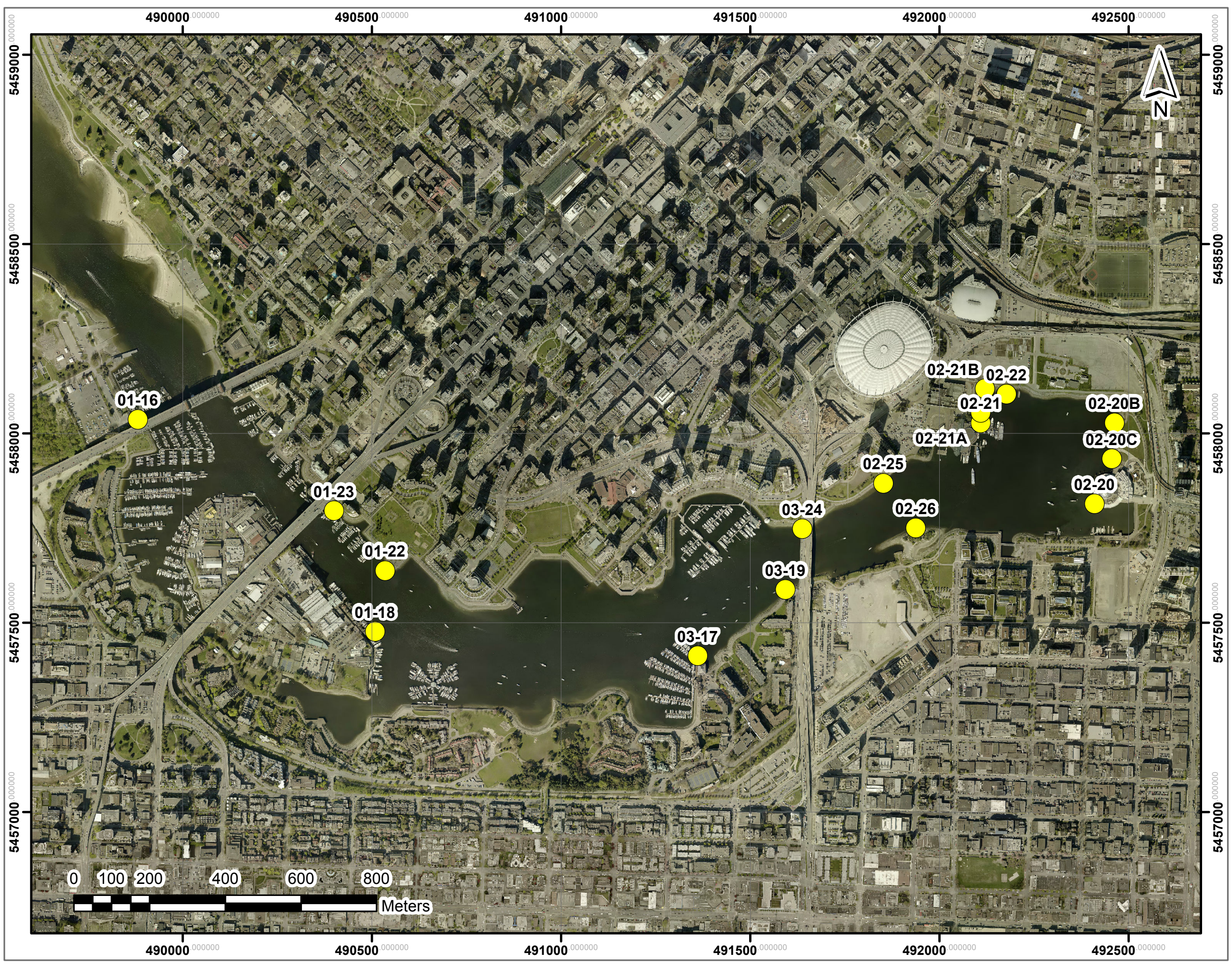


Figure 1: Metro Vancouver's False Creek (FC) shoreline *E. coli* collection points. 01 refers to west FC, 02 refers to east FC, and 03 refers to central FC. Sample sites 01-22; 02-21A; 02-21B; 02-20B; and 02-20C are currently inactive.

4. **Biological source tracking (BST)**: Bacterial source tracking uses genetic techniques to determine the sources of fecal bacteria in environmental samples. BST analysis can narrow down the sources of *E. coli* contamination in summer months by determining which animals the majority of *E. coli* pollution is coming from. 3 samples were collected for BST analysis in a previous study in January 2015 (Anony et al., 2015). After the samples were analyzed, it was confirmed that all three samples contained human fecal matter. Other suspected sources, such as gull and dog feces, were not found. However, False Creek experiences higher users in the summer, as well as frequently high levels of *E. coli*. In order to get a more complete picture of fecal contamination sources in False Creek, this analysis was completed again on samples collected on July 11th, 2016. 4 samples were collected from 4 of the mid-channel *E. coli* sample sites (BFC-04-01, BFC-04-02, BFC-04-04, and BFC-04-08 (Figure 2)). These samples were collected shortly after a rain event (32.2 mm of rain in the previous 36 hours) to ensure stormwater runoff sources were included.

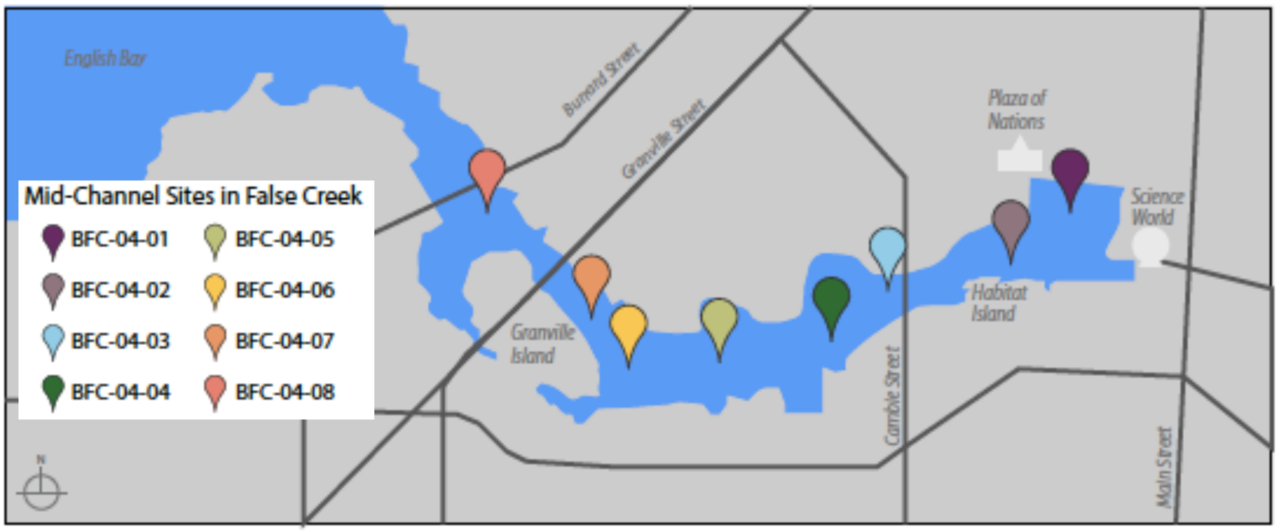


Figure 2: Map of the mid-channel sampling sites of False Creek, Vancouver, B.C.

Data Analysis

The normality of data was determined before any statistics were performed. If the data were not found to be normal, they were transformed using progressively more severe transformations until their distribution was normal. The following transformations were applied using Microsoft Excel:

- **No transformation**: air temperature (°C), salinity (mg/L; PSU), solar radiation (kWh/m^2/day), wind speed and direction (km/hr), water temperature (°C), pH, Oxygen (% and mg/L), ORP (mV), conductivity (µS/cm), TDS (mg/L).
- **Ln**: average geometric mean *E. coli* & fecal coliform for west, central, & east False Creek
- **Log_{10}**: site-by-site *E. coli* concentrations, turbidity (NTU).

Detection limits depended on the techniques being used and the bacterial indicator used. Generally, if a result was above or below the detection limit, the detection limit was used for that sample. Therefore, it is possible that some concentrations have been over estimated, and some have been underestimated.

To aid in examining spatial patterns, the 30-day geometric mean was calculated for each site from 2013 to 2015. Relationships between *E. coli* concentrations and environmental variables were examined. Data collected by Metro Vancouver prior to 2013 were fecal coliform concentrations; therefore, after correlations were examined between *E. coli* and various environmental variables from 2013-2015, the significant relationships were explored for fecal coliforms from 1992-2012 to provide a longer-term perspective.

Due to the relatively small size of the drainage basins around False Creek, water travel times from catch-basins near the top of the drainage, through the sewer system, and into False Creek is generally on the order of one hour or less (BC MOE, 2006). Therefore, a 24-hour precipitation period was selected, as rainfall in the preceding twenty-four hours is likely to affect bacterial levels. These precipitation data were not found to be normal; they were highly skewed and contained too many 0 values to be transformed easily. Therefore, no transformation was applied, and a non-parametric technique was used to examine the relationship between the concentration of *E. coli* in False Creek and the preceding 24 hours of precipitation. Spearman's rank correlation coefficient examines the relationship between the two variables using ranks instead of absolute values, and was used here. All other correlations were done using a Pearson correlation coefficient in the software R.

Results

Spatial and Temporal Patterns of *E. coli* and Fecal Coliform

Objective 1: Determine spatial and temporal patterns of *E. coli* concentrations in False Creek.

Spatial distribution of *E. coli* in False Creek, 2013-2015

In 2013, Metro Vancouver switched its indicator of sewage pollution from fecal coliforms to *E. coli*. General trends have emerged over the past 3 summers which match fecal coliform trends from previous research (Anony et al., 2015; BC MOE, 2006). One of the strongest recurring trends is that of increasing *E. coli* counts from the west to the east. The average geometric mean is consistently highest in east False Creek and lowest in west False Creek (Figure 3).

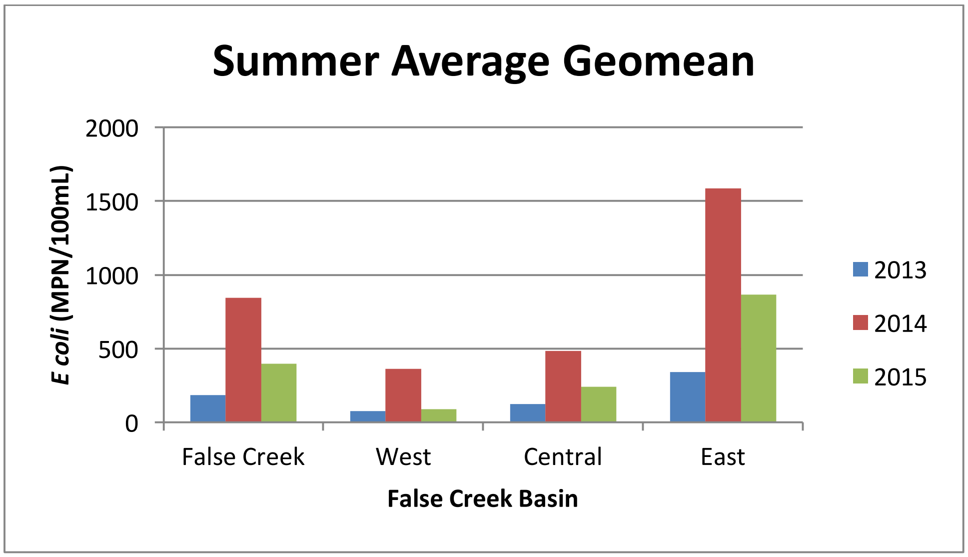
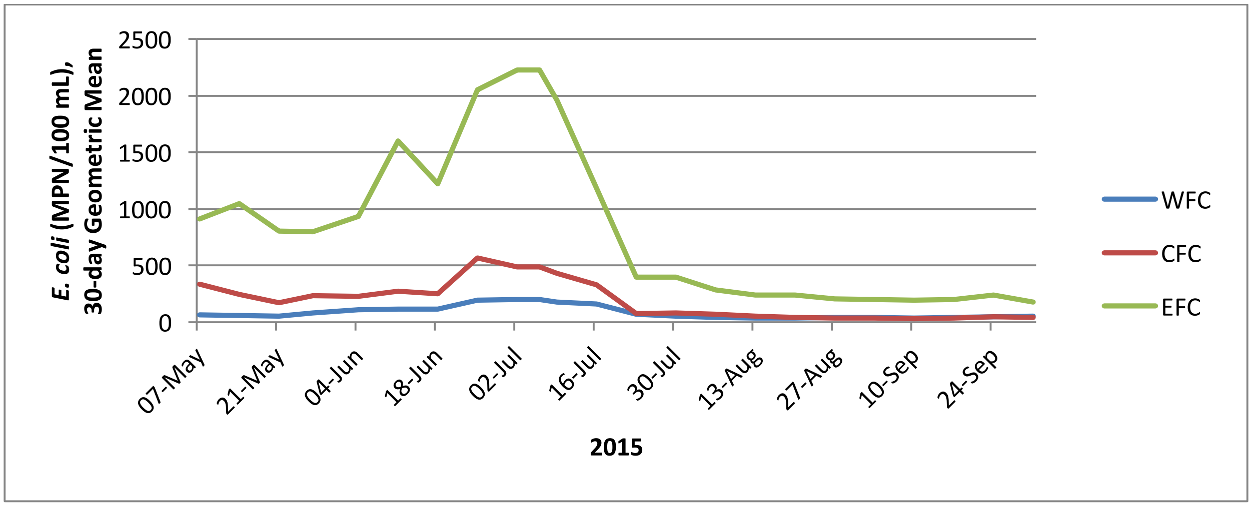


Figure 3: Average geometric mean of *E. coli* counts in False Creek. 30-day Geometric means were calculated and averaged for west, central, and east False Creek for 2013, 2014, and 2015. These were then averaged to find the yearly False Creek values.

Regardless of the year, the average *E. coli* geometric mean in the east basin of False Creek is above guidelines set by Health Canada for primary contact recreation, 200 *E. coli*/100 mL. In 2014, east False Creek exceeded the working secondary contact guideline of 1000 *E. coli*/ 100 mL by late July, and was still in exceedance in October when sample collection stopped (Figure 4). That same year, west and central average *E. coli* geometric mean exceeded secondary contact guidelines at the end of July, declining by the end of September. Both primary and secondary geometric mean contact guidelines were regularly exceeded in 2013-2015, with most exceedances occurring in east False Creek (Table 2). Exceedances were calculated as the % of calculated geometric means between May and September that exceeded the guideline.

Table 2: % Exceedances of the 30-day Geometric Mean Recreational Water Quality Guidelines, 2013-2015. Sites BFC-02-22 and BFC-02-26 were added in 2014, and contain 2 years of data.

% Exceedances of Recreational Water Quality Guidelines, 2013-2015									
	West False Creek	Central False Creek	East False Creek	East False Creek, by site (BFC-02-XX)					
				20	20A	21	22	25	26
Primary	15%	43%	77%	89%	64%	85%	66%	57%	43%
Secondary	4%	8%	27%	58%	17%	28%	28%	13%	18%

a)


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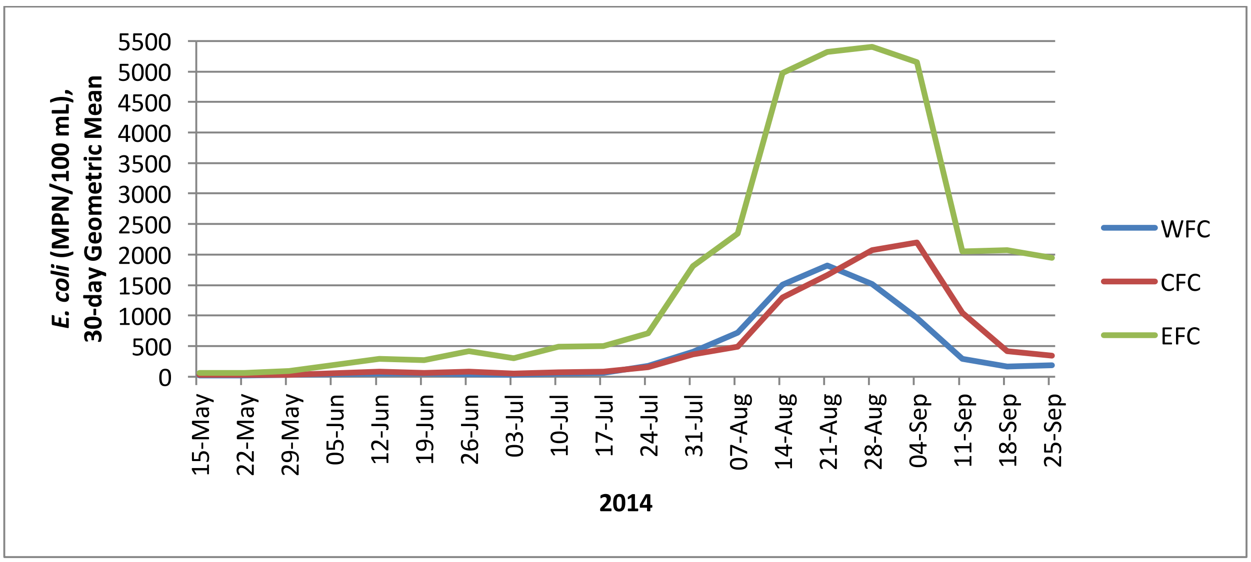


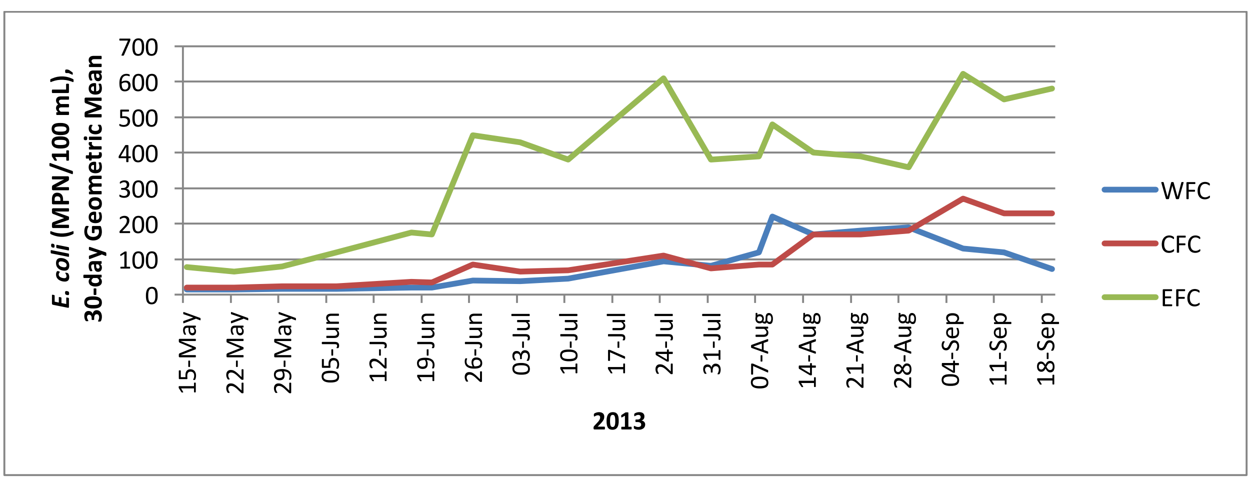
c)


Figure 4: The running 30-day geometric mean of *E. coli* concentrations in False Creek, broken down by western, central, and eastern basins for a) 2015, b) 2014 and c) 2013. Note: the y scales are different between the 3 years as different magnitudes of *E. coli* were reached each year.

Table 3: The % exceedances of primary and secondary contact *E. coli* single sample recreational water quality guidelines in False Creek, from 2013 to 2015. Sites BFC-02-22 and BFC-02-26

% Exceedances of the Single Sample Recreational Water Quality Guidelines, 2013-2015												
	West False Creek, by site (BFC-01-XX)			Central False Creek, by site (BFC-03-XX)			East False Creek, by site (BFC-02-XX)					
	16	18	23	17	19	24	20	20A	21	22	25	26
% primary exceedance	11%	20%	27%	24%	26%	35%	67%	43%	68%	70%	35%	45%
% secondary exceedance	4%	6%	5%	10%	9%	15%	47%	17%	18%	29%	18%	18%

Across May to September, 2013-2015, west False Creek met Canadian recreation guidelines more often then not, with 85% of 30-day geometric means meeting primary contact guidelines and 96% of them meeting secondary contact guidelines (Table 2). Central False Creek was compliant with primary contact guidelines 57% and secondary contact guidelines 92% of the time. East False Creek exceeded primary contact geometric mean guidelines 77% and secondary contact guidelines 27% of the time (Table 2). Site BFC-02-20 is located in front of Science Centre in East False Creek, and exceeds contact guidelines more often than any other shoreline collection site. 89% of the calculated geometric means exceed primary and 58% exceed secondary contact guidelines. When using single sample guidelines, samples from BFC-02-20 exceed primary contact guidelines 67% of the time, and secondary contact guidelines 47% (Table 3).

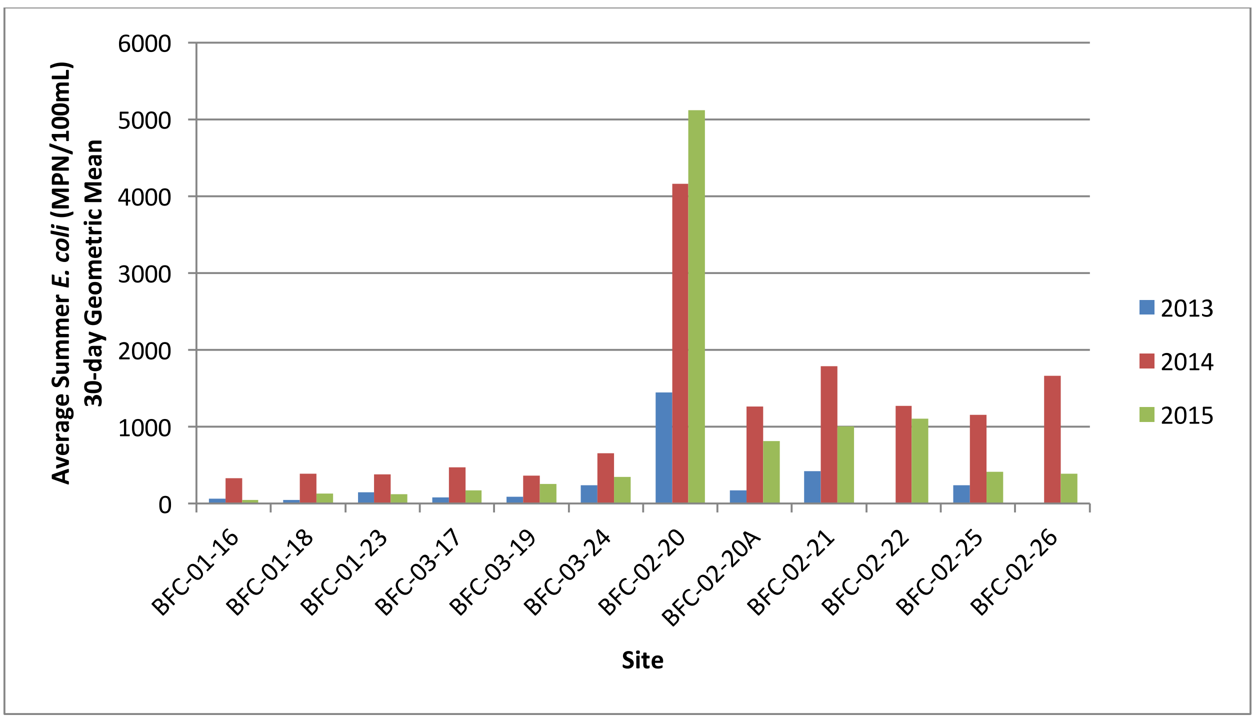


Figure 5: Average 30-day running geometric mean for 12 sites in False Creek for 2013, 2014, and 2015 summers. Sites BFC-02-22 and BFC-02-26 were added in 2014.

Examining the average 30-day geometric mean per site for each year further verifies that *E. coli* concentrations increase west to east in False Creek in the summer (

Figure 5). The eastern end of False Creek generally has the highest concentrations, regularly going over both primary and secondary Canadian recreational contact guidelines and bringing up the average geometric mean for False Creek. Across all 3 summers, BFC-02-20 consistently has the highest average *E. coli* concentration; however, sites BFC-02-22 and BFC-02-26 only started in 2014, so 2013 concentrations do not exist for these sites. Variability in *E. coli* counts between sites was highest in 2014, and in east False Creek.

Temporal distribution of *E. coli* in False Creek, 2013-2015

Examining the 30-day geometric mean *E. coli* concentrations for summer months in False Creek does not show an obvious consistent peak during a specific month (Figure 6). This is also true when breaking it out into west, central, and eastern basins (Figure 4). Few winter samples of *E. coli* are collected in False Creek from 2013-2015. The geometric mean for December of 2014 was 252 MPN/100mL, and 470 MPN/100mL for 2015. Neither of these reached the values of summer peaks, and both are within secondary contact guidelines.

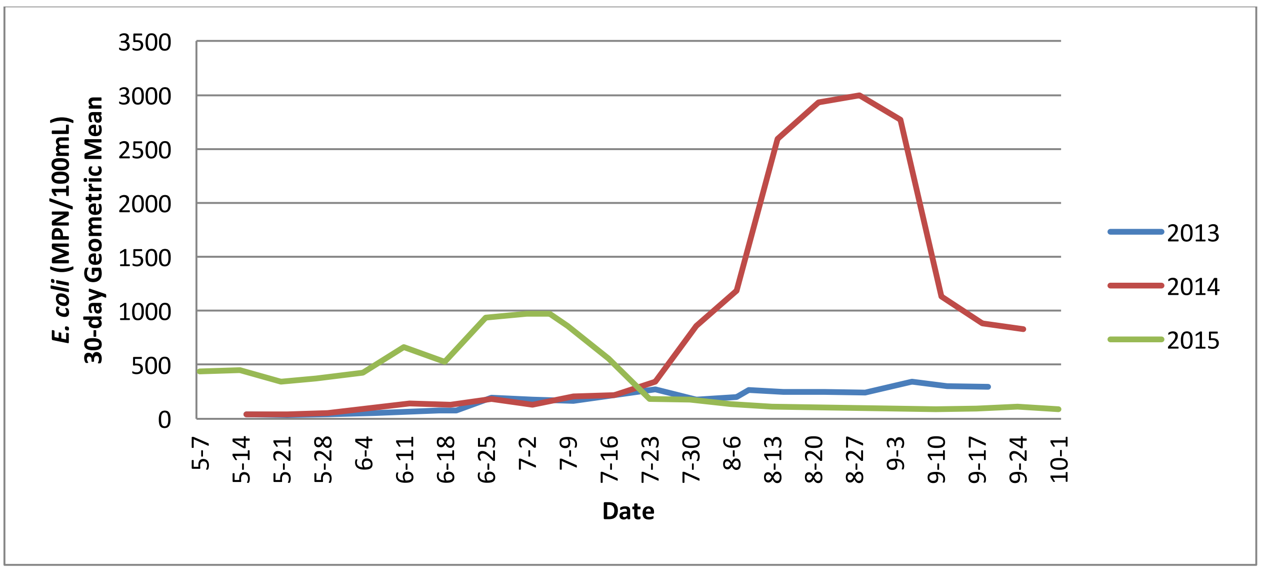


Figure 6: 30-day geometric mean *E. coli* for False Creek from May to Sept. for 2013, 2014, and 2015.

Fecal coliform in False Creek, 1993-2012

The spatial pattern of the highest concentrations of bacteria existing in east False Creek holds true for fecal coliform from 1993 to 2012 (Figure 7, Figure 9). Central False Creek was not treated as its own basin during fecal coliform collection until 2003. It is unclear what concentrations of fecal coliform would have existed in False Creek before 2003; however, after 2003 it had fecal coliform concentrations higher than west and lower than east (Figure 8).

Examining fecal coliform trends over time in False Creek, fecal coliform concentrations tended to be higher in the winter months. Winter sampling was much more common in the past; however, it was not done consistently. Over the years with winter sampling, counts exceeding secondary contact guidelines were much more common in the winter than summer. However, this was not always consistent as some years had higher fecal coliform concentrations in the summer.

With two exceptions in 2008 in east False Creek, monthly average 30-day geometric fecal coliform means for west, central, and east False Creek were under the secondary contact guideline of 1000 fecal coliforms/100 mL in the summer months (April to September) from 1993 to 2012. All other secondary contact exceedances that occurred were in the winter months (October to March) in central or east False Creek. Average monthly fecal coliform concentrations in west False Creek were consistently under secondary contact guidelines, and, with one exception in 2003 and one in 2008, were under primary contact guidelines in summer months.

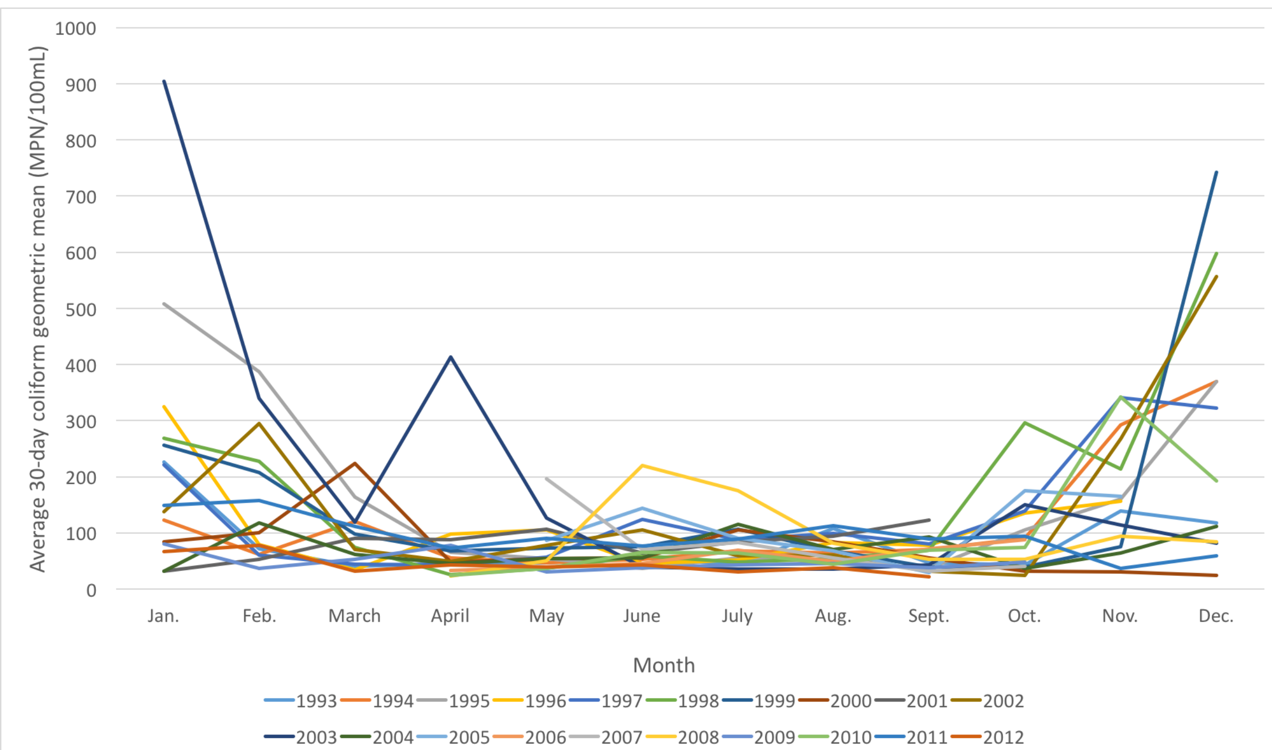


Figure 7: Average monthly 30-day geometric mean of fecal coliform counts for west False Creek, 1993-2012.

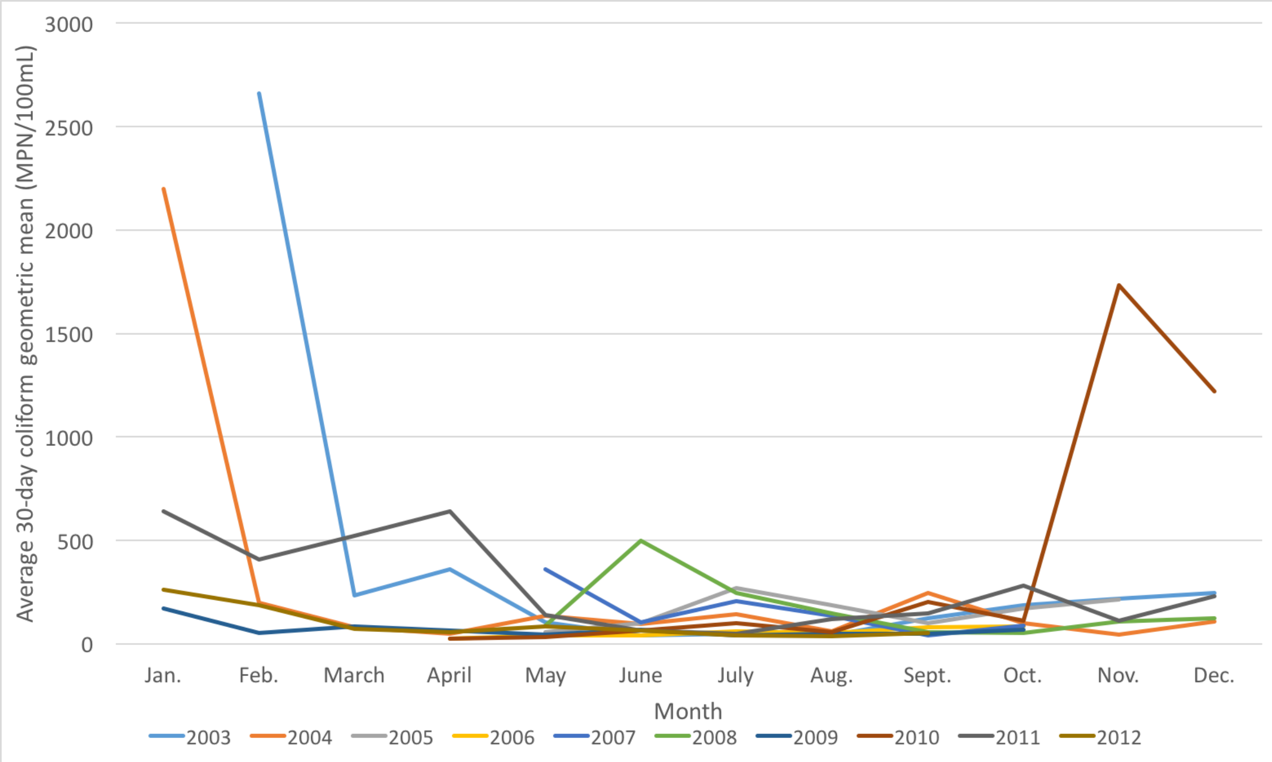


Figure 8: Average monthly 30-day geometric mean of fecal coliform counts for central False Creek, 2003-2012.

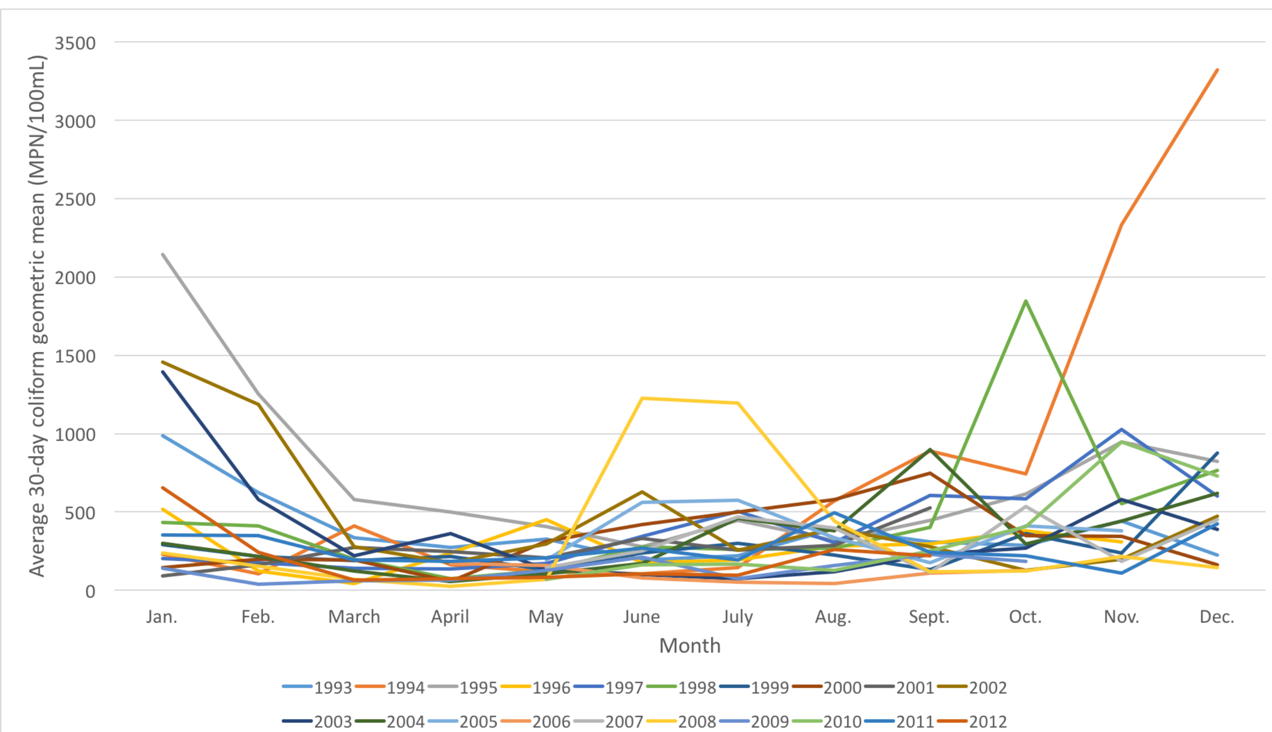


Figure 9: Average monthly 30-day geometric mean of fecal coliform counts for east False Creek, 1993-2012.

Environmental variables and their relationship to *E. coli*

Objective 2: Analyse environmental variables, determine correlations to *E. coli* & fecal coliform

Temperature

There is a significant positive correlation between air temperature in Vancouver Harbour and the average 30-day geometric mean for *E. coli* from 2013-2015 in False Creek at temperatures above 11°C (r=0.416, R^2=0.173, p=<0.001). However, in winter months where temperatures are below 11°C, this relationship appears to break down, with a lower correlation value and less variance explained (r=0.158, R^2=0.025, p=0.128).

When comparing air temperature to fecal coliform 30-day geometric means in False Creek from 1993 to 2012, a weak but significant negative relationship is found in west (r=-0.309, R^2=0.096, p=<0.001) and central (r=-0.345, R^2=0.119, p=<0.001), but not east False Creek. When examined without values below 11°C, the relationship breaks down and no correlations are observed.

Salinity

From 2013 to 2015, the average winter salinity was 23.8 psu, while the average summer salinity was 16.8 psu. There is a weak positive correlation between average salinity and the average 30-day geometric mean *E. coli* concentration from 2013-2015 in False Creek (r=0.208, R^2=0.0432, p=0.047). The relationship is slightly stronger in West and Central False Creek, but weaker and not significant in East False Creek (r=0.163, R2=0.016, p=0.121).

When fecal coliform bacteria concentrations are compared to salinity from 2006 to 2012 (salinity measured in PSU), a weak positive correlation was found for the central basin (r=0.166,R^2=0.028, p=0.002), and a weak negative correlation in the east basin (r=-0.190, R^2=0.036, p=<0.001). West and the average of all three basins were not correlated to salinity. When compared from 1993 to 2005 (salinity measured in mg/L), all three basins individually and averaged (r=0.251, R^2=0.063, p=<0.001) were found to be weakly positively correlated with fecal coliform.

Precipitation

A significant relationship was not found between average 30-day geometric mean for *E. coli* concentrations in False Creek from 2013-2015 and the preceding 24 hours of precipitation (spearman, rho=-0.070, p=0.502). High *E. coli* counts do not consistently coincide with high precipitation events; however, high precipitation events tend to coincide with high *E. coli* 30-day geometric mean concentrations. When examined site-by-site, there were two sites that were significantly correlated with precipitation: BFC-03-17 (Spearman, rho=0.295, p=0.00161), and BFC-03-19 (Spearman, rho=.263, p=0.00507).

A weak positive correlation was found between precipitation and 30-day geometric means of fecal coliform from 1993 to 2012 in all three basins individually, when averaged for False Creek, and at all sites. However, when the data was examined visually, the relationships were likely influenced by high variability and the large sample size. A variety of fecal coliform concentrations were found over a range of precipitation values, with no visible patterns.

No correlation (Solar, Tide, Wind)

Solar, tide, and wind speed and direction were not found to have a significant correlation with the average 30-day geometric mean *E. coli* concentration from 2013-2015 in False Creek.

Bacterial Source Tracking (BST)

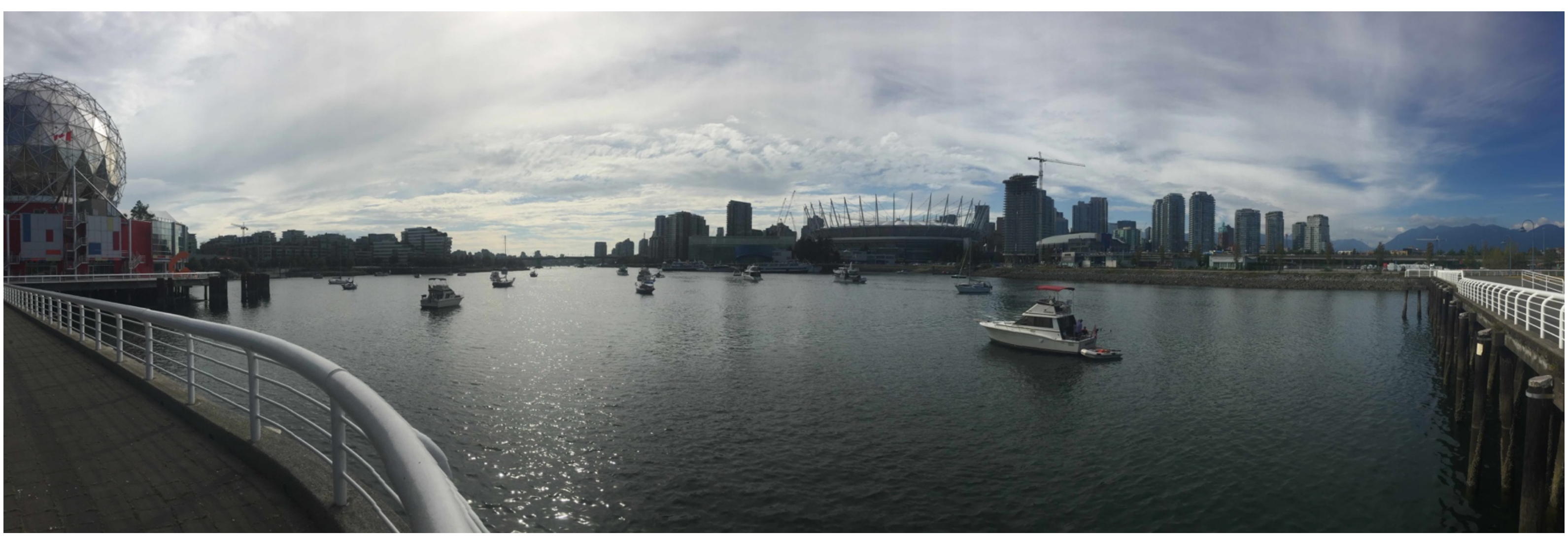
Objective 3: Improve our understanding of the sources of *E. coli* in False Creek.

4 BST samples were collected from the mid-channel on July 11th, 2016 from sites BFC-04-01, BFC-04-02, BFC-04-04, and BFC-04-08 (Figure 2). At that point, it had rained 32.2 mm in the previous 36 hours, triggering a CSO event and releasing stormwater into False Creek. This suggests that sources of *E. coli* from the combined sewer system, as well as from the stormwater system, should be captured in these 4 samples.

BST analysis revealed that general *E. coli* bacteria strains were present in the False Creek samples, as well as human and dog specific strains (Table 4). Human strains were found in all 4 samples, while dog was found in 3 of the 4. *E. coli* from gulls, elks, horses, pigs and ruminant animals were not detected. While this does not rule out contributions from these animals in small localized areas, it does suggest that the concentration of *E. coli* from the undetected animals are not high enough to contribute to the mid-channel of False Creek. Geese could not be tested for this time; however, geese populations in Vancouver are high, so it is possible they are contributing to the general bacteroide strains of *E. coli* detected. They should be tested for in future samples, if possible.

Table 4: Bacterial Source Tracking (BST) results from False Creek. If a bacterial source was detected, a + appears in the column, while a - sign indicates it was not detected.

Bacterial Source Tracking BST								
Sample ID	General Bacteroides	Human	Ruminant Animal	Pig	Horse	Dog	Elk	Gull
BFC-04-01	+	+	-	-	-	+	-	-
BFC-04-02	+	+	-	-	-	+	-	-
BFC-04-04	+	+	-	-	-	-	-	-
BFC-04-08	+	+	-	-	-	+	-	-
Legend: + = detected, - = not detected								



E. coli counts in the 20 samples collected on July 11th, 2016 were fairly low (Table 5). Only two of the samples were above the primary contact recreational guideline of 200 MPN/100 mL; BFC-01-23 and BFC-04-06. The BST results may have been different if the samples had been taken on a different day. Samples should be collected and analyzed in the future on a day with higher *E. coli* counts, as well as after a dry spell to capture different sources of *E. coli*. Ideally samples should be collected and analyzed throughout the summer for the most accurate understanding of where *E. coli* are coming from in False Creek.

Table 5: *E. coli* concentrations from the shoreline and mid-channel sites on July 11, 2016. Mid-channel sites are placed under the closest corresponding shoreline site(s), and sorted into West, Central, and East False Creek.

E. coli concentrations collected on July 11th, 2016, BFC-XX-XX							
	West			Central			
Shoreline Sites	01-16	01-18	01-23	03-17	03-19	03-24	
E. coli (MPN/100mL)	30	41	414	96	98	41	
Mid-channel Sites	04-08	04-07	04-06	04-04	04-03		04-05
E. coli (MPN/100mL)	75	73	336	211	121		199

E. coli concentrations collected on July 11th, 2016, BFC-XX-XX						
	East					
Shoreline Sites	02-20	02-20A	02-21	02-22	02-25	02-26
E. coli (MPN/100mL)	135	134	189	231	195	160
Mid-channel Sites	04-01				04-02	
E. coli (MPN/100mL)	199				108	

Relationship between shoreline and mid-channel *E. coli* concentrations

Objective 4: Further our understanding of the relationship between the mid-channel and shoreline of False Creek to determine if shoreline samples are representative of False Creek.

Samples were collected from 8 different locations in the mid-channel of False Creek 5 times in July of 2016. These *E. coli* concentrations were used to create 1 geometric mean per site in False Creek (Table 6). These mid-channel sites were then compared to the sites along the shoreline (Table 7). In west False Creek, the geometric means for sites 6, 7, and 8 were lower than their corresponding shoreline samples. In central False Creek, mid-channel geometric means were higher than the shoreline values for sites 3 and 4. Site 5 was in a similar range as the shoreline values. Site 2 is between sites 25 and 26 at the western edge of east False Creek, and had a geometric mean in a similar range as the shoreline sites. Site 1 is at the eastern end of False Creek near 4 shoreline samples. It had a geometric mean much lower than all 4 shoreline sites.

Of the 8 mid-channel site-by-site geometric means, all were below the Canadian secondary contact guideline (1000 *E. coli*/100mL). Only one site was above the guideline for primary contact guideline (200 *E. coli*/100mL), BFC-04-03. However, the primary contact guideline also recommends that no single sample exceed 400 *E. coli*/100mL. Of the 40 samples collected from the mid-channel in False Creek in July 2016, 4 samples exceeded 400 *E. coli*/100mL, two at site 1 and two at site 3. All four of these exceedances occurred at different times; therefore, 4 of the 5 sampling dates experienced one site with *E. coli* concentrations exceeding the primary contact guidelines. Mid-channel values exceeding guidelines at site 1 were accompanied by shoreline values that exceeded guidelines. Site 3 is under Cambie St. Bridge at the eastern edge of central False Creek. High mid-channel values for site 3 did not correspond with high shoreline *E. coli* geometric means or individual samples; therefore, shoreline samples were not accurately representing *E. coli* concentrations under Cambie St. Bridge.

Table 6: The 30-day geometric means (*E. coli* MPN/100mL) for 8 mid-channel sample sites in False Creek for July 2016.

July 30-day Geometric Mean of *E. coli* (MPN/100mL) in False Creek								
Sample ID (BFC-04)	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**
Coordinates (N 49')	16'28.3"	16'22.8"	16'19.1"	16'13.1"	16'11.3"	16'10.5"	16'15.8"	16'28.7"
Coordinates (W 123')	06'22.9"	06'33.8"	06'56.1"	07'07.5"	07'27.0"	07'45.0"	07'50.7"	08'10.4"
Geometric mean	142.3	97.4	247.8	108.6	90.1	46.1	45.5	22.4

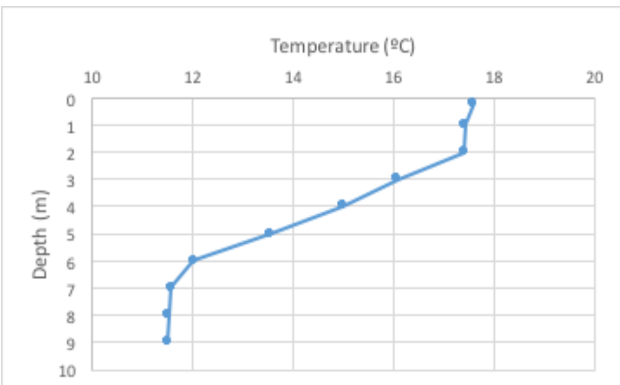
Table 7: The 30-day geometric means (*E. coli* MPN/100mL) for 12 shoreline sample sites in False Creek for July 2016.

	West False Creek (BFC-01-XX)			Central False Creek (BFC-03-XX)			East False Creek (BFC-02-XX)					
	16	**18**	**23**	**17**	**19**	**24**	**20**	**20A**	**21**	**22**	**25**	**26**
E. coli 30-day geometric mean (MPN/100mL)	36.7	63	130	63	72	138	1799	296	307	860	298	60

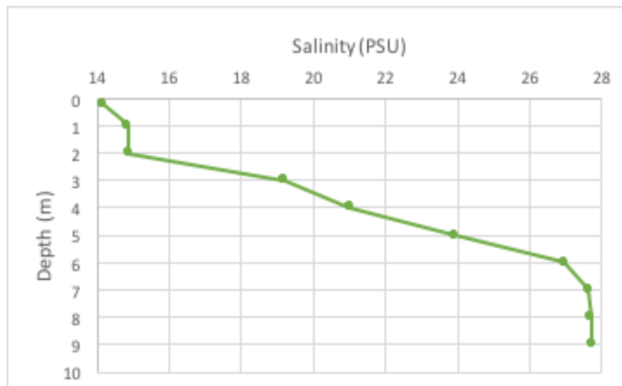
Chemical properties of False Creek, and their relationship to *E. coli*

Objective 5: Collect water chemistry variables, increasing knowledge of False Creek and determining correlations to *E. coli* concentrations.

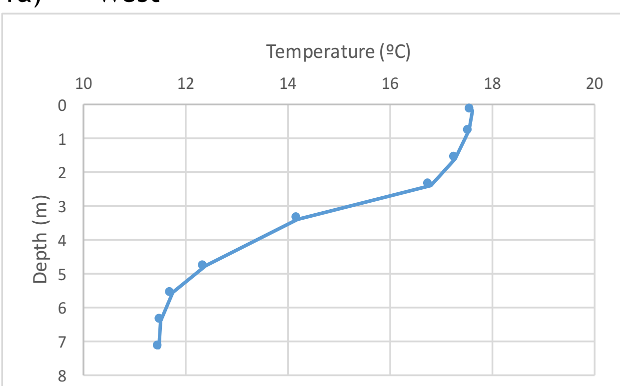
Depth profiles were collected in each of west, central, and east False Creek. This provides an understanding of the stratification of False Creek. Depth profiles suggest that all three sections of False Creek stratify both chemically and thermally between 3 and 6 m (Figure 10). This means that a warmer, lower salinity layer (epilimnion) is found in the first 2 to 3 meters, with a cooler, higher salinity layer below. This stratification is strongest in east False Creek, and starts to break down at the mouth of False Creek, with the depth of the epilimnion declining from east to west. Oxygen is high throughout the water column, with 67% saturation at its lowest.



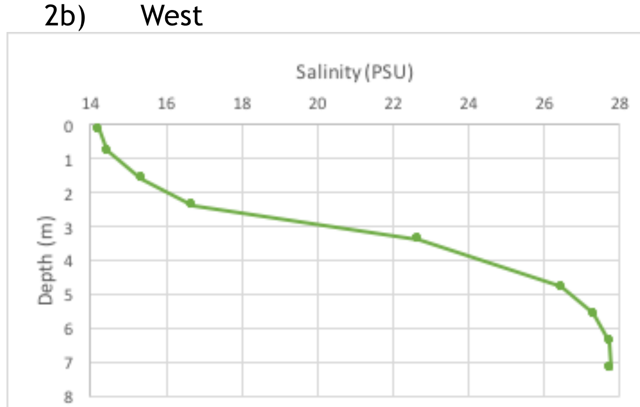
1a) West



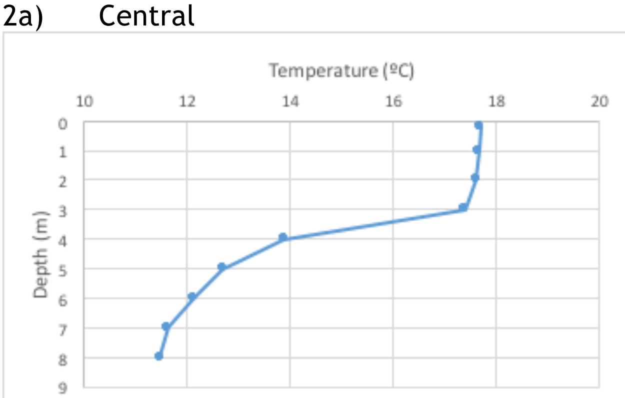
2b) West



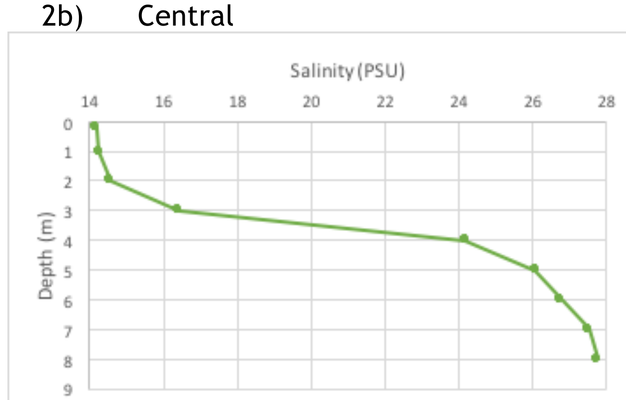
2a) Central



2b) Central



3a) East



3b) East

Figure 10: a) Temperature and b) salinity depth profiles for 1) west 2) central and 3) east False Creek.

Surface data were collected 6 times along shoreline sites, and 4 times at mid-channel sites from June 20th to July 19th, 2016. These were averaged to provide a typical value for measured chemical variables in False Creek (Table 8). There is not a lot of variation among sites for most chemical variables. However, mid-channel sites tend to have slightly higher salinity and total dissolved solids (TDS). The temperature is also often slightly higher in east False Creek. There are two chemical variables that show more variability between sites, ORP (mV) and turbidity (NTU). ORP is variable, but always positive and generally between 83 and 123 in False Creek. Turbidity in False Creek is consistently relatively low, averaging between 0.6 and 3.2.

Table 8: Average chemical values for all shoreline and mid-channel collection sites in False Creek for July 2016. (TDS = Total Dissolved Solids; ORP=Oxidation-Reduction Potential)

Site	Temp.(°C)	Conductivity adj. for °C (mS/cm)	TDS (g/mL)	Salinity (PSU)	Oxygen (mg/L)	pH	ORP mV	Turbidity (NTU)
BFC-01-16	18.9	20.8	13.5	12.5	10.1	8.0	105.4	0.8
BFC-01-18	18.7	22.1	14.3	13.3	9.9	8.0	102.9	0.6
BFC-01-23	18.4	22.2	14.4	13.4	9.3	7.7	109.4	1.3
BFC-03-17	18.6	22.2	14.4	13.4	9.7	8.0	111.1	1.5
BFC-03-19	18.7	22.3	14.5	13.5	9.9	8.1	113.3	1.0
BFC-03-24	18.8	22.1	14.4	13.4	8.7	7.9	115.6	2.5
BFC-02-20	18.8	22.3	14.5	13.5	9.7	7.9	120.1	1.3
BFC-02-20A	19.5	22.1	14.3	13.3	9.7	8.0	112.2	1.4
BFC-02-21	19.1	21.9	14.3	13.3	9.4	8.0	107.8	1.8
BFC-02-22	19.3	20.9	13.6	12.5	9.6	8.0	106.1	2.2
BFC-02-25	19.3	22.0	14.3	13.3	9.2	8.0	112.5	3.2
BFC-02-26	19.2	22.4	14.6	13.6	9.6	8.0	93.2	1.7
BFC-04-01	19.1	23.1	15.0	14.0	9.7	8.1	83.3	1.1
BFC-04-02	19.0	23.2	15.1	14.1	10.1	8.1	105.7	0.6
BFC-04-03	18.8	23.4	15.2	14.2	9.9	8.2	116.1	1.8
BFC-04-04	18.8	23.3	15.1	14.1	9.7	8.2	118.2	0.8
BFC-04-05	18.9	23.3	15.1	14.1	10.0	8.2	108.4	1.6
BFC-04-06	18.8	23.0	15.0	14.0	9.7	8.2	123.3	1.8
BFC-04-07	18.8	23.2	15.1	14.1	9.9	8.2	122.5	1.2
BFC-04-08	18.7	23.3	15.1	14.1	9.9	8.2	123.8	1.6

Nutrient samples were analyzed for shoreline and mid-channel samples. All sites had a nitrate concentration below the detection limit of 0.5 mg/L, except for site BFC-02-22 (behind Plaza of Nations) which had a concentration of 0.55 mg/L. It also had the highest total phosphorus (TP) concentration of 0.12 mg/L, suggesting there may be local nutrient inputs to this site. All other sites had TP levels between 0.012 and 0.033, several times less than the concentration at site BFC-02-22.

Water temperature was measured via temperature probes in two locations in False Creek, one in the west (Figure 11) and one in the central (Figure 12) area. Surface water temperature generally increased throughout the summer, with daily variability matching the timing of the sun. There was one downturn early July that lasted about a week and a half in both west and central False Creek, before it continued the warming trend. There was one day mid-June with a drop of almost 3 degrees in west False Creek, which was likely the result of a localized input of water, as it dropped and recovered quickly, and no similar drop was recorded in central False Creek. Mean air temperature in Vancouver Harbour is strongly correlated to water temperatures in west ($r=0.743$, $R^2=.552$, $p=<0.001$) and central ($r=0.808$, $R^2=0.6526$, $p=<0.001$) False Creek. This suggests that as air temperature rises in False Creek, surface water temperature increases as well.

Figure 11: Surface temperature 1 m below surface in west False Creek, at Burrard Civic Marina. Temperature was measured in 30 minute intervals.

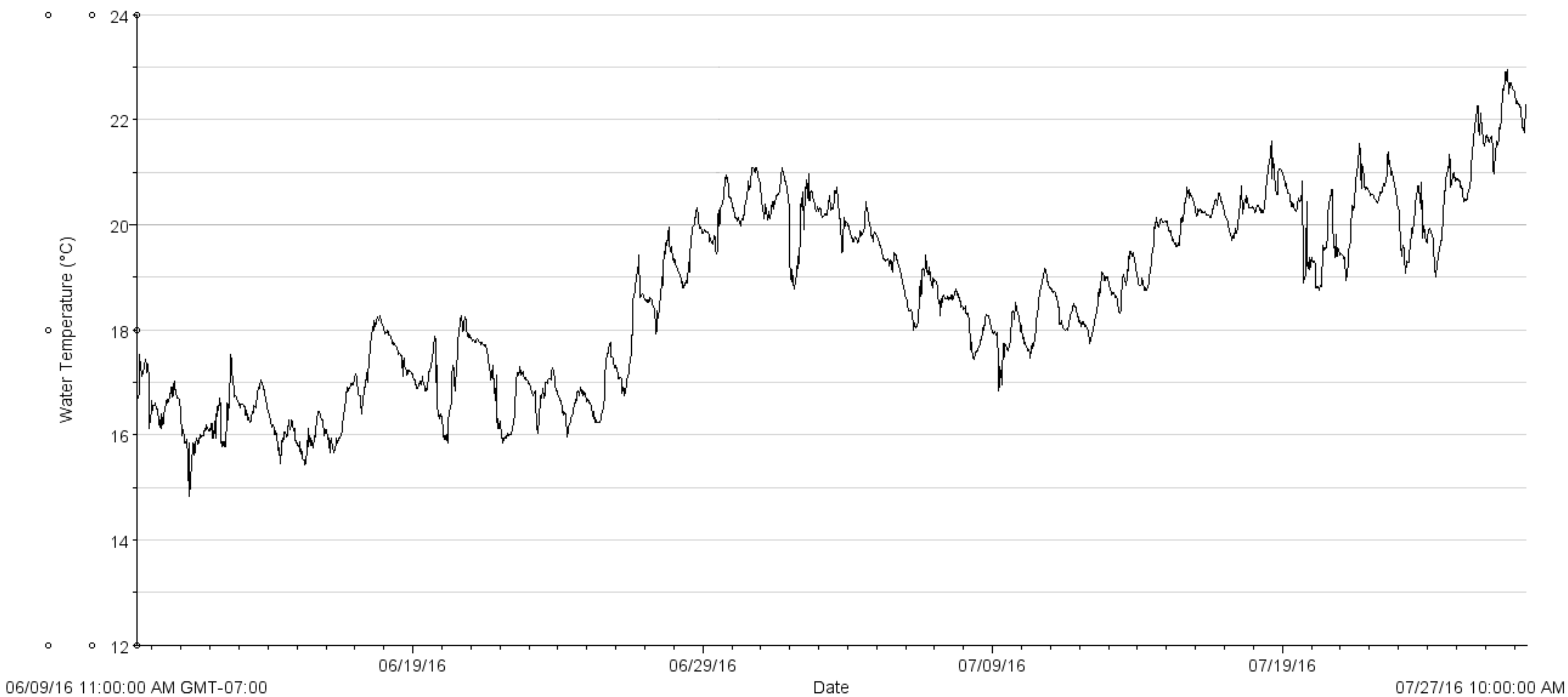


Figure 12: Surface temperatures 1 m below surface in central False Creek, at Heather Civic Marina. Temperature was measured in 30 minute intervals.

As in previous years, the highest concentrations of *E. coli* are still found in east False Creek (Figure 13). At the start of the summer central False Creek had higher average geometric means than the western edge; however, by June the two were fairly similar. There are two visible peaks in *E. coli* concentrations, one before regular summer sampling began, and another at the end of July. This timing does not coincide with previous *E. coli* peaks, further supporting the notion that *E. coli* sources are not consistent or seasonally dependent.

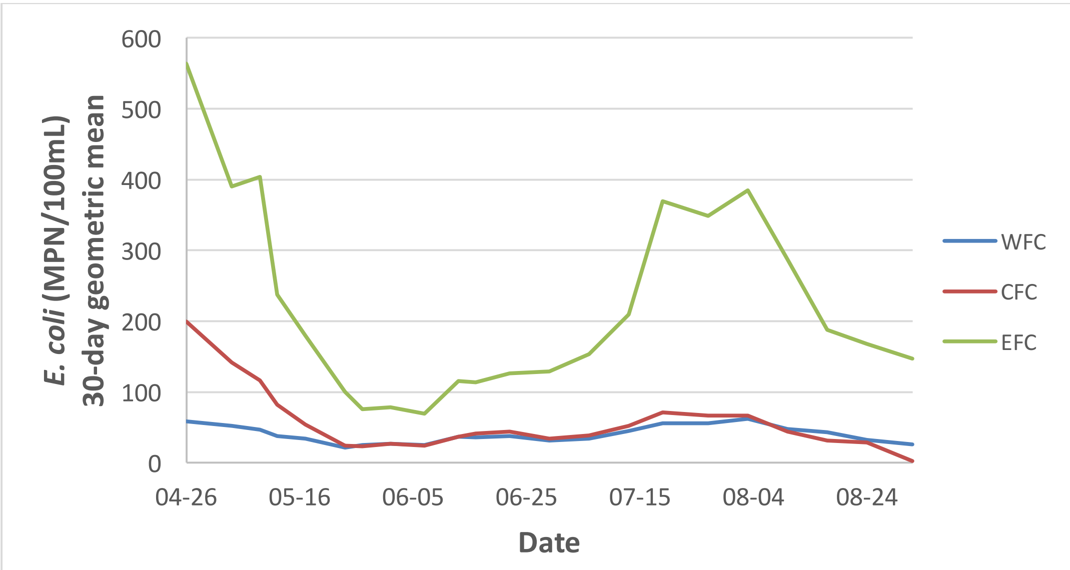


Figure 13: 30-day geometric mean concentrations of *E. coli* in False Creek for summer 2016. WFC=West False Creek; CFC=Central False Creek, EFC=East False Creek.

The magnitude of *E. coli* concentrations in 2016 is drastically lower than in 2014 or 2015. While east False Creek still regularly exceeds primary contact guidelines, with the geometric means exceeding guidelines 41% of the time, it did not exceed secondary contact guidelines. However, numerous shoreline sites, mostly in east False Creek, exceed primary and secondary contact guidelines. The four sites at the end of False Creek exceeded primary contact guidelines between 65% and 82% of the time, and occasionally exceeded secondary contact guidelines. All 6 east False Creek shoreline sites exceeded single-sample maximums at some point during the summer.

Statistically significant negative correlations were found between *E. coli* concentrations and the following chemical variables: conductivity, total dissolved solids (TDS), salinity, pH, and oxidation-reduction potential (ORP) (Table 9). There is variability in the data points, but in general *E. coli* concentrations decline as the previously mentioned variables increase.

Table 9: Statistically significant correlations between $\log_{10}$ *E. coli* concentrations and measured chemical variables across all sample sites in False Creek for June-July 2016.

	Conductivity (mS/cm)	Total Dissolved Solids (mg/L)	Salinity (PSU)	pH	ORP (mV)
R^2	0.048	0.047	0.047	0.060	0.068
r	-0.219	-0.219	-0.218	-0.246	-0.260
p-value	0.027	0.027	0.028	0.013	0.018

Discussion

Spatial patterns of *E. coli* and fecal coliform in False Creek.

E. coli and fecal coliform concentrations in False Creek follow similar spatial patterns from 1993 to 2015. They both increase from west to east in False Creek, with the highest concentrations found at sites near Science World and Plaza of Nations. These patterns are supported by previous research that found the bacterial concentration almost invariably increased west to east in False Creek, with the highest concentrations near the Plaza of Nations and Science World (BC MOE, 2006). It has been suggested that elevated fecal coliform counts in eastern False Creek could be due to either localized sources or localized nearshore trapping of effluent (Sea Science, 1997). Variability in *E. coli* counts for False Creek between sites is generally highest in east False Creek. This high variability suggests that east False Creek likely receives the highest *E. coli* inputs, but that they are not consistent. This supports the idea that the sources of *E. coli* in east False Creek are likely variable and local.

Temporal patterns of *E. coli* and fecal coliforms in False Creek

There is no obvious summer peak for *E. coli* concentrations in False Creek; both the timing and magnitude of peaks differ from year to year. *E. coli* concentrations do appear to increase at some point during the course of the summer, but the timing of this increase and its eventual decline are not consistent. This suggests that the main sources of *E. coli* in False Creek are not entirely dependent on the time of year, but may be related to seasonal factors. No site experiences consistent weather from year to year, so it could be that different *E. coli* sources are dependent on weather or weather-related activities. Fecal coliform concentrations from 1993 to 2012 generally experienced higher concentrations in the winter, with summer concentrations below secondary contact guidelines. There are not currently enough winter *E. coli* samples from 2013-2015 to discern a seasonal pattern for the winter months.

Correlations between *E. coli* concentrations and Environmental Variables

The relationship between *E. coli* geometric means and temperatures above 11°C from 2013 to 2015 suggests that in summer months, as temperatures rise, either *E. coli* survival increases or there are higher inputs of *E. coli*. However, in winter months where temperatures are below 11°C, this relationship appears to break down. This could be due to different sources of *E. coli* in winter changing or masking the relationship between water temperature and *E. coli*. Alternatively, it could be due to high variability and a lack of data, as there were few data points collected in winter months.

It was expected that there would be a negative correlation between salinity and *E. coli* concentrations. However, this study found a weak positive correlation between average salinity and the average 30-day geometric mean *E. coli* concentration from 2013-2015 in False Creek. The relationship is slightly stronger in West and Central False Creek, but weaker and not significant in East False Creek. It is possible that this correlation is picking up on a confounding variable. For example, higher salinities are usually associated with fewer freshwater inputs. If the majority of *E. coli* entering False Creek is not through stormwater, then stormwater inputs would dilute the concentration of salinity and *E. coli*, giving the appearance of a positive relationship between the two. Additionally, the average open ocean salinity is around 35 PSU, while the average surface salinity in False Creek is between 17 and 24 PSU. Therefore, it could be that salinity does not reach concentrations high enough for the detrimental effects of salinity on *E. coli* survival to occur.

High *E. coli* counts do not consistently coincide with high precipitation events; however, high precipitation events tend to coincide with high *E. coli* 30-day geometric mean concentrations. This suggests that high precipitation events can lead to elevated *E. coli* concentrations, but are not the exclusive source of *E. coli* contamination, as many high *E. coli* concentrations are not associated with precipitation. There were two sites where *E. coli* counts were significantly correlated with precipitation: BFC-03-17 and BFC-03-19 (Figure 1). BFC-03-17 is the only location with an active combined sewer outfall, while BFC-03-19 is located under Cambie St. Bridge, near numerous stormwater outfalls and is the next site east from BFC-03-17. None of the other sites had a significant correlation with precipitation, suggesting the stormwater system likely is not contributing significant inputs of *E. coli* to other locations.

Solar, tide, and wind speed and direction were not correlated to *E. coli* geometric means in False Creek from 2013 to 2015. There are several reasons why the expected negative relationship between solar and *E. coli* was not found. First of all, the available solar data was very broad in scale, as it covered 1 degree of latitude and longitude. Another possibility is that there could be a high turnover rate of the individual bacteria in False Creek, with consistent inputs of *E. coli* into the water. A third possibility is that turbidity is high enough in False Creek that *E. coli* can take refuge in suspended particulate matter; however, this is unlikely as there was a negative correlation between TDS (a measurement similar to turbidity) and *E. coli* concentrations. Tide may not have a large effect on *E. coli* concentrations in False Creek due to its shape and stratification, which could trap *E. coli* in surface waters. Wind speed and direction data were for Vancouver International Airport, and were only recorded for winds over 30 km/hr. It is possible that this data was collected too far from False Creek, with local wind patterns having a greater impact in False Creek.

Correlations between fecal coliform and environmental variables

Long-term fecal coliform trends (1993-2012) were different than the *E. coli* trends. Significant correlations between fecal coliform and temperature were only found in western and central False Creek, and were both negative. This could be due to changing sources of *E. coli* in False Creek over time, as all but one CSO outfall have been separated in False Creek. More CSOs combined with high winter precipitation and lower summer precipitation may have meant more *E. coli* inputs into False Creek in the winter from 1993 to 2012. A weak positive correlation was found between the preceding 24 hours of precipitation and 30-day geometric means of fecal coliform from 1993 to 2012 in False Creek, further supporting this theory.

The relationship between salinity and fecal coliform is unclear. Significant correlations between the two were not found from 2006-2012 in west False Creek. Correlations for central and east False Creek were contradictory and weak. When compared from 1993-2005, salinity was found to be weakly positively correlated with fecal coliform. It is possible that this is picking up on a correlational relationship, with a confounding variable that ties the two together, or that salinity did not reach high enough concentrations to have a detrimental effect on fecal coliform.

Sources of *E. coli* in False Creek

Currently, there are too many sources of *E. coli* in False Creek to easily pinpoint one main source. However, the results of the BST analysis helped to narrow down and improve our understanding of the sources of *E. coli* in False Creek. Since *E. coli* from humans were found at all 4 points tested, it is likely the majority of *E. coli* in False Creek are from human-based sources. In addition, *E. coli* species from dog were found at three of the sites. The most common way for dog waste to appear in local water ways is through stormwater runoff. The 32.2 mm of rain in the preceding 36 hours to BST sample collection suggests that stormwater runoff is collecting and carrying *E. coli* from dog waste around the city, either overland directly into the False Creek, or through stormwater outfalls. General bacteriode *E. coli* strains were also found at all four sites, but could not be assigned to a particular species. *E. coli* from gulls, elks, horses, pigs and ruminant animals were not detected at any of the 4 sites. While this does not completely rule out contributions from these animals, it does suggest they are not the main sources of *E. coli* in False Creek. Canadian Geese, another suspected source of *E. coli*, could not be directly tested for; therefore, they could be neither confirmed nor denied as a source of *E. coli* in False Creek.

Narrowing down the species that *E. coli* are coming from can help to narrow down the sources of *E. coli* in False Creek. BST analysis revealed that no *E. coli* from ruminant animals were found in False Creek; therefore, it is unlikely that manure is a source. This makes contamination from urban farming and food trucks unlikely. However, since ruminant strains were found in January of 2015 (Anony et al., 2015), it is possible that urban farming previously contributed *E. coli* to False Creek, or that it is seasonal in nature. RVs releasing their waste into the stormwater system is still a possible source. However, this is likely to be at most a relatively small, localised source of contamination contributing to peaks in False Creek *E. coli* concentrations, but not the base load. Other possible human sources that need to be narrowed down with further tests include: combined sewer overflows, crossed connections, discharges from a variety of boats, inputs into the stormwater sewer system (RVs, etc.), as well as others.

Relationship between mid-channel and shoreline *E. coli* concentrations

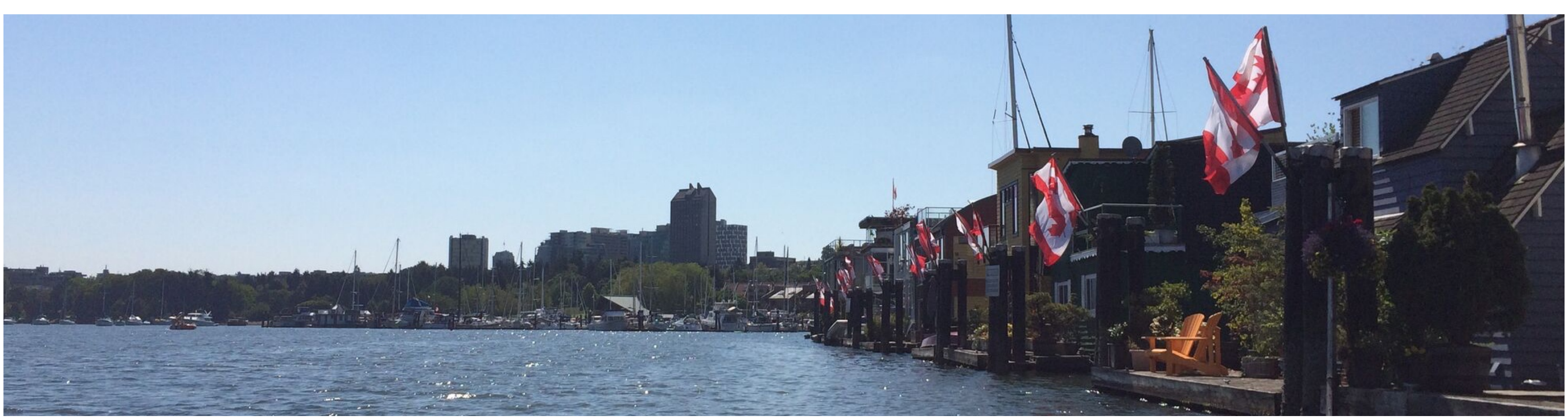
The samples collected and analyzed for this study suggests that for most of False Creek, shoreline values provide an indication of the concentration of *E. coli* mid-channel. Only at sites BFC-04-03 (site 3) and BFC-04-04 (site 4) in central False Creek did shoreline values underestimate the mid-channel concentrations. Site 4 is located above the Heather St. CSO outfall, which is a source of human fecal coliforms during large precipitation events when a CSO is triggered. This could explain why it had a higher geometric mean than the nearby shoreline sample if *E. coli* are not reaching the shore. Site 3 is under Cambie street bridge, where several stormwater outfalls are located. This, in conjunction with the many birds nested under the bridge, could be contributing *E. coli* that are not being captured by the shoreline samples. Further comparing mid-channel and shoreline *E. coli* samples from July 2016 shows that shoreline values are often much higher than the mid-channel in east False Creek. This, combined with the shape of False Creek, further supports the idea that fecal coliforms are getting trapped along the shoreline of eastern False Creek, or are due to localized sources.

2016 *E. coli* concentrations and water chemistry variables in False Creek

The pattern found in both fecal coliforms from 1993 to 2012 and in *E. coli* from 2013 to 2015 of highest bacterial concentrations found in east False Creek holds true for 2016. The concentrations of *E. coli* continue to increase west to east in False Creek, with the highest concentrations near Plaza of Nations or Science World. This further supports the notion that *E. coli* may be getting trapped along the shoreline in east False Creek. The timing of peaks in *E. coli* concentrations are still quite variable throughout the summer, with no consistent time of year peak. However, concentrations are often high at the start of the summer in April and May, so it may be useful to start sampling a little earlier in the year, so 30-day geometric means can be reported earlier.

False Creek currently stratifies with a less dense, warmer, lower salinity layer on top of a denser, colder, higher salinity layer below. *E. coli* can get trapped at the surface layer, unable to disperse throughout the entire water column. This can lead to higher concentrations of *E. coli* in surface waters, and may be contributing to the trapping of *E. coli* around the shoreline of east False Creek. Surface water temperature in both west and central False Creek is strongly correlated to air temperature in Vancouver Harbour; therefore, air temperature can be used as a proxy if needed to get an understanding of surface temperatures.

Several measured water chemistry variables were statistically significantly negatively correlated to *E. coli* concentrations in False Creek: conductivity, TDS, salinity, pH, and ORP. As any of these increased, *E. coli* concentrations were found to decrease. These correlations match the expected relationships found in the literature. There were not significant correlations between *E. coli* concentrations and temperature, oxygen, or turbidity. Generally, a positive relationship is found between temperature and *E. coli* concentrations in water bodies. It may be that there is another, over-riding correlation that may be masking or counter-acting the effects of temperature on *E. coli* concentrations. There likely was not a relationship between oxygen and *E. coli* as they are often able to survive in both aerobic and anaerobic environments, and oxygen was not a limiting factor in False Creek. Nutrients do not appear to be supporting or limiting *E. coli* growth in False Creek. Nitrates were around or below 0.5 ppm, while limitation starts around 0.1 ppm and do not have a positive impact on *E. coli* survival until concentrations higher than 1 ppm. TP is more variable, but is not known to have a significant impact on *E. coli* survival. It is interesting to note that site BFC-02-22 had both high nitrate and TP values, suggesting there is a source of nutrient inputs to this site. This could be from either the resident goose population existing on its banks, or from the stormwater outfalls nearby. Turbidity and *E. coli* concentrations exhibited a positive relationship, but it was not statistically significant. This could be due to turbidity concentrations too low to have a large enough influence on *E. coli* survival to be statistically significant.



Primary and secondary contact Canadian guideline exceedances in False Creek

Both primary and secondary contact Canadian recreational water quality guidelines were regularly exceeded in 1993-2015, with most exceedances occurring in east False Creek. While the western edge of False Creek often meets Canadian primary contact guidelines, central and especially east False Creek do not. Across 2013-2015, 85% of 30-day geometric mean *E. coli* concentrations in west False Creek met primary contact guidelines, 57% in central, and only 23% in east False Creek. When examining secondary contact guidelines, 96% of 30-day geometric mean *E. coli* concentrations in west False Creek met the guidelines, 92% in central, and 73% in east False Creek. While the magnitude of *E. coli* peaks has declined in 2016, they are still often above primary contact guidelines in east False Creek. While secondary contact guidelines are rarely exceeded, single-sample secondary contact guidelines have been exceeded at each site in east False Creek at some point during the summer of 2016. Therefore, it is recommended that VCH continue to not classify False Creek as a Primary Contact Recreational Water Body until more consistently low *E. coli* concentrations are observed. East False Creek in particular requires reduced *E. coli* concentrations, as it can often even exceed secondary contact guidelines. Secondary contact users should be extra cautious in front of the Science Centre, as this site exceeded contact guidelines more often than any other shoreline collection site, with 89% exceeding primary and 58% exceeding secondary contact guidelines from 2013-2015. Most mid-channel sites experienced *E. coli* concentrations lower than their nearby shoreline samples, with all mid-channel sites below the secondary contact guidelines. This suggests that if shoreline *E. coli* concentrations in False Creek are within the secondary contact guidelines, then the mid-channel in False Creek should be as well.

Stormwater Management

One of the most important anthropogenic factors associated with fecal coliform abundance is percentage watershed-impervious surface coverage, which explains up to 95% of variability in average estuarine fecal coliform abundance (Mallin et al., 2000). Impervious surfaces can consist of roofs, roads, driveways, sidewalks, balconies, and parking lots, and can concentrate and convey biological and chemical contaminants to local waterbodies. As the quantity of impervious surfaces increase in a developing area, the amount of contaminants conveyed to local waterbodies generally increases as well. Therefore, in urbanizing coastal areas, environmentally sound land use planning and development that minimizes impervious surfaces while maximizing the passive water treatment function of wetlands and other green areas can reduce the frequency of waterborne health risks (Mallin et al., 2000). A watershed management approach is considered key to understanding and reducing the impact development will have on local waterbodies, as sources of contaminants are not always confined to shoreline areas. Green stormwater infrastructure in an urban watershed can help to reduce the quantity and speed of urban runoff, as well as improve the quality of the water reaching local waterbodies. The city is currently working on increasing green rainwater infrastructure through its Integrated Rainwater Management Plan (COV, 2016). One of the aims of this plan is to maintain water quality for beaches and recreation around Vancouver. It recognizes the need to decrease the amount and increase the quality of rainwater reaching local waterbodies, to reduce the introduction of contaminants through stormwater and combined sewer outfalls. It acknowledges that False Creek is an area with confined receiving waters, which can make dilution or dispersal of pollutants difficult. As such, green rainwater management tools need to continue to be considered and applied as False Creek develops.

Recommendations and Future Directions

1. **Health Canada's primary contact guidelines are regularly exceeded in False Creek; secondary contact guidelines are occasionally exceeded**. According to Vancouver Coastal Health (VCH), False Creek is not classified as a Primary Contact Recreational Water Body; therefore, it is not currently a swimming/bathing beach. Water quality in 2016 has drastically improved compared to the previous two summers; however, primary contact guidelines are still regularly exceeded in east False Creek, supporting the decision to not classify it for primary contact. While 30-day geometric mean secondary contact guidelines were met throughout False Creek this summer, single-sample secondary contact guidelines were exceeded at numerous sites around the eastern shoreline of False Creek, near Science World and Plaza of Nations. As such, secondary users should be cautious around the eastern end of False Creek and, according to VCH, should wash thoroughly after contact with the water. For up to date *E. coli* concentrations in False Creek and all lower mainland beaches go to www.vch.ca.

2. **Collect more data to narrow down sources of *E. coli* from human waste contamination**. While geese could not be directly tested for, BST analysis did not find gull, elk, pig, horse and cow specific *E. coli* strains, making contamination from urban farming and resident gull populations unlikely. However, BST analysis revealed strains of human specific *E. coli* at all sites, and dog specific at 3 of the sites. This suggests that the majority of *E. coli* contamination in False Creek is likely human in origin, with some dog, likely through urban runoff and the stormwater system. Possible human-based sources of *E. coli* in False Creek are many, including: wastewater from boats, CSOs, crossed sewer connections, inputs to the stormwater system, etc. As sources of human-based *E. coli* contamination are uncovered, these sources of contamination should be reduced or eliminated.

3. **Options to remove *E. coli* or to improve dispersal of *E. coli* throughout False Creek should be explored**. East False Creek is receiving consistent localized inputs, or *E. coli* are getting trapped along the edges, as shoreline samples there consistently have the highest mean *E. coli* concentrations. Additionally, the current u shape of False Creek can prevent flushing of water, resulting in little water circulation and promoting stagnation. Changing the shape or improving water circulation in this end of False Creek would help to dilute high concentrations by dispersing the *E. coli* throughout False Creek and ultimately out into English Bay; however, this would likely be expensive and difficult to achieve. However, if current planning processes are looking to change the shape of east False Creek, improving circulation should be considered.

   The use of bivalves should be explored as a potentially useful approach to remove *E. coli*. Bivalves filter large volumes of water, and can remove particulate matter from the water column as well as from deposited sediment (Ismail et al., 2014). Previous studies have shown that when bivalves filter water for food, they also filter out some contaminants. This suggests that they can be used to improve water quality by removing hydrophobic trace organic compounds, as well as bacteria and phytoplankton (Ismail et al., 2014). These pathogens and contaminants accumulate in tissues, or can settle out as excrement, removing bacteria and viruses associated with waste from the water. Mussels can be deployed on ropes or in cages, providing habitat to invertebrates while filtering the water column (Greenberg, 2013). They are adaptable and extremely hardy, surviving a wide range of conditions including severe storms. Native species of mussels could be placed in cages in targeted locations around False Creek, restoring ecological functions while removing both biological and chemical contaminants.

4. **Understand the amount and spatial distribution of contamination through the stormwater system, and work to reduce it**. Currently, it is unknown how much *E. coli* contamination comes through the stormwater system. However, the presence of dog *E. coli* at 3 of the 4 tested sites, combined with 2 of the shoreline sampling sites being correlated to precipitation, suggests that at least some of the contamination is coming through the stormwater system. Samples should be collected for *E. coli* enumeration from stormwater outfalls in False Creek. They would need to be taken upstream of the outfall to ensure they are not contaminated by back flow from False Creek, and would need to be taken over a period of time experiencing both dry and wet weather events. By testing stormwater outfalls around False Creek, we can gain an understanding of both the amount of *E. coli* entering through the stormwater system, as well as its spatial distribution. By improving our understanding of which stormwater outfalls are contributing *E. coli* to False Creek, more specific sources of *E. coli* can be narrowed down and further explored. More generally, stormwater management techniques should continue to be improved, and impervious surfaces decreased, throughout Vancouver. Green stormwater infrastructure should continue to be supported, especially around False Creek and its watershed as it continues to be developed, as it allows some of the stormwater to percolate into the ground. This will decrease the quantity and increase the quality of water reaching the stormwater system, thereby reducing sources of *E. coli* through the stormwater system and urban runoff.

5. **Shoreline sample sites are likely sufficient in False Creek**. Previous studies have called for offshore bacteriological sampling to gain a better understanding of the general quality of the water in False Creek (Sea Science, 1997). Preliminary results from this study suggest that shoreline samples over-estimate the concentration of *E. coli* in the open water throughout most of False Creek. Therefore, if shoreline sites are within the secondary contact guidelines, the open water likely will be too. Shoreline samples do however, under-estimate the concentration of *E. coli* under Cambie St. Bridge and over the Heather St. CSO. Further samples should be collected and analyzed to confirm shoreline sampling is consistently estimating the concentration of *E. coli* in False Creek.

6. **Additional *E. coli* sampling such as sediment testing, winter samples, BST analysis and ecosystem interactions could provide more insight into *E. coli* sources and patterns in False Creek**. In 2006, the British Columbia Ministry of the Environment wrote "More research and investigations are needed to understand a number of pertinent factors, including the relative contributions of contaminants from various sources within the inlet, and the timing of these releases, as well as conditions affecting circulation and mixing within False Creek and the survival times of bacteria within the inlet." (BC MOE 2006). While this study has begun to address some of these, additional testing will need to be carried out to address others. *E. coli* can survive in the sediments at the bottom of waterbodies, creating a possible source of (re)contamination. *E. coli* concentrations should be measured in the sediments to improve understanding of *E. coli* survival in the sediments of False Creek. False Creek is currently used as a recreational waterbody, regardless of the time of year. However, there are currently very few samples taken in winter months. Additional sampling during the winter, as well as occasional mid-channel sampling, could provide additional data for secondary contact recreation users looking to use False Creek. BST samples from more locations and done throughout the summer after both dry and wet weather would further improve understanding of the various sources of *E. coli* contamination in False Creek. This should include testing for geese. Future studies should consider ecosystem interactions such as predation and resource competition with algal and zooplankton communities to gain a more thorough understanding of how they are interacting with *E. coli* in False Creek.

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