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**Seasonal and yearly trends of fecal coliform
across four different land use types in Skagit County, Washington**

by

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ABSTRACT

Fecal coliform pollution in watersheds puts human health at risk. In watersheds with mixed land use, it is hard to distinguish pollution sources. In Skagit County, Washington, elevated fecal coliform levels have led to public beach closures and shellfish harvesting closures. Different sources of fecal coliform pollution in Skagit County include agricultural runoff, mismanaged livestock and domestic waste, faulty septic systems, and stormwater runoff. Identifying specific pollution sources is difficult, but a broader analysis of fecal coliform trends in different land use areas will help guide mitigation efforts. In this paper, sampling sites were categorized into four different land use types: rural, marine, residential, and commercial. Using four long term monitoring datasets, yearly and seasonal trends were detected. Rural sites, including agricultural land, had predictable seasonal patterns with high fecal coliform in the summer and low fecal coliform in the winter. Conversely, marine areas had high fecal coliform in the winter and low fecal coliform in the summer. The seasonal trends identified in this paper can help inform future planning and strategies to reduce fecal coliform pollution in different land use areas in Skagit County, Washington.

INTRODUCTION

Water quality parameters are monitored in drinking water and coastal bodies of water to ensure safe and clean water. Contaminants in coastal waters can lead to human illnesses (Myers, n.d.). One of the main water quality parameters that is monitored to measure contamination is fecal coliform.

Fecal coliform is a comprehensive water quality parameter for fecal bacteria that comes from the intestine track of warm-blooded animals (Washington Department of Health (WADOH), n.d. a). High levels of fecal coliform in groundwater and watersheds are a human health risk. Fecal coliform is measured in water samples as an indicator for harmful pathogens that can be human health hazards, such as *Salmonella*, and is used as indicator for nutrient loading since waste from warm-blooded animals contain high concentrations of nitrogen and phosphorus (WADOH, n.d. a).

Federal requirements: fecal coliform monitoring

Federal legislation requires fecal coliform to be monitored nationwide to ensure clean water in drinking water and coastal waters. In 2000, the Environmental Protection Agency (EPA) amended the Clean Water Act with the Beaches Environmental Assessment and Coastal Health Act of 2000 (BEACH) to

help monitor human health risks in coastal waters. The BEACH Act provides grants and guidelines to state, tribal nations, and local agencies to develop programs to monitor and reduce fecal contamination in recreational coastal waters (BEACH Act of 2000). In 2013, the EPA put forth the Revised Total Coliform Rule, which requires public drinking water systems to be regularly tested for fecal contamination and addressed by local and state agencies when detected (Revised Total Coliform Rule , 2013).

Federal legislation has helped fund long-term monitoring projects, which have allowed many coastal states to expand water quality monitoring (BEACH Act of 2000). States and tribal nations are required to submit water quality data to the EPA. This data is used to create an interactive map that reports beach closings and advisories called the BEach Advisory and Closing Online Notification (BEACON) system (EPA, 2023). Continued monitoring is vital to identify fecal coliform sources and protect human health.

Shellfish regulation and monitoring

Because eating contaminated shellfish is a threat to human health, shellfish growing and harvesting is another area in which federal monitoring and regulation is crucial. As an indicator for harmful pathogens, fecal coliform is monitored in shellfish and areas where shellfish are grown and harvested.

Shellfish are filter feeders, which makes them susceptible to contamination with pathogens (Office of Habitat Conservation, 2022). *Olalemia*

et al. (2016) found that fecal coliform and *E.coli* concentrations in Pacific oysters (*Crassostrea gigas*) reached maximum levels at twelve hours and six hours of exposure, respectively. In addition, fecal coliform concentrations in oysters remained for more than 48 hours (Olalemia et al., 2016). Bioaccumulation of fecal coliform in oyster tissues is a concern when harvesting. Measuring fecal coliform in harvesting areas is a good indication of fecal coliform contamination. However, even if the amount of fecal coliform in the area is acceptable on the day of harvesting, oysters may still have high concentrations in their tissues if the levels of fecal coliform were high in the previous days.

In the United States, shellfish growing and harvesting areas are required to monitor fecal coliform. The National Shellfish Sanitation Project (NSSP) is a combined project with federal agencies, state agencies, shellfish growers, producers, and dealers, and led by the US Food and Drug Administration (FDA). Every few years, the program updates and publishes a guide that outlines regulations and certifications needed to ensure that shellfish harvesting and production is sanitary and safe (FDA, 2020). In addition, the guide provides recommendations and guidance to shellfish producers to ensure their stock is safe. The program breaks down best methods to collect and process water samples as well as how to calculate and determine if samples pass federal and state standards (NSSP, 2019). Monitoring fecal coliform is crucial for shellfish farmers so they can guarantee that their shellfish is safe for consumption.

Fecal coliform sources

Fecal coliform contamination in watersheds mainly comes from stormwater overflow, leaking septic tanks, inefficient management of domestic and livestock waste, and natural wildlife waste (EPA, 2016). While fecal coliform pollution sources are broadly known, both point source and nonpoint source pollution need to be analyzed in the context of specific watersheds (Dressing et al., 2014). This is particularly important in coastal areas where upstream inputs, such as agricultural and septic systems, greatly affect marine bodies of water.

Land use influences fecal coliform levels in watersheds. In agricultural areas, livestock waste and manure fertilizer are main contributors to fecal coliform pollution (Ercument et al., 2017). Water runoff and mismanagement of livestock waste can introduce fecal coliform into the watershed. Jamieson et al. (2003) suggests that high loads of fecal coliform that enter streams can cause long term high levels of fecal coliform. In agricultural dominated watersheds, sampling sites near farms with continuous grazing had higher fecal coliform levels than sites near farms with rotational grazing (Sovell et al., 2007; Vondracek et al., 2005). Runoff of manure fertilizer from produce farms can also enter the watershed and cause high levels of fecal coliform (Ercument et al., 2017; ECY, 2009; St Laurent & Mazumder, 2014). St Laurent and Mazumder (2012) suggested that the percentage of agricultural land in a watershed was the best proxy for the degree of fecal coliform pollution.

In more developed areas, such as residential and commercial areas, fecal coliform has many sources. It can be introduced into the watershed through stormwater and leaking or overflowing waste systems. Many papers report that samples taken in urban areas had the highest fecal coliform compared to other land types (Schoonover & Lockaby, 2006). In more urbanized areas, stormwater is a significant source of fecal coliform pollution in the watershed (Cahoon et al., 2006). Stormwater can intensify overflowing waste systems, and in residential and commercial areas, impervious paved surfaces do not allow stormwater to be easily absorbed into the ground (Center for Watershed Protection, 2003; Mallins et al., 2000). This creates standing water which can collect fecal coliform. Many papers report that fecal coliform and the percentage of development and impervious surfaces have a positive linear relationship (Mallins et al., 2000, 2009). Mismanagement of domestic pet waste also can contribute to high fecal coliform levels in developed land where stormwater can easily pick up domestic pet waste (Overstreet & Bryant, 2011).

Marine areas are the recipients of fecal coliform from all the upstream sources so the levels there are greatly influenced by those sources. In marine areas, fecal coliform is a particular threat to human health. Humans may encounter fecal coliform through recreational activities in contaminated bodies of water and from eating contaminated shellfish. This threat to human health is the impetus for research into fecal coliform variables and trends.

Accumulation of fecal coliform in watersheds can be linked to heavy precipitation, which causes surface water runoff and stormwater overflow to flow downstream towards marine areas (Cahoon et al., 2006). Bioaccumulation of fecal coliform in watersheds is a result of upstream water sources flowing downstream and collecting inputs of fecal coliform pollution for more downstream sources (Portnoy & Allen, 2006). In places with dikes, tide gates, and dams, freshwater from upstream sources can carry high levels of fecal coliform and sediment which can accumulate and become stagnant (Portnoy & Allen, 2006). These stagnant waters are suitable areas for fecal coliform survival. When this freshwater is released, marine waters are introduced to high concentrations of fecal coliform and low salinity waters.

Fecal coliform variables and trends

Research on large estuary trends of fecal coliform shows that fecal coliform is influenced by many variables, including water temperature, salinity, and precipitation (Cho et al., 2016; Soueidan et al., 2021; Mallin et al., 2009). However, the degree of influence of these variables can depend on location, season, and year. For example, in the Mississippi Sound in 1990, salinity and water temperature had a significant relationship with fecal coliform, however in other years, there was no significant relationship between salinity and fecal coliform (Chigbu et al., 2005). Generally, salinity and fecal coliform have been found to be correlated. Soueidan et al. (2021) found that low salinity levels are

correlated with high fecal coliform levels. This trend is more evident in downstream water near freshwater outlets into marine bodies of water. Soueidan et al. (2021) inferred that low salinity levels and high fecal coliform levels were indicators of stormwater runoff and high precipitation events. Breaking down the influence of individual variables on fecal coliform is useful to contextualize and predict fecal coliform levels.

Water temperature has been found to help predict fecal coliform levels in surface water. Cho et al. (2016) reports that water temperature and fecal coliform levels showed a positive relationship, but at temperatures exceeding 30°C, fecal coliform levels dropped significantly. On the other hand, Mancini (1978) found that water temperature has a positive linear relationship with fecal coliform mortality rates in both saltwater and freshwater. Generally, short term water temperature increases, such as seasonal and daily fluctuations, can increase fecal coliform levels, but long term water temperature changes caused by climate change, can decrease average fecal coliform levels (Cho et al., 2016; Dakhlalla & Parajuli, 2020). Different land uses in the watershed also affect the relationship between fecal coliform and temperature. Cha et al. (2016) found that fecal coliform in urban areas had a weaker correlation to water temperature than forested areas.

Precipitation can sometimes, but not always, be used to predict fecal coliform levels. Multiple studies have reported that fecal coliform levels increase

as much as four to ten times after substantial rainfall (Dakhlalla & Parajuli, 2020; Mallin et al., 2009). Hong et al. (2010) found that fecal coliform levels had a high correlation with water chemistry factors that are directly influenced from surface water runoff, including total suspended solids and turbidity. An increase in total suspended solids provides more particles for fecal coliform to attach itself to and travel on (Davies et al., 1995). Mallin et al. (2009) also reported that fecal coliform densities were positively correlated with turbidity. However, other studies have found no correlation between fecal coliform and precipitation (Cho et al., 2016). Even when land use is taken into consideration, some agricultural dominated watersheds have a high correlation with precipitation (Dakhlalla & Parajuli, 2020), but others have no correlation with precipitation (Cho et al., 2016). Urban areas had a higher correlation between fecal coliform and precipitation than watersheds influenced by forests (Cha et al., 2016). Using precipitation as a predictor for fecal coliform varies between land use types.

Even though the significance of water quality parameters and fecal coliform varies, Chigbu et al. (2005) and Lipp et al. (2001) found significant relationships between seasonality, El Niño/La Niña cycles, and fecal coliform on the Gulf of Mexico shore. Long term analysis of fecal coliform and weather patterns can be useful to predict long term fecal coliform trends. One study in the Chesapeake found that sea level barometric pressures were shown to predict yearly fecal coliform trends (Leight et al., 2016). Weather patterns and conditions helped in determining seasonal and yearly patterns of fecal coliform.

Study area

Skagit County is in the northwest of Washington State and east of the Puget Sound. Major cities in Skagit County include Anacortes, Mount Vernon, and Sedro-Wooley (Skagit County, n.d. a). As of 2020, it had roughly 130,000 residents. Skagit County has a total land area of 1,731.20 square miles, and the majority of the developed and agricultural land is located near the shore, west of Sedro-Wooley (Skagit County GIS, 2020; US Census Bureau, n.d.). Skagit County contains four watersheds: Skagit Bay, Fidalgo Bay, Padilla Bay, and Samish Bay (Skagit County, n.d. a).

Skagit County is home to four federally recognized tribes: Swinomish Indian Tribal Community, Samish Indian Nation, Upper Skagit Indian Tribe, and the Sauk-Suiattle Tribe (Skagit County, n.d. b). Historically, indigenous tribes relied on shellfish and fish as a main source of protein. Today, Samish Indian Nation, Upper Skagit Indian Tribe, and Swinomish Indian Tribal Community have long-term water quality monitoring in Skagit County. Their water quality monitoring is used to create a baseline dataset (Samish Indian Nation, Upper Skagit Indian Tribe, & Swinomish Indian Tribal Community, n.d.). Tribes that are members of the Northwest Indian Fisheries Commission (NIFC), which includes Upper Skagit Indian Tribe and Swinomish Indian Tribal Community, can harvest shellfish from their historical harvesting areas (NIFC, n.d.). High levels of fecal coliform in the historical harvesting areas can hamper tribal rights and pose a human health risk to tribes.

Sources of fecal coliform in Skagit County

In Skagit County, residential and commercial waste contribute to fecal coliform pollution in the watershed. Most residential and commercial buildings rely on septic tank systems which are at risk for leaking and overflowing during a storm (ECY, 2020). Septic tanks are widely used in Skagit County because the bedrock is not suitable for central waste systems (Stream Team volunteer, personal communication, July 23, 2022). While there is a threat of overflowing or leaking septic tanks, Skagit County Public Works requires septic tank owners to have their systems inspected every year (WAC 246-272A-0270).

Agriculture inputs of fecal coliform pollution include mismanagement of livestock waste and runoff containing manure fertilizer (Ercument et al., 2017; ECY, 2009). Farms account for about 141 square miles of the total 1,920 square miles that make up Skagit County, with another 189 square miles of the county made up of bodies of water. (Skagit County, n.d. a; US. Census Bureau, n.d.). The types of farms include cattle, dairy, and produce. (Skagit County, n.d. a). From many of these farms, water runoff and mismanagement of livestock waste can introduce fecal coliform into the watershed.

Wildlife waste can contribute to fecal coliform levels, and in Skagit County, overwintering birds and small and medium-sized mammals, such as deer and rabbits, can contribute to pollution (ECY, 2020). Near shores, sea birds waste has been found to add to fecal coliform pollution (Meerburg et al., 2011). Wildlife

waste should not be overlooked as a pollution source, but it is difficult to quantify it since it is a nonpoint source.

Harmful pathogens in coastal waters, as indicated by high fecal coliform levels, pose a human health risk, both directly through swimming, boating, and other recreation and indirectly through eating contaminated shellfish (WADOH, n.d. a). The BEACH Act requires beaches with public access to undergo routine water quality monitoring to detect bacteria contamination (BEACH Act of 2000). The water at Padilla, Skagit, Fidalgo, and Samish Bay public beaches is monitored, and the Department of Ecology releases swimming advisories and beach closures depending on the level of bacteria (WADOH, 2023). From 2011 to 2015, public beaches in Bayview State Park consistently surpassed Washington State standards for fecal coliform (ECY, n.d.). As a result, the Skagit County Pollution Identification and Correction Program identified the Bayview community as a potential source of pollution. In response, the Bayview community successfully reduced this fecal coliform pollution in 2015 through better maintenance of residential septic tanks (ECY, n.d.).

Fecal coliform pollution can contaminate shellfish, and eating this shellfish can cause human illness. For this reason, the WADOH monitors water quality. Shellfish beds cover about 4,000 acres in Samish Bay, and they close when fecal coliform levels are high (Skagit Conservation District (SCD) et al., 2011). Commercial harvesting closures have negatively impacted harvesting periods and revenue for shellfish farms (SCD et al., 2011; WADOH, 2023).

In addition to monitoring water quality and closing shellfish farms, the WADOH uses water quality to determine the classification of marine areas for commercial shellfish growing and harvesting as approved, conditionally approved, or closed due to pollution (WADOH, n.d. b). In Skagit County, most of Samish Bay is conditionally approved, but the area at the mouth of the Samish River is closed due to pollution (Figure 1) (WADOH, 2022b). In Padilla Bay, the area surrounding the north side of the Anacortes oil refinery is closed due a nearby wastewater treatment plant outfall (Figure 2) (WADOH, 2022a). Many public beaches are also closed for recreational shellfish harvesting because of the threat of fecal coliform (WADOH, 2023).

Due to the impact of public beaches and shellfish harvesting closures, local and state agencies have analyzed fecal coliform pollution in Skagit County. Fecal Coliform Bacteria Total Maximum Daily Load (TMDL) and Water Quality Implementation Plans have been conducted for Samish Bay and Padilla Bay in 2009 and 2020, respectively. The reports from both years provided an analysis of fecal coliform levels from major bay inputs in accordance with Washington state standards. In 2009, many sites in Samish Bay watershed failed state standards, and in 2020, all four major inputs into Padilla Bay failed state standards (ECY, 2009 & ECY, 2020).

Both reports also outlined feasibility plans to improve water quality and detailed roles and responsibilities for different government agencies and stakeholders. For example, Samish Bay TMDL report states that “livestock

operations next to streams or ditches” should consult Skagit Conservation District and develop a farm plan to set up best management practices, such as exclusion fencing, to decrease the likelihood of fecal coliform pollution (ECY, 2009). Exclusion fencing has been shown to reduce fecal coliform levels in streams (Bragina et al., 2017).

The success of the plans outlined in the reports is hard to quantify, but there are some data that provide clues. Before 2015, a majority of Samish Bay was classified as approved for shellfish growing and harvesting, but after 2015, Samish Bay was reclassified as conditionally approved (Upper Skagit Indian Tribe, 2016). This reclassification suggests that the level of fecal coliform in Samish Bay increased. Because the report on the Padilla Bay TMDL was published fairly recently in 2020, it is difficult to determine the success of its plans.

Purpose

Skagit County and the Department of Ecology are determined to decrease fecal coliform pollution. High levels of fecal coliform have closed both public beaches in Padilla Bay and shellfish harvesting in Samish Bay. In Samish Bay, the shellfish growing area that is classified as conditionally approved was closed 14 times in 2022 (WADOH, 2022b).

Previously, analyses of fecal coliform levels in Skagit County have been limited to individual watersheds with yearly data from one or two agencies. Now

Padilla Bay NERR and the Washington State Department of Ecology want to find county-wide patterns and influences of fecal coliform to help direct mitigation efforts in Skagit County.

The objectives of this paper are to first, do a countywide analysis on fecal coliform levels in four different land use types: rural, residential, commercial, and marine; second, identify the proportion of sites that fail fecal coliform state standards for each of the land use types; and finally, determine yearly and seasonal patterns of fecal coliform. Identifying seasonal and annual patterns of fecal coliform in four different land use types has the potential to inform the Washington State Department of Ecology and Skagit County agencies on where and when to direct their efforts to mitigate fecal coliform pollution.

Previous publications report that agricultural and residential areas notably contribute to fecal coliform pollution in Skagit County (ECY, 2009 & ECY, 2020). Anecdotally, some have observed high fecal coliform in the summertime (Dr. Sylvia Yang, personal communication, June 2022). Thus, rural sites, which include agriculture, are expected to have a seasonal pattern of fecal coliform levels. Rural areas are also expected to have the highest proportion of sites that failed at least one state standard between all the land use types.

Residential and commercial sites are hypothesized to have lower proportion of failure than rural sites, but higher proportion of failure than marine sites. Fecal coliform levels in suburban and urban watersheds have been found to have a positive linear correlation with human population density. In 2020, the

population density of Skagit County was 74.9 people per square mile (US Census Bureau, n.d.). Thus due to the lower population density in Skagit County, residential sites and commercial sites will have a lower proportion of sites that failed at least one state standard. In residential and commercial sites, levels of fecal coliform are likely to have a seasonality because stormwater and septic overflows are more likely to occur during rainy periods (Cahoon et al, 2006; Mallin et al., 2009).

Marine sites are hypothesized to have the lowest proportion of sites that failed at least one state standard out of all the land use types. There will be seasonal trends in the proportion of marine sites that failed at least one state standard. Seasonal trends in Samish Bay were reported by the Department of Ecology TMDL report in 2006 which reported marine sites had peaks of fecal coliform levels in the winter and in June (ECY, 2009).

METHODS

Data collection

I gathered and assessed data collected by four different agencies: Samish Nation Department of Natural Resources (SNDNR), Skagit County Public Works (SCPW), Skagit Stream Team (ST), and Washington Department of Health (WADOH). Over all four datasets, 44,484 water samples collected from 1990 to 2021 were tested for fecal coliform abundance.

Dataset details

From 2003 to 2021, SCPW collected on average two water samples per month from each site. The agency collected 19,415 samples from sloughs in fields zoned as Rural Reserve, Agricultural-Natural Resource Lands, and Public Open Space of Regional/Statewide Importance. Over all the years, SCPW water samples are from 45 different sites, but every site is not sampled each year. All fecal coliform samples were analyzed using the Most Probable Number (MPN) method at Skagit County Health Department Water Lab, and fecal coliform measurements were reported as colony forming units per 100mL (cfu/100mL) with a precision of 33% relative standard deviation (SCPW, 2003).

WADOH collected on average one water sample per month from each site from 1990 to 2021. The agency collected 7,798 water samples from 18 sites in Padilla Bay and 34 sites in Samish Bay. Fecal coliform was reported as fecal coliform per 100mL. WADOH collects fecal coliform samples to help classify shellfish growing areas (WADOH b, n.d.).

SNDNR collected a total of 5,178 samples from 2005 to 2020. SNDNR collected water samples from 136 sites, but many sites were removed from the sampling over the years due to low fecal coliform levels. All sites were identified as stormwater outfalls into Fidalgo Bay. The SNDNR efforts were directed towards sites with consistently high fecal coliform levels. From 2005 to 2010, two water samples were collected per month from 43 sites, and from 2010-2020, one water sample was collected from 16 sites. All water samples were analyzed using the MPN methods at a ECY accredited lab. Fecal coliform levels were reported in cfu/100mL, and fecal coliform levels above 1600 cfu/100mL were reported as “>1600” (SNDNR, 2019).

ST collected on average two water samples per month from 59 sites. From 2003-2021, this volunteer group collected 12,093 water samples. Site locations spread across the Padilla Bay and Samish Bay watersheds and included samples from agricultural, residential, and urban areas. Samples from Bayview, Lower Nookachamps, Upper Nookachamps, Lower Samish River, Upper Samish River, Joe Leary Slough, and No Name Slough were analyzed at Padilla Bay NERR volunteer lab (SCD & PBNERR, 2020). Volunteers used membrane filtration

using Millipore Sterifil aseptic system with 47 mm membrane filters and 0.45 um pore spaces. Samples were incubated in a Millipore single chamber incubator at a temperature range of 30C to 44.5C. fecal coliform levels were reported as cfu/100mL. Water samples from all other sites were analyzed by Burlington Wastewater Treatment Plant, Mount Vernon Wastewater Treatment Plant, or Anacortes WasteWater Treatment Plant. All wastewater treatment plants used the MPN method and reported fecal coliform levels in cfu/100mL (SCD & PBNERR, 2020).

Data synthesis

All data sets from the four agencies were synthesized into one file. Previous Padilla Bay NERR interns synthesized SCPW and WADOH dataset in 2022. Their dataset was checked to ensure that all samples and sites were included. ST data was synthesized into one dataset with the help of Padilla Bay NERR Education Coordinator Susan Wood.

Before 2022, the SNDNR dataset had been synthesized by a Padilla Bay NERR intern. However, there were some discrepancies between the intern's dataset and the original one. For some water samples in the original SNDNR dataset, there were two fecal coliform measurements. In the intern's synthesized data set, only one of the measurements was recorded; there was no indication of whether both water samples were analyzed or one water sample was analyzed

twice. To address this discrepancy and include all possible data, my current dataset averages the two fecal coliform measurements from the original dataset.

Data standardization

Washington State fecal coliform state standards were used to standardize the dataset. Most of the water samples were collected before 2020, so fecal coliform state standards prior to 2020 were used for all year to keep the analysis consistent (SCPW, 2022). The state standards prior to 2020 are as follows and are broken up into two parts. For Washington state standards, all geometric means must be calculated using at least three water samples. To pass the first state standard, the geometric mean of fecal coliform must be less than 100 cfu or MPN per 100mL for freshwater samples, and the geometric mean of fecal coliform must be less than 14 cfu or MPN per 100mL for marine samples. To pass the second state standard, 10% of samples must be less than 200 cfu or MPN per 100mL for freshwater samples, and 10% of samples must be less than 43 cfu or MPN per 100mL for marine samples (WAC 173-201A-210 Marine water designated uses and criteria, WAC 173-201A-200 Fresh water designated uses and criteria). For each site, the annual geometric mean (geomean) and monthly geomeans were calculated.

Because all the agencies collected data differently, the fecal coliform measurements had to be standardized. To do this, all fecal coliform measurements that were more than 1600 cfu/100mL or were ‘too many to count’ were converted

to 1600 cfu/100mL. Because 1600 cfu/100mL is well above the state standards, measurements over 1600 cfu/100mL still were effective in determining whether a site passed or failed the state standards.

Each site was categorized as Rural, Residential, Commercial, or Marine. Those sites categorized as Rural, Residential, and Commercial reflected Skagit County's Comprehensive Plan Designations and Zoning Plan (Figure 3). Rural sites were in land zoned as Rural Reserve, Agricultural-Natural Resource lands, or Public Open Space of Regional/Statewide Importance. Residential sites were in land zoned as Rural Village Residential, Urban Incorporated Area, Urban Reserve Residential, Rural Intermediate, and Rural Reserve. Commercial sites were in land zoned as Urban Incorporated Area, Anacortes UGA Development District, and Commercial/Industrial (Skagit County GIS, 2020). In addition to zoning plans, satellite maps helped to distinguish between rural, residential, and commercial. For example, if a site was in an Urban Incorporated Area zone, satellite images were used to determine if the site was in a residential area or in a commercial area. All marine sites were collected in Fidalgo, Padilla, or Samish Bay.

There were 60 rural sites, 37 residential sites, 32 commercial sites, and 54 marine sites (Figure 4). All residential, rural, and commercial sites were sampled after 2003, and all marine sites were sampled after 1990. 105 sites from SNDNR were excluded from the analysis due to infrequent sampling and unknown locations. Remaining are a total of 187 sites and 42,616 water samples.

Calculations

For every month and year, each site's fecal coliform data was analyzed using the state standards, which deemed a site as either pass or fail. The monthly proportion of sites that failed at least one state standard for each month was calculated for every land use type. For residential, rural, and commercial sites, the following equation was used.

Let $J = \{\text{January, February, ..., December}\}$

Let $I = \{2003, 2004, \dots, 2021\}$

Let $G = \{\text{rural, residential, commercial}\}$

$\forall j \in J$ and $\forall g \in G$

$$AvgMonthlyProportion_{jg} = \frac{\sum_{i=2003}^{2021} (Proportion\ of\ Failed\ Sites)_{ijg}}{|I|}$$

For marine sites, the following equation was used.

Let $J = \{\text{January, February, ..., December}\}$

Let $I = \{1990, 1991, \dots, 2021\}$

$\forall j \in J$

$$AvgMonthlyProportion_j = \frac{\sum_{i=1990}^{2021} (Proportion\ of\ Failed\ Marine\ Sites)_j}{|I|}$$

The annual (yearly) proportion of sites that failed at least one state standard was calculated as the average of the 12 monthly proportions of fails for each site. For residential, rural, and commercial sites, the following equation was used.

Let $J = \{\text{January, February, ..., December}\}$

Let $I = \{2003, 2004, \dots, 2021\}$

Let $G = \{\text{rural, residential, commercial}\}$

$\forall i \in I \text{ and } \forall g \in G$

$$\text{YearlyProportion}_{ig} = \frac{\sum_{j=Jan}^{Dec} (\text{Proportion of Failed Sites})_{ijg}}{|I|}$$

For marine sites, the following equation was used.

Let $J = \{\text{January, February, ..., December}\}$

Let $I = \{1990, 1991, ..., 2021\}$

$\forall i \in I$

$$\text{YearlyProportion}_i = \frac{\sum_{j=Jan}^{Dec} (\text{Proportion of Failed Marine Sites})_{ij}}{|I|}$$

The global proportion of sites that failed at least one state standard was calculated as the average of the proportion of sites that failed at least one state standard for each land use type across all the years. The following equation was used to calculate the global proportions.

Let $J = \{\text{January, February, ..., December}\}$

Let $I = \{1990, 1991, ..., 2021\}$

Let $G = \{\text{rural, residential, commercial, marine}\}$

$\forall j \in J, \forall i \in I, \forall g \in G$

$$\text{GlobalProportion}_g = \frac{\sum (\text{Proportion of Failed Sites})_{ijg}}{|I| * |J|}$$

Statistical analysis

The standard deviation and standard error were calculated for yearly proportions, global proportions, and the averaged monthly proportions. Analysis of variance and Tukey HSD were performed in R to determine if the proportion of sites that failed at least one state standard were statistically different between each land use type and to determine if the proportion of sites that failed at least one

state standard were statistically different between each year. To test if there were seasonal patterns for each land use type, time series for each land use type were calculated, and autocorrelation functions were plotted. Durbin-Watson tests were performed for each land use type time series.

RESULTS

Rural

All land use types had significantly different global averages of proportion of failed sites (Figure 5 & Table 1). Of all the land use types, rural sites have the highest average proportion of sites that failed at least one state standard. Rural sites have a consistent proportion of sites that failed at least one state standard over the years with no obvious spikes from 2003 to 2019 (Figure 6). In 2020, the proportion of sites that failed at least one state standard for rural sites had an upward trend. For rural sites, the average proportion of sites that failed at least one state standard each year has a seasonal trend with a higher proportion of sites that failed at least one state standard from May to September and a low proportion of sites that failed at least one state standard from November to April (Figure 7).

The time series for rural sites from 2003 to 2021 visually shows seasonal trends (Figure 8). There are multiple autocorrelations that are significantly non-zero, with strong correlation at all lags except for lag 3 and lag 9 (Figure 9). Thus, the time series for rural sites is nonrandom. True autocorrelation is greater than zero ($p < 0.001$).

Marine

Marine sites had the lowest proportion of sites that failed at least one state standard out of all land use types (Figure 5). The proportion of failed marine sites varied year by year with the highest proportion of failures in 1998 (Figure 6). The average proportion of sites that failed at least one state standard from 1990 to 2005 was 14.37%, whereas the average proportion of sites that failed at least one state standard from 2005 to 2021 was 6.62%. Highest proportion of sites that failed at least one state standard happened during the rainy season from November to January with the lowest proportion of sites that failed at least one state standard during the dry season from July to September (Figure 7). Figure 10 shows that some autocorrelations are greater than zero with a strong correlation at lag 1. True autocorrelation is greater than zero ($p < 0.001$), and thus the time series for marine sites is nonrandom.

Residential and commercial

Compared to rural sites, residential and commercial sites had lower average proportions of sites that failed at least one state standard. However, they had higher average proportions of sites that failed at least one state standard than marine sites (Figure 6). From 2003 to 2021, proportions of residential and commercial sites that failed at least one state standard varied. The year with the

highest proportion of residential sites that failed at least one state standard was 2008; the years with the highest proportions of commercial sites that failed at least one state standard were 2016 and 2021 (Figure 6). For residential sites, Figure 7 shows a seasonal pattern where the highest proportion of sites that failed at least one state standard is observed in June and the lowest proportion of sites that failed at least one state standard is observed in September, December, and January. Residential sites have a nonrandom time series with strong correlation at lags 1, 3, and 4. True autocorrelation is greater than zero ($p < 0.001$) (Figure 11). Seasonally, commercial sites have a higher proportion of failures in June and from August to October (Figure 7). Figure 12 reports that almost all autocorrelations are significantly nonzero with strong correlation at all lags except for lag 10. Hence, the time series for commercial sites is nonrandom. True correlation is greater than zero ($p < 0.001$).

DISCUSSION

Rural, marine, residential, and commercial sites all had significantly different global proportions of sites that failed at least one state standard (Table 1). Different land use types have significantly different fecal coliform levels (Schoonover & Lockaby, 2006). In mixed land use watersheds, high fecal coliform is correlated with a high percentage of impervious surfaces (Mallins et al. 2009; Schoonover & Lockaby, 2006). While impervious surface coverage was not a factor in this analysis, it can be inferred that rural sites have the lowest percentage of impervious surfaces, which, according to literature, would have the lowest fecal coliform levels. In spite of that, in Figure 5, rural sites have a higher proportion of sites that failed at least one state standard compared to residential and commercial sites. While the literature suggests that higher fecal coliform levels would be found in residential and commercial sites in most watersheds, analysis of fecal coliform levels in mixed land use watersheds should be done in the context of individual watersheds.

Rural

Rural sites have the highest average proportion of sites that failed at least one state standard which was expected (Figure 5). Rural sites had little variation year to year which suggest that long term weather patterns do not greatly influence fecal coliform levels in rural sites. June to August—the dry season in

Skagit County—is the peak for high fecal coliform levels at rural sites (ECY, 2020). Typically, high fecal coliform levels in most places can be attributed to heavy rainfall which can cause overflowing streams and surface runoff (Dakhlalla & Parajuli, 2020). However in rural Skagit County, high fecal coliform levels are observed in the dry season (Dr. Sylvia Yang, personal communication, June 2022). As the Department of Ecology reports, there is low water flow in non-marine sites during the summer months in Skagit County (ECY, 2009). This is atypical; most rural areas have low fecal coliform levels during dry periods with low water flow.

Krstulovic et al. (2007) and Soueidan et al. (2021) report that solar radiation and salinity have a negative linear relationship with fecal coliform levels. Theoretically, shallow sloughs are exposed to high solar radiation and low precipitation during the summer months. Low precipitation would decrease surface runoff from nearby farms and would increase the salinity in shallow sloughs. Hence fecal coliform levels should decrease in the summer. However, the opposite seasonal pattern is seen at rural sites in Skagit County where a high proportion of sites failed at least one state standard in summer. These high fecal coliform levels observed in summer in Skagit County could be caused by an increase in livestock activity and the application of manure on fields.

Residential and commercial

Residential and commercial sites had similar seasonal patterns and similar overall proportions of sites that failed at least one state standard. The autocorrelation function of commercial sites shows a seasonal trend, but it is not as extreme as seasonal trends in rural and marine sites (Figure 12). This pattern suggests that residential and commercial sites are not influenced by external seasonal patterns, such as precipitation or temperature, but rather influenced by sporadic fecal coliform inputs. More data is needed to determine similarities and differences of fecal coliform levels between residential and commercial sites.

Sources of fecal coliform pollution in residential and commercial sites are hard to pinpoint. Both residential and commercial sites have more impervious surfaces than rural sites, and Mallins et al. (2000) found that fecal coliform and the percent of watershed impervious surface coverage are correlated ($r=0.95$). Impervious surfaces, such as pavement and concrete, are unable to absorb storm overflow and septic tank leaks and instead create standing water. This can lead to high volumes of contaminated water flowing into the watershed (Mallins et al., 2000).

The data from commercial sites can be used as an estimate for the impact of urban stormwater overflow in future research. But because most commercial sites included in this data were sampled in Anacortes, additional commercial sites outside Anacortes are needed to get a more complete picture of urban stormwater overflow in Skagit County

In residential and commercial areas, most houses and commercial buildings rely on septic systems. Currently there are over 18,000 septic systems in Skagit County. Because leaking and overflowing septic systems are known to contribute to fecal coliform pollution (ECY, 2020), Skagit County requires septic tanks to be inspected every year, or, if the building has a simple gravity system, every three years (Skagit County Health Department (SCHD), n.d).

To help address faulty septic systems and decrease fecal coliform entering shellfish growing areas, Skagit County Public Health implemented the On Site Sewage Management Plan in 2008. This plan outlined Marine Recovery Areas (Figure 14), which are areas of Skagit County that contributed to significant fecal coliform pollution and now require additional constraints and inspections for septic systems (SCHD, n.d.). As seen in Figure 14, most of the marine recovery areas in Skagit County are a part of the Samish Bay watershed.

In 2018, SCPW tried a complementary approach to address the problem of high coliform levels from faulty septic systems. The agency contacted the Environmental Canine Service and hired a dog named Crush that was specially trained to identify human sources of fecal coliform pollution (EPA & Skagit County, 2018). Crush visited sites that had previously had high levels of fecal coliform but no clear source. Crush examined areas with septic tanks, along with ditches and streams, to sniff out human sewage. This project coupled with required inspections has identified direct septic tank failures (EPA & Skagit County, 2018). While there is no data to support the success of this project, Figure

6 shows a decrease in the proportion of residential sites that failed at least one state standard after 2017. From 2017 to 2019, there was a 29.9% decrease in the proportion of residential sites that failed at least one state standard.

Mismanaged pet waste in residential and public spaces can add to fecal coliform pollution in the watershed. To reduce it, some Skagit County organizations have spread information to county residents on how to effectively manage pet waste (Olsen, 2008; Skagit County Clean Water, n.d.). For example, the Skagit County Conservation District identified frequently used public spaces, such as the Padilla Bay Shore Trail, as potential sources of fecal coliform pollution. In 2020, the Conservation District organized a volunteer system to monitor public spaces for mismanaged pet waste (SCD, n.d. c).

Some efforts to reduce Skagit County's fecal coliform pollution from residential and commercial spaces appear to be working, but more data is needed to determine the success of these efforts. Skagit County should continue to monitor and inspect septic systems in efforts to reduce point source pollution. Citizen science volunteers have the potential to make a significant impact on decreasing pollution by identifying and cleaning up public spaces and by spreading information to other county residents.

Marine

Marine sites have lowest fecal coliform levels during the late spring and summer months, which make up the dry season in Skagit County. The highest

fecal coliform levels occur in winter months, which is the rainy season (Figure 13). According to the Department of Ecology, low water flow in freshwater sites during spring and summer months slows fecal coliform input into marine bodies of water, but faster water flow during the fall and winter months increases freshwater input. (ECY, 2009) With faster water flow in the winter, fecal coliform from upstream sites is more likely to reach marine bodies.

The seasonal trend of fecal coliform levels at marine sites is reflected in the WADOH shellfish growing classifications. The majority of Samish Bay is classified as conditionally approved, which requires sites to pass different thresholds depending on the season (WADOH, n.d. b). For example, from November to February, if fecal coliform levels are 400 cfu/100mL or more, shellfish harvesting is closed, whereas from May to October, if fecal coliform levels are 100 cfu/100mL or more, shellfish harvesting is closed. The high fecal coliform threshold in the winter for shellfish harvesting suggests that WADOH and the Department of Ecology recognize that there are fecal coliform spikes in the winter months, which is consistent with data shown in Figure 7 (ECY, 2009; WADOH, n.d. b).

Watershed to bay trends

The synthesis of four different datasets allows for a broader analysis of watershed-to-bay trends. Inputs of fecal coliform in upstream sites travel downstream towards bays. In Skagit County, the watersheds of each bay have

different proportions of land use type. For example, fecal coliform levels in Fidalgo Bay are probably most influenced by commercial and residential stormwater overflow from Anacortes (SNDNR, 2021). But in Samish Bay, rural and agriculture sites are more likely to influence the fecal coliform levels (ECY, 2009). Deciphering where high loads of fecal coliform are entering the watershed can help Skagit County agencies by directing mitigation efforts and stopping high fecal coliform levels from entering bays.

In Skagit County, fecal coliform from rural sites is more likely to enter the watershed during the summer months. The summer months are the ideal time for livestock to graze, but this can lead to unmanaged livestock waste. Livestock waste can enter the watershed both when livestock are close to sloughs and during short rainfall events (ECY, 2020). Myers and Kane (2011) also showed that fecal coliform levels in streams near cattle farms increased after extended grazing. In addition, runoff from manure used as fertilizer for produce farms can drain into nearby sloughs (ECY, 2020).

Efforts to decrease fecal coliform levels at rural sites in Skagit County have been directed towards developing best management practices (BMPs) for local farmers. Skagit Conservation District outlines BMPs for managing summertime grazing for livestock (SCD, n.d. a). The SCD advises farmers to limit grazing during the rainy season and winter months. During the rainy season, livestock are more likely to inadvertently kick up the root systems of grazing fields. Without a root system for grazing fields, more runoff from grazing fields is

likely since the top layer of the soil is overturned (Hartman, 2022). Fields without a root system are also unlikely to recover and regenerate. During the winter months, it is unlikely that fields will continue to grow. Since there is no regrowth, livestock are more likely to overgraze (Hartman, 2022). Because grazing is not recommended in the rainy winter months, livestock are less likely to be in the fields, leading to less unmanaged livestock waste.

During the dry summer months, rotation grazing is recommended as a BMP. It is recommended that livestock start to graze in one field when the grass is six to eight inches, and when the grass is three inches, livestock should be moved to a different field (SCD, n.d. b). Once grass in the fields reaches three inches, the grass should be regrown. The BMPs suggest that farmers mow and spread manure and fertilizer on recovering fields, and these practices should take place during April to October (SCD, n.d. b).

Because there is little precipitation in the summer, fecal coliform input from farms during the spring and summer months is more likely to stay in sloughs close to farms due to low water flow. Additionally, Davies et al. (1995) report that fecal coliform can survive in the sediment of sloughs and streams. Fecal coliform in the sediment can be resuspended into the water column if the sediment is disturbed. In shallow sloughs, precipitation during the fall and winter months can disturb sediment (Howell et al., 1995; Jamieson et al., 2003).

As seen in Figure 7, rural sites have the highest proportion of failed sites during the dry season, but marine sites have the highest proportion of failed sites

during the rainy season. It is possible that at rural sites fecal coliform in sediment is resuspended during the start of the rainy season, and due to high water flow from precipitation, high fecal coliform levels travel downstream into marine areas (Howell et al., 1995). Schoonover and Lockaby (2006) report similar findings. They report that light rainfall, that often occurs in the summer, might not increase the flow of streams and sloughs enough for the high levels of fecal coliform to travel downstream near marine bodies of water.

More data is needed to support this hypothesis, but it would be useful to measure fecal coliform levels in the sediment year-round. Coupling fecal coliform levels in the water column and the sediment could give a bigger picture on watershed-to-estuary trends of fecal coliform.

Politics

Shellfish harvesting closures in Skagit County have pushed state and local agencies to trace fecal coliform pollution sources. Many publications direct their attention to decreasing fecal coliform pollution from agriculture. In response, Skagit Conservation District has developed many BMPs specifically designed to help farmers reduce fecal coliform pollution. BMPs, such as livestock exclusion fencing, can be helpful, but the implementation of these practices, such as installing and maintaining fencing, may not be feasible due to limited funding and extensive labor (ECY, 2020; Robinson & Schroeder, 2017). If farmers do not implement required BMPs, the Department of Ecology can issue citations which

cause additional financial burdens on farmers (Robinson & Schroeder, 2017). In addition to being a burden on farmers, BMPs are a burden on the few inspectors. For example, if Department of Ecology inspectors find a broken exclusion fence, they may have to take the time and limited funds to set up a temporary fence. In recent years, there has been a push to pinpoint faulty septic systems. Yearly inspections of residential systems are required, but if a system fails, the homeowner is required to fix it, which could be costly (WAC 246-272A-0270). Recently, residents are able to apply for loans to help cover the cost of repairs (Craft3, n.d.). In addition, inspectors may not be able to complete their annual inspections in a timely way or there might be no follow up after a system fails inspection (Robinson & Schroeder, 2017).

In 2014, Results Washington, a government consulting agency, held a conference on how to address fecal coliform pollution. It included stakeholders such as local, state, and federal agencies; indigenous tribes in the county; farmers; shellfish growers; and residents (Robinson & Schroeder, 2017). Stakeholders were receptive to data driven solutions which created better understanding and unity between the stakeholders at the conference (Robinson & Schroeder, 2017). Another result of this conference was the media campaign Clean Samish Initiative launched to inform residents about their role in fecal coliform pollution. Residents received letters and infographics outlining resources and suggestion tips (SCPW, n.d.; WADOH, 2010). At the end of the conference, stakeholders agreed to pursue more long-term monitoring of fecal coliform, open communication between

stakeholders, data driven solutions, and flexibility to change policies (Robinson & Schroeder, 2017). Today, Clean Samish Initiative continues to provide resources, volunteer opportunities, and events (Skagit County Clean Water, n.d.).

Next steps for data analysis

From 2003 to 2021, the proportion of rural sites that failed state standards was constant, which suggests that fecal coliform levels around rural areas do not fluctuate year by year. Analysis into rural sites from specific watersheds could be useful in determining if mitigation efforts by the Department of Ecology have been successful. A further breakdown of the Samish Bay watershed would provide statistical feedback for the 2009 TMDL for Samish Bay. As agencies collect more data, more statistical analysis could help provide sufficient evidence on the success of mitigation efforts in Padilla Bay and Samish Bay.

The data from this paper helps identify potential fecal coliform sources in Skagit County, but due to the bias sampling of the data and nonpoint source pollutants, the data does not fully explain the sources of fecal coliform. Both SCPW and SNDNR focus their sampling on sites that have historically high fecal coliform levels. SCPW focuses their sampling in sloughs and streams by agricultural land, which does not fully capture all sources of pollution in Skagit County (SCPW, 2003), and SNDNR focuses their sampling near sites that are prone to stormwater overflow in mostly residential and commercial areas (SNDNR, 2019). While ST does sample from residential, rural, and commercial

sites, their sample processing is not standardized: some samples are processed using an incubation method, while other samples are processed using the most probable number method (SCD & PBNERR, 2020). The dataset does contain a variety of different types of sites; sampling additional sites in the future would be helpful in obtaining a broader picture of fecal coliform levels in Skagit County. Unfortunately, adding additional sites in data collection is limited due to lack of funding and labor.

In addition, sites were categorized using the Skagit County Zoning Plan, which fails to recognize other pollution influences at individual sites. For example, a site might be categorized as residential, but if the site is located downstream from a cattle farm, that would influence fecal coliform levels at the residential site. Thus, two next steps in data analysis are to identify potential pollution sources for each site and to identify the downstream versus upstream sites. Coupling sites could help in finding cause and effect relationships between upstream and downstream sites.

Furthermore, fecal coliform levels should be analyzed with precipitation data from the Padilla Bay NERR weather station. Precipitation data could help explain the frequency of stormwater overflows, runoff from farms, and major input events into marine areas (Hill et al., 2006). Identifying El Niño and La Niña cycles in Skagit County also could shed some light on yearly variations in the data (Lipp et al., 2001). For example, in Figure 6, there is an increase in the proportion of sites that failed at least one state standard from 2015 to 2016. Skagit

County had less than average precipitation in 2015, but in 2016, precipitation was above average (Skagit County Public Works, 2017). Analyzing fecal coliform levels in the context of individual watersheds, precipitation, and upstream versus downstream would help to capture more complex interactions in Skagit County.

Next steps for Skagit County

As fecal coliform pollution continues to be an issue in Skagit County, more communication between stakeholders and immediate action are needed. This paper's data shows that rural sites continue to have the highest proportion of sites that failed at least one state standard compared to all the other land use types, in spite of the many efforts to decrease fecal coliform pollution from agriculture. The BMPs for farmers from Skagit Conservation District are straightforward and well researched, but their enforcement is inconsistent, infrequent, and underfunded. Both government agencies and farmers have limited resources to abide by and enforce BMPs.

Skagit County should consider developing a new program that helps farmers pay for maintenance of vegetative buffer zones near streams and sloughs that have historically high fecal coliform levels. Currently, Skagit Conservation District has developed a program to help farmers build and pay for forested buffer zones, but the buffer zone must be next to a salmon stream (SCD, n.d. a). A similar project for farms in Marine Recovery Areas could decrease fecal coliform levels. Buffer zones have been shown to decrease fecal coliform pollution by 99% (Sullivan et al., 2007).

Skagit County should continue to inspect residential septic systems and push for adequate waste management of pets. Strengthening social media campaigns and volunteer monitoring programs could increase residents' awareness and influence their actions. Small steps from residents can and will make a difference in fecal coliform pollution.

As Skagit County continues to identify more fecal coliform sources and collect more water quality data, communication between stakeholders is essential to decrease fecal coliform pollution from all land use types. Data driven solutions are the key to implementing and maintaining mitigation strategies. Seasonal trends identified in this paper should be taken into consideration when developing new strategies. Efforts to decrease high fecal coliform levels from rural sites in the summer would be beneficial and might help decrease high fecal coliform inputs into marine bodies of water in the fall and winter. While further analysis into influential factors in residential and commercial areas is needed, the continuation of current strategies, such as mandatory septic systems inspection, will decrease fecal coliform pollution. This study highlights the importance of long term water quality data analysis to recognize and respond to yearly patterns and seasonal patterns of fecal coliform.

FIGURES

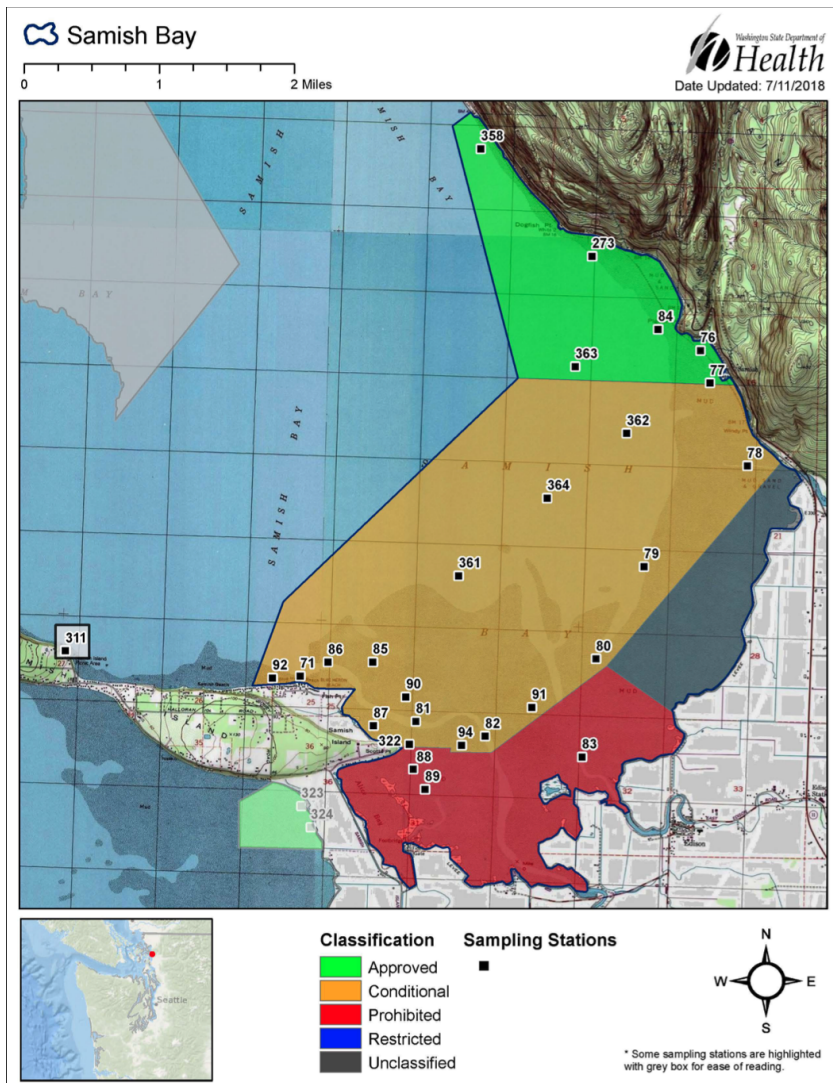


Figure 1. Map of Samish Bay commercial shellfish growing area classifications in 2018 (WADOH, 2022a)

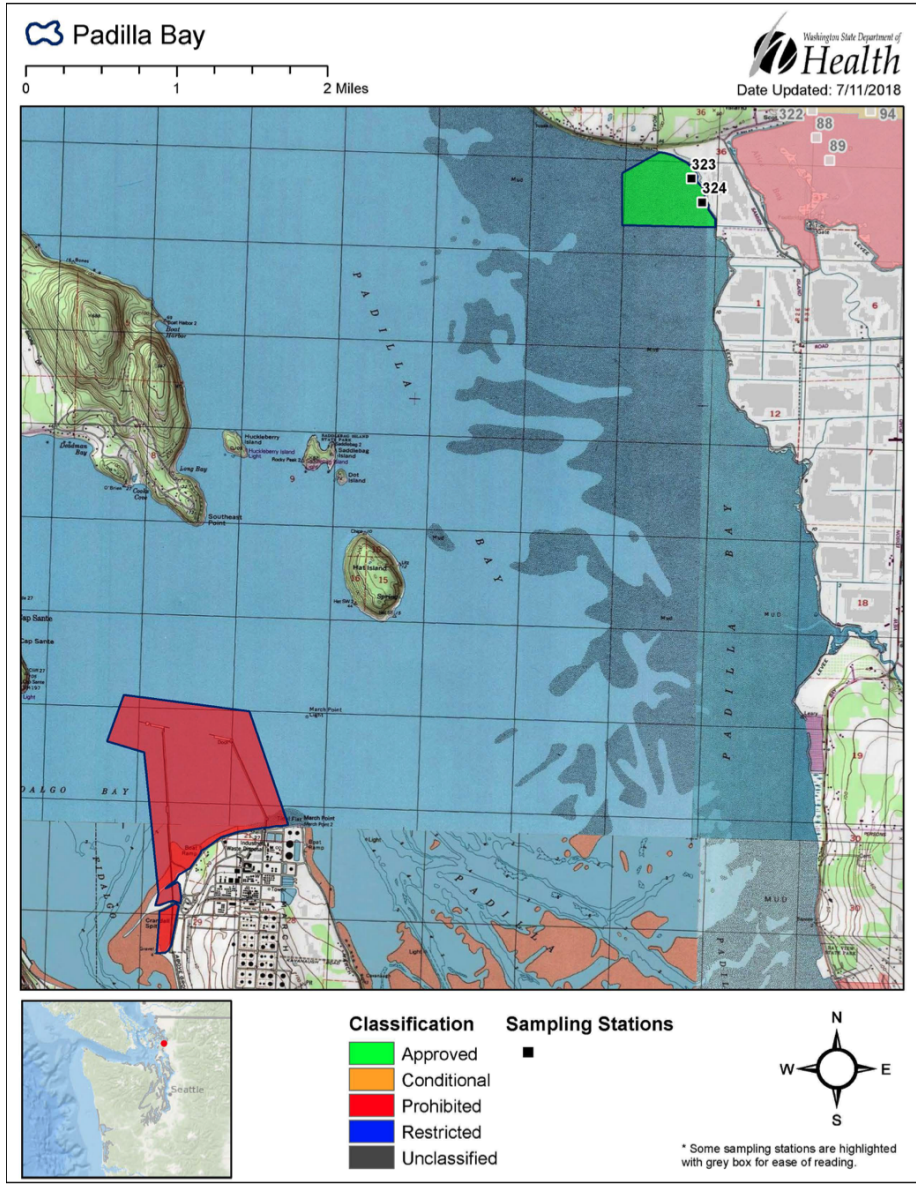
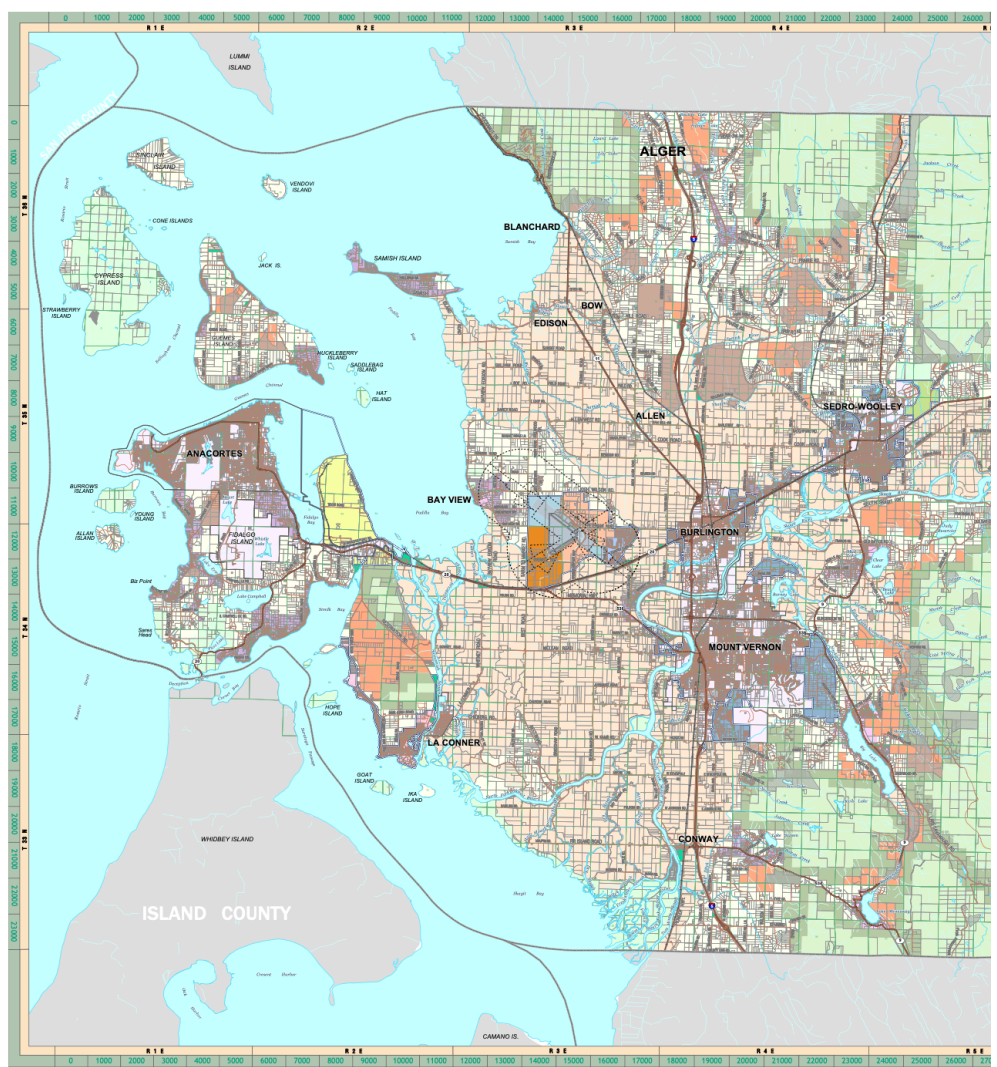


Figure 2. Map of Padilla Bay commercial shellfish growing area classifications in 2018 (WADOH, 2022b)



UGA ZONING		URBAN		NATURAL RESOURCE LANDS		COMMERCIAL / INDUSTRIAL	
[UGA] Urban Growth Area	[UR] Urban Reserve Residential	[H-I] Hamilton Industrial	[I] Incorporated Area	[RR-NRL] Rural Resource - NRL	[RB] Rural Business	[RC] Rural Center	[RVC] Rural Village Commercial
[AVR] Aviation Related	[URC] Urban Reserve Commercial Industrial	[H-R] Hamilton Residential	[RR] Rural Reserve	[Ag-NRL] Agricultural - NRL	[RF] Rural Freeway Service	[NR] Natural Resource Industrial	[SRT] Small-Scale Recreation & Tourism
[AVR-L] Aviation Related - Limited	[URP-OS] Urban Reserve Public Open Space	[H-URV] Hamilton Urban Reserve	[RI] Rural Intermediate	[SF-NRL] Secondary Forest - NRL	[SSB] Small-Scale Business	[RM] Rural Marine Industrial	[MID] Major Industrial Development
[BR-H] Bayview Ridge Heavy Industrial	[A-UD] Anacortes USA Development District		[RV] Rural Village Residential	[IF-NRL] Industrial Forest - NRL	[M] Master Planned Resort		
[BR-L] Bayview Ridge Light Industrial	[C-UD] LaConner USA Urban Development District						
[BR-R] Bayview Ridge Residential	[MV-UD] Mount Vernon USA Urban Development District						
	[R] Residential (Swinomish UGA)						
	[C] Commercial (Swinomish UGA)						

Figure 3. Skagit County Comprehensive Plan and Designation and Zoning Districts (Skagit County GIS).

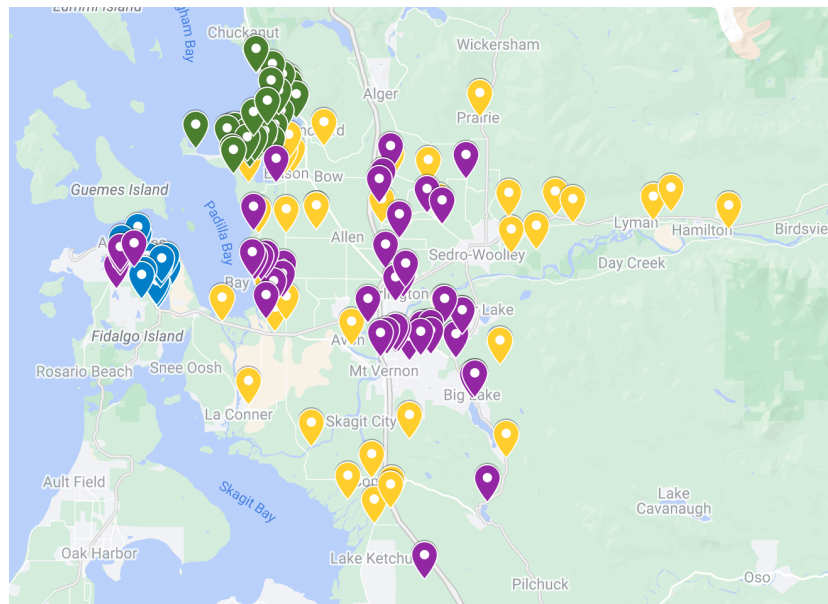


Figure 4. Map of sites sampled in Skagit County, Washington. Yellow points are sites sampled by Skagit County Public Works. Purple points are sites sampled by the Stream Team. Blue points are sites sampled by the Samish Indian Nation Department of Natural Resources. Green points are sites samples by the Washington State Department of Health.

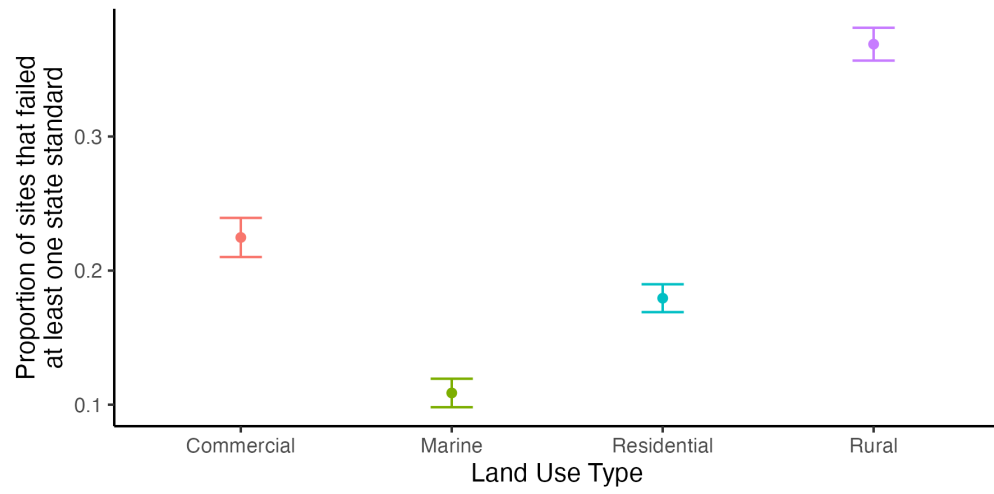


Figure 5. Overall averages of proportion of sites that failed at least one state standard for each land use type.

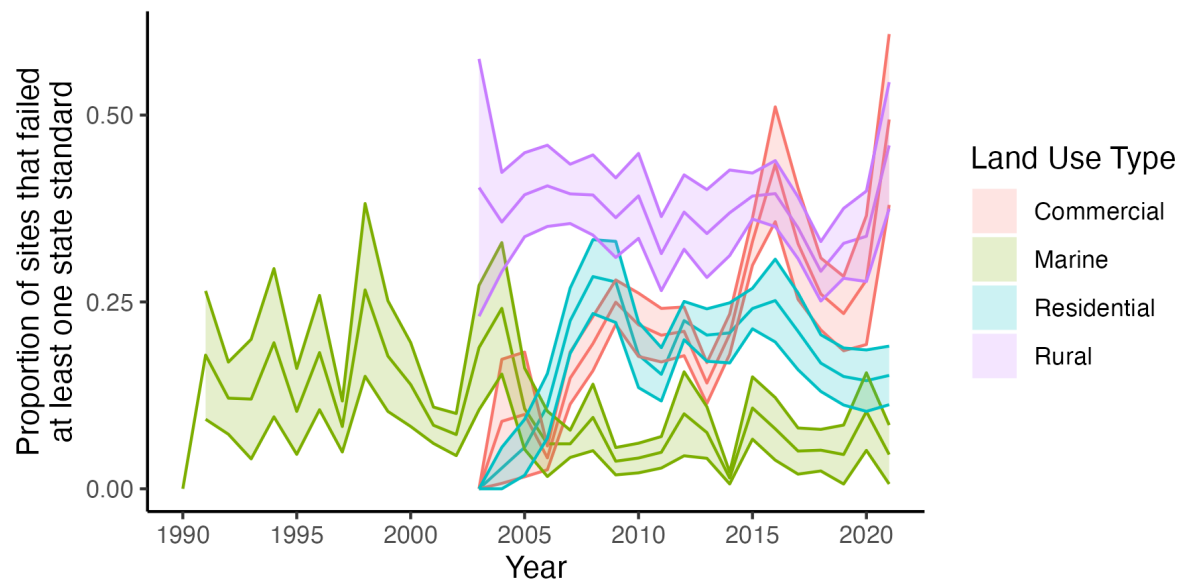


Figure 6. Graph of yearly averages of proportion of sites that failed at least one state standard for all land use types. Shaded regions represent standard errors. Residential, commercial, and rural sites were sampled starting in 2003, and marine sites were sampled starting in 1990.

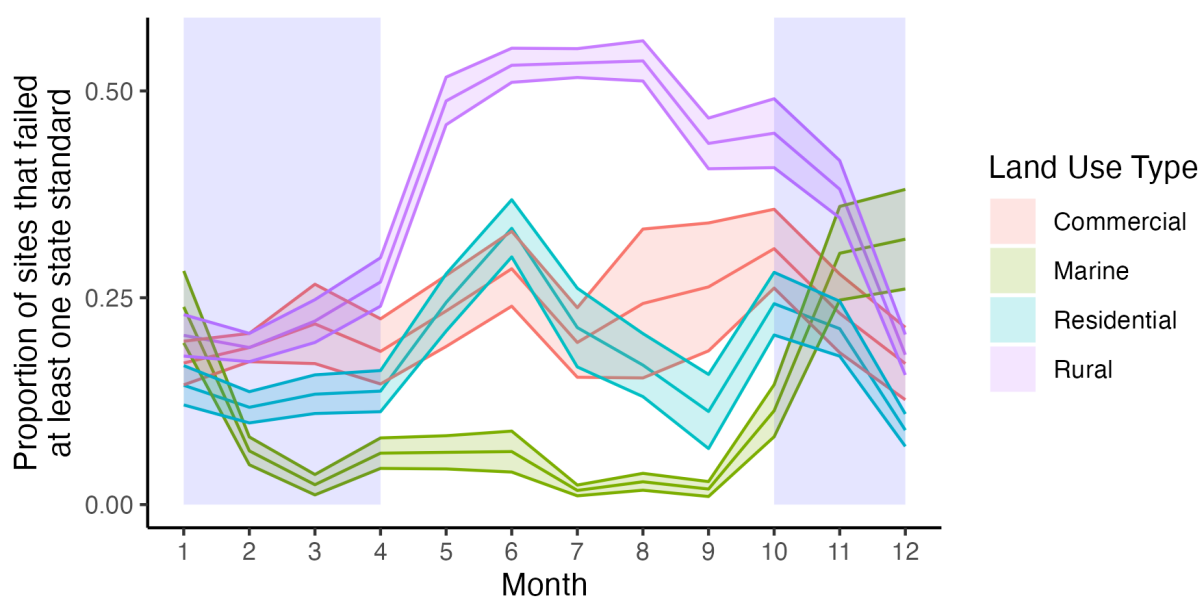


Figure 7. Graph of monthly averages of proportion of sites that failed at least one state standard for all land use types. Shaded regions represent standard errors. Shaded blue region represents the rainy season—October to April— in Skagit County (ECY, 2020).

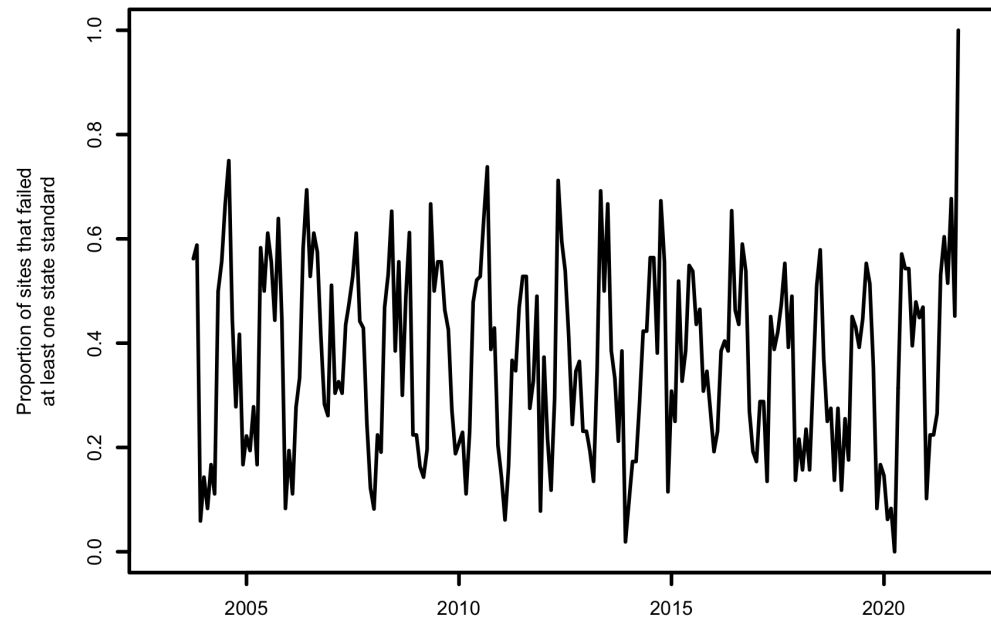


Figure 8. Rural site time series. Monthly averages of proportion of rural sites that failed at least one state standard are plotted across 2003 to 2021.

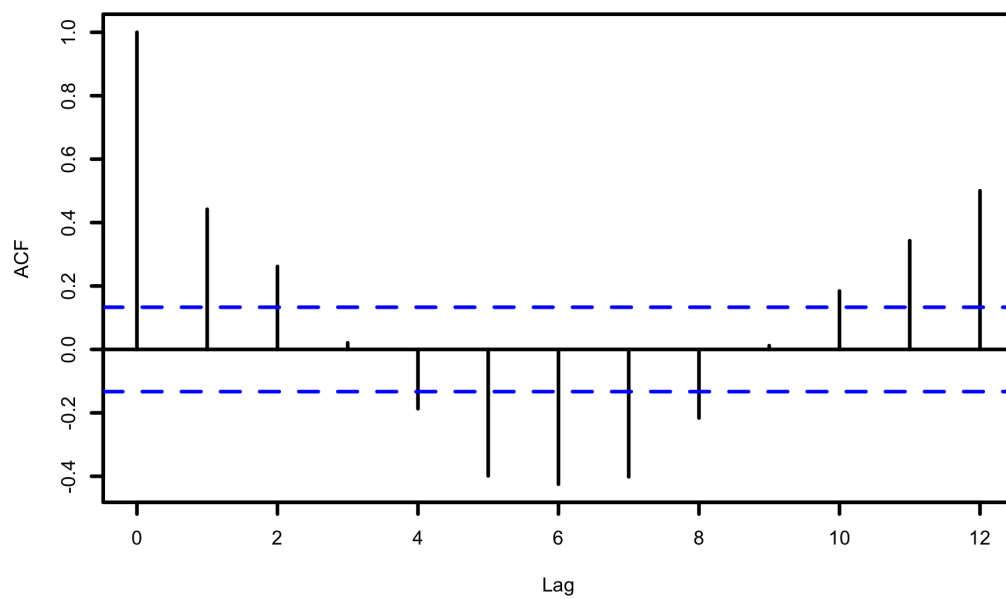


Figure 9. Rural sites autocorrelation function for monthly proportion of rural sites that failed at least on state standard.

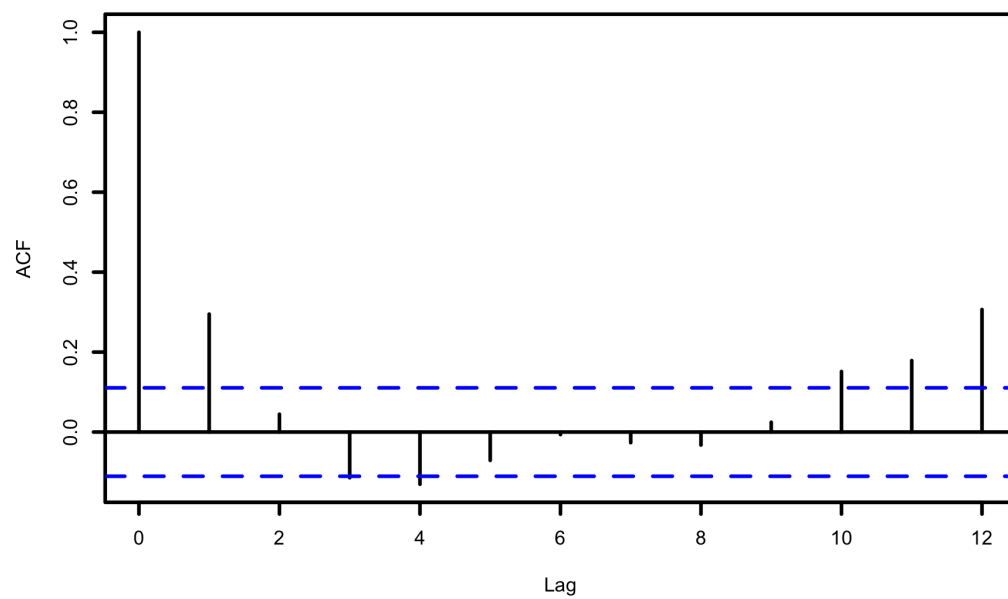


Figure 10. Marine sites autocorrelation function for monthly proportion of marine sites that failed at least on state standard.

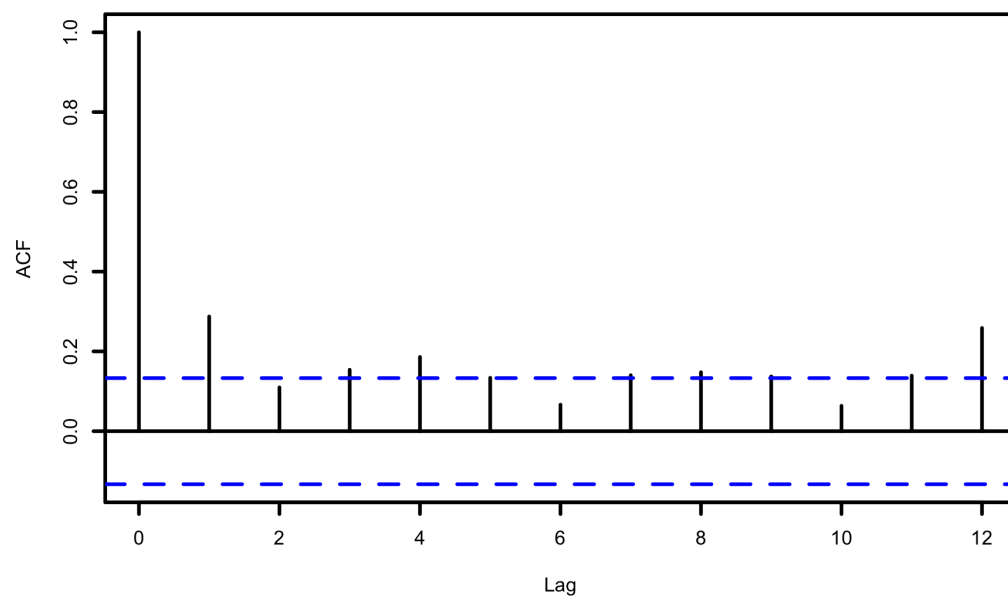


Figure 11. Residential sites autocorrelation function for monthly proportion of residential sites that failed at least on state standard.

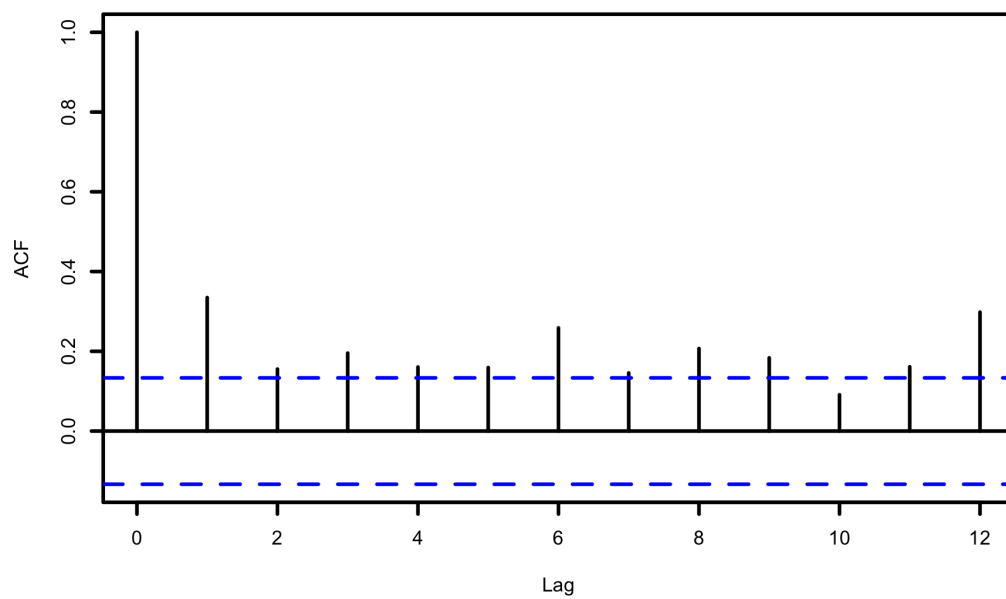


Figure 12. Commercial sites autocorrelation function for monthly proportion of commercial sites that failed at least on state standard.

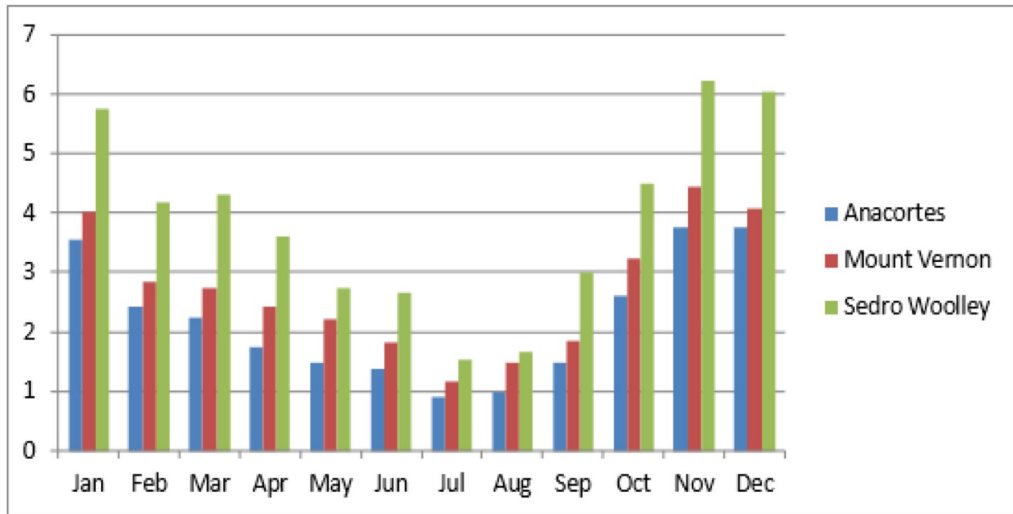


Figure 13. Average total precipitation (inches) for three Washington State University weather stations: Anacortes (450176), Mount Vernon (455678), and Sedro-Woolley (457507). (ECY, 2020).

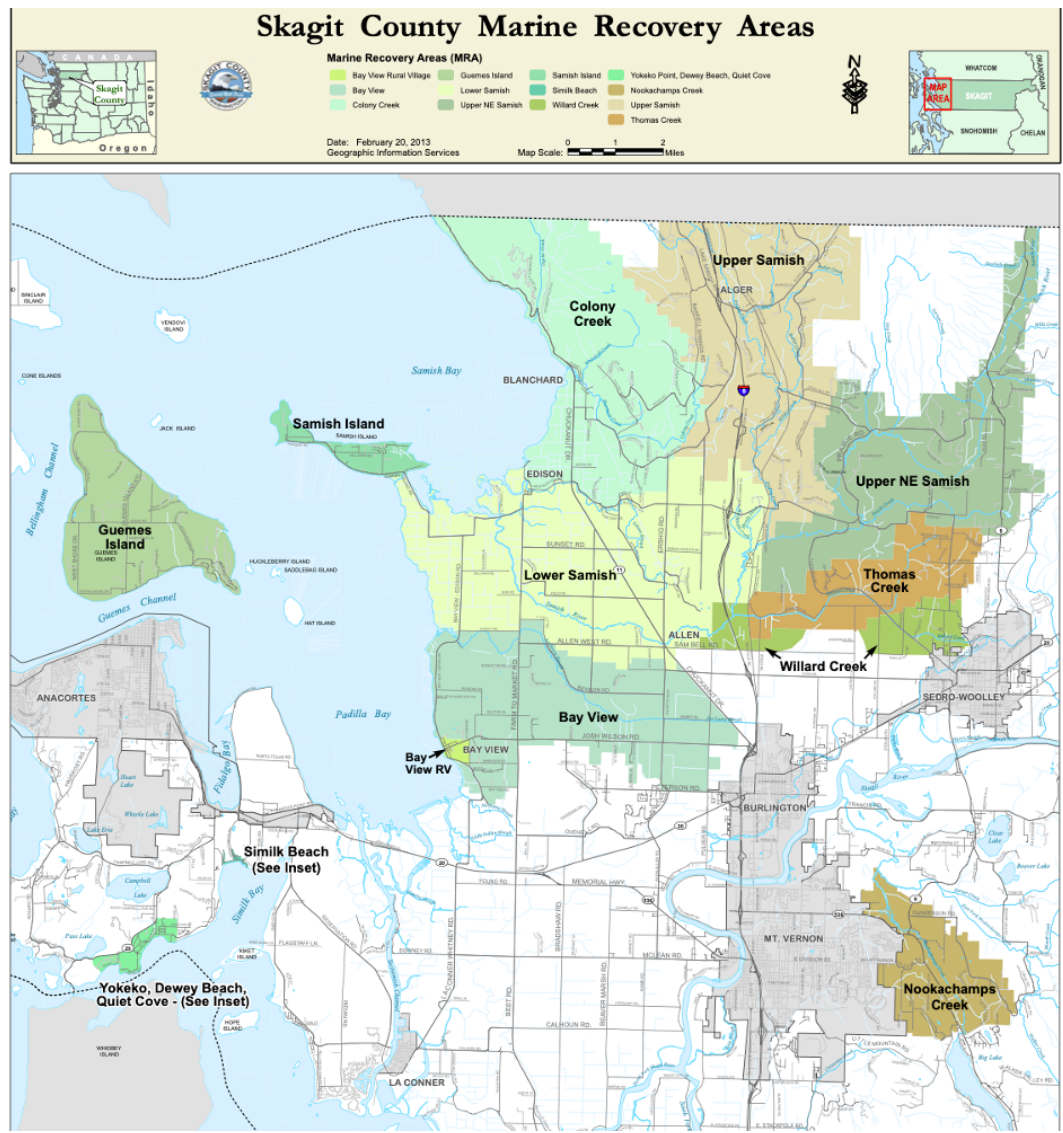


Figure 14. Skagit County marine recovery areas. Shaded areas represent marine recovery areas that require additional regulations of septic tanks.

TABLE

Table 1. Tukey HSD for overall averages of proportion of sites that failed at least one state standard between all land use types.

Land Use Type Comparison	p-value
Marine-Commercial	0.00
Residential-Commercial	0.04
Rural-Commercial	0.00
Residential-Marine	0.00
Rural-Marine	0.00
Rural-Residential	0.00

APPENDIX

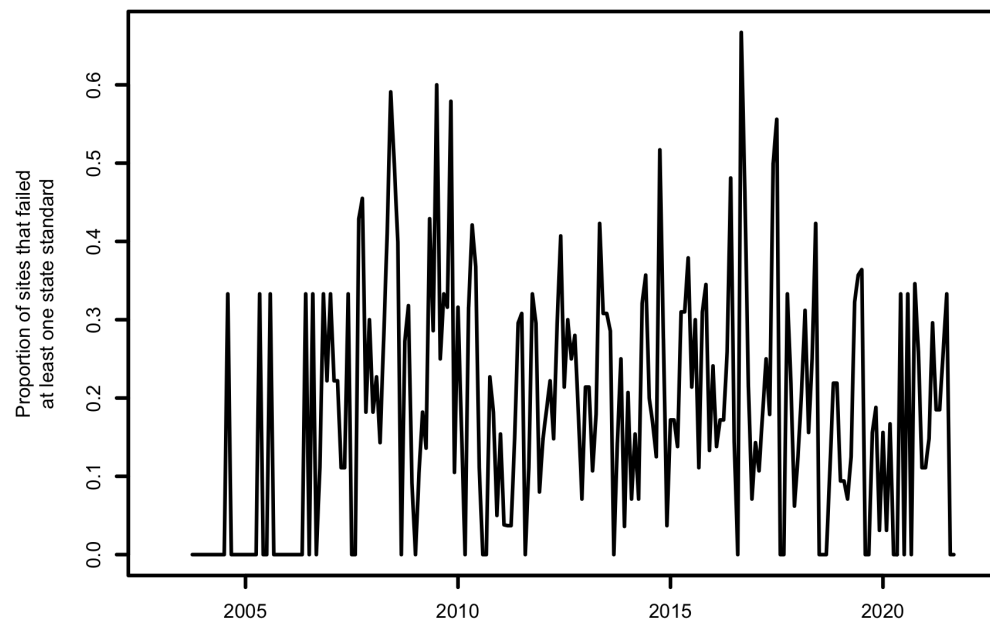


Figure A1. Residential site time series. Monthly averages of proportion of residential sites that failed at least one state standard are plotted across 2003 to 2021.

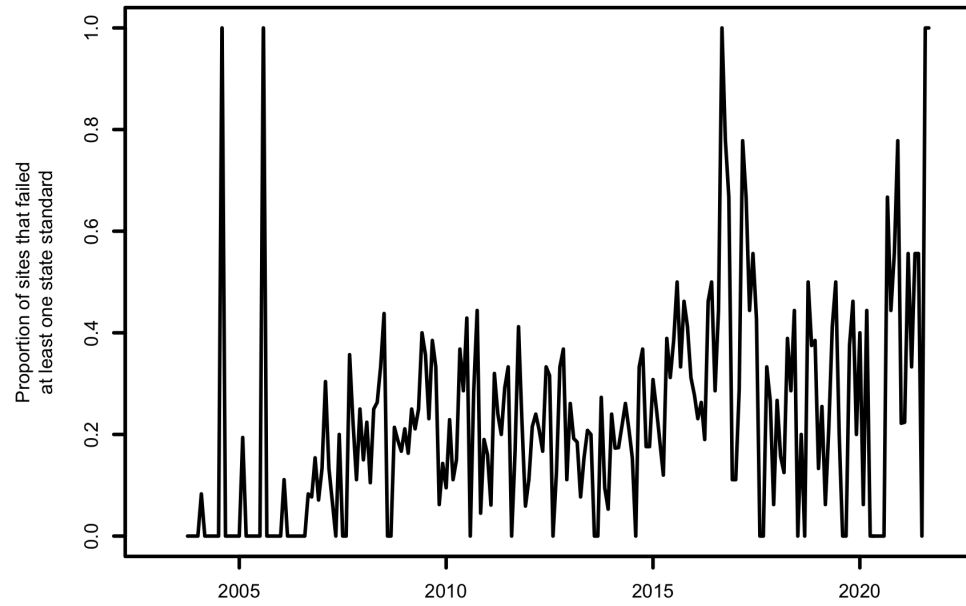


Figure A2. Commercial site time series. Monthly averages of proportion of commercial sites that failed at least one state standard are plotted across 2003 to 2021.

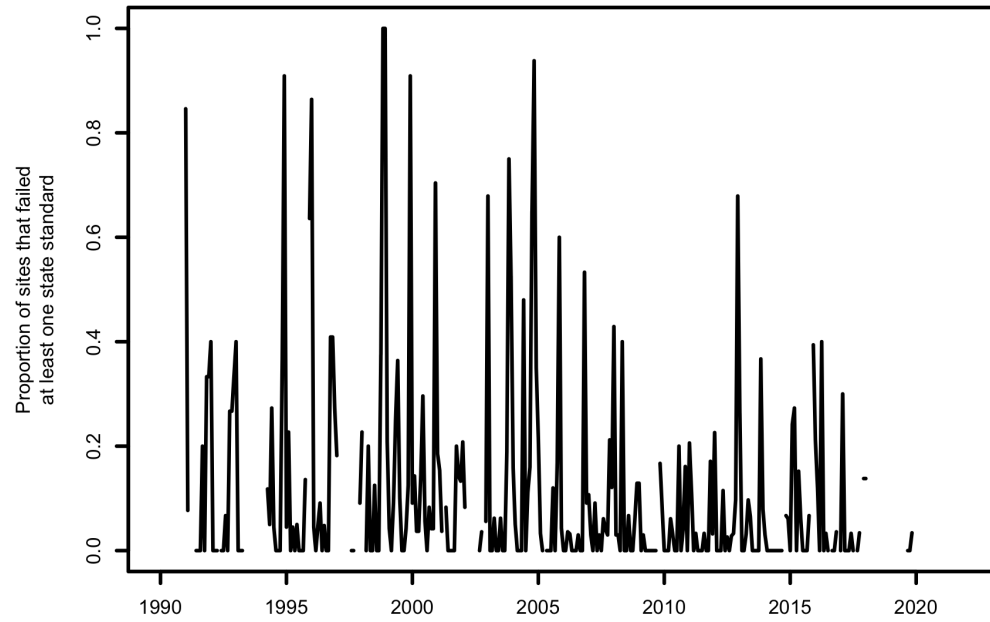


Figure A3. Marine site time series. Monthly averages of proportion of marine sites that failed at least one state standard are plotted across 2003 to 2021.

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Thesis Code

Julia Wolf

2023-04-11

Load Libraries and Import Datasets

```
library(stringi)
library(psych)
library(stringr)
library(lubridate)
library(tidyverse)
library(forecast)

#Set working dictionary
wd<-setwd("~/Desktop/Senior Thesis /R working Dic")

#Stream Team Dataset
st <- read.csv('StreamTeam_cumulative_10142022.csv')

#Skagit County Public Works Dataset
scpw <- read.csv('scpw_cumulative.csv')

##Washington Department of Health Dataset
wadoh<- read.csv('WADOH_cumulative.csv')

#Samish Nation Department of Natural Resources Dataset
dnr<-read.csv('dnr_cumulative.csv')
```

Merge Datasets and Data quality control

```
sub_df<- merge(st, scpw, all=TRUE)
sub2_df<-merge(sub_df, dnr, all=TRUE)

#Final Dataset
all_df<-merge(sub2_df,wadoh, all=TRUE)

#Reformat Dates
all_df$Date2 <- as.Date(all_df$Date, format = '%m/%d/%y')
all_df$jDate <- julian(all_df$Date2)
all_df$Year <- year(all_df$Date2)
all_df$Month <- month(all_df$Date2)
```

```

#Clean up Fecal Coliform Column

#TNTC and TNTC are 'Too numerous to count'
#Any fecal coliform value over 1600 fc/100mL is set to 1600
all_df$FecalColiform[all_df$FecalColiform=='TNTC'|all_df$FecalColiform=='TNTC']<-1600
all_df$FecalColiform2 <- as.numeric(as.character(all_df$FecalColiform))

```

```
## Warning: NAs introduced by coercion
```

```
all_df$FecalColiform2[all_df$FecalColiform2>1600]<-1600
```

Monthly Proportion Loop

```

#Setup dataframe for proportions
#Type is land use type

monPropdf<-data.frame(matrix(ncol=4, nrow=0))
colnames(monPropdf)<-c("Month", 'Year', 'Type', 'PropFail')

#Loop for monthly proportions

for (i in 1:32) {
  all_df$Year<-as.factor(all_df$Year)
  allsub <- all_df[all_df$Year == levels(droplevels(all_df$Year))[i], ]
  yearVar<-levels(droplevels(all_df$Year))[i]

  #New Dataframe for FC Geomeans
  #All FC value=0 get assigned 0.01 so geomean can be calculated
  allsub$FecalColiform2[allsub$FecalColiform2 == 0] <- 0.01
  allsub$AgencySitecode<-paste(allsub$Agency, allsub$SiteCode)
  allsub$MonthSite<-paste(allsub$AgencySitecode, allsub$Month)

  subyrsFCmean <-
    tapply(allsub$FecalColiform2, allsub$MonthSite, geometric.mean, na.r = TRUE)

  #New Data Frame for FC geomeans
  subyrsFCgeodf<- data.frame(FCgeomean = subyrsFCmean)
  subyrsFCgeodf$MonthSite <- row.names(subyrsFCgeodf)
  subyrsFCgeodf$Month<-as.factor(str_sub(subyrsFCgeodf$MonthSite, -2, -1))
  subyrsFCgeodf$AgencySitecode<- as.factor(str_sub(subyrsFCgeodf$MonthSite, end=-3))
  subyrsFCgeodf$AgencySitecode<-str_trim(subyrsFCgeodf$AgencySitecode, side='right')
  subyrsFCgeodf$Agency<-as.factor(substr(subyrsFCgeodf$AgencySitecode, 1, 2))

```



```
resPropJul<-resFailJul/resTotJul
```

```
resPassAug<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 8Residential' & subyrsFCgeodf$BothStand=='Pa  
resTotAug<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 8Residential',])  
resFailAug<-resTotAug-resPassAug  
resPropAug<-resFailAug/resTotAug
```

```
resPassSep<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 9Residential' & subyrsFCgeodf$BothStand=='Pa  
resTotSep<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 9Residential',])  
resFailSep<-resTotSep-resPassSep  
resPropSep<-resFailSep/resTotSep
```

```
resPassOct<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='10Residential' & subyrsFCgeodf$BothStand=='Pa  
resTotOct<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='10Residential',])  
resFailOct<-resTotOct-resPassOct  
resPropOct<-resFailOct/resTotOct
```

```
resPassNov<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='11Residential' & subyrsFCgeodf$BothStand=='Pa  
resTotNov<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='11Residential',])  
resFailNov<-resTotNov-resPassNov  
resPropNov<-resFailNov/resTotNov
```

```
resPassDec<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='12Residential' & subyrsFCgeodf$BothStand=='Pa  
resTotDec<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='12Residential',])  
resFailDec<-resTotDec-resPassDec  
resPropDec<-resFailDec/resTotDec
```

```
#Rural Sites (the code uses agriculture as the land use type but this is corrected to rural later in the  
agPassJan<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 1Agriculture' & subyrsFCgeodf$BothStand=='Pa  
agTotJan<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 1Agriculture',])  
agFailJan<-agTotJan-agPassJan  
agPropJan<-agFailJan/agTotJan
```

```
agPassFeb<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 2Agriculture' & subyrsFCgeodf$BothStand=='Pa  
agTotFeb<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 2Agriculture',])  
agFailFeb<-agTotFeb-agPassFeb  
agPropFeb<-agFailFeb/agTotFeb
```

```
agPassMar<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 3Agriculture' & subyrsFCgeodf$BothStand=='Pa  
agTotMar<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 3Agriculture',])  
agFailMar<-agTotMar-agPassMar  
agPropMar<-agFailMar/agTotMar
```

```
agPassApr<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 4Agriculture' & subyrsFCgeodf$BothStand=='Pa  
agTotApr<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 4Agriculture',])  
agFailApr<-agTotApr-agPassApr  
agPropApr<-agFailApr/agTotApr
```

```
agPassMay<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 5Agriculture' & subyrsFCgeodf$BothStand=='Pa
```

```

agTotMay<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 5Agriculture',])
agFailMay<-agTotMay-agPassMay
agPropMay<-agFailMay/agTotMay

agPassJun<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 6Agriculture' & subyrsFCgeodf$BothStand=='Pass
agTotJun<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 6Agriculture',])
agFailJun<-agTotJun-agPassJun
agPropJun<-agFailJun/agTotJun

agPassJul<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 7Agriculture' & subyrsFCgeodf$BothStand=='Pass
agTotJul<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 7Agriculture',])
agFailJul<-agTotJul-agPassJul
agPropJul<-agFailJul/agTotJul

agPassAug<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 8Agriculture' & subyrsFCgeodf$BothStand=='Pass
agTotAug<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 8Agriculture',])
agFailAug<-agTotAug-agPassAug
agPropAug<-agFailAug/agTotAug

agPassSep<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 9Agriculture' & subyrsFCgeodf$BothStand=='Pass
agTotSep<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 9Agriculture',])
agFailSep<-agTotSep-agPassSep
agPropSep<-agFailSep/agTotSep

agPassOct<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 10Agriculture' & subyrsFCgeodf$BothStand=='Pass
agTotOct<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 10Agriculture',])
agFailOct<-agTotOct-agPassOct
agPropOct<-agFailOct/agTotOct

agPassNov<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 11Agriculture' & subyrsFCgeodf$BothStand=='Pass
agTotNov<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 11Agriculture',])
agFailNov<-agTotNov-agPassNov
agPropNov<-agFailNov/agTotNov

agPassDec<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 12Agriculture' & subyrsFCgeodf$BothStand=='Pass
agTotDec<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 12Agriculture',])
agFailDec<-agTotDec-agPassDec
agPropDec<-agFailDec/agTotDec

#Commercial Sites (the code uses industrial as the land use type but this is corrected to commercial l
IPassJan<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 1Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotJan<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 1Industrial',])
IFailJan<-ITotJan-IPassJan
IPropJan<-IFailJan/ITotJan

IPassFeb<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 2Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotFeb<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 2Industrial',])
IFailFeb<-ITotFeb-IPassFeb
IPropFeb<-IFailFeb/ITotFeb

IPassMar<-nrow(subyrsFCgeodf[subyrsFCgeodf$IDMonthType==' 3Industrial' & subyrsFCgeodf$BothStand=='Pass

```

```

ITotMar<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 3Industrial',])
IFailMar<-ITotMar-IPassMar
IPropMar<-IFailMar/ITotMar

IPassApr<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 4Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotApr<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 4Industrial',])
IFailApr<-ITotApr-IPassApr
IPropApr<-IFailApr/ITotApr

IPassMay<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 5Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotMay<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 5Industrial',])
IFailMay<-ITotMay-IPassMay
IPropMay<-IFailMay/ITotMay

IPassJun<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 6Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotJun<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 6Industrial',])
IFailJun<-ITotJun-IPassJun
IPropJun<-IFailJun/ITotJun

IPassJul<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 7Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotJul<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 7Industrial',])
IFailJul<-ITotJul-IPassJul
IPropJul<-IFailJul/ITotJul

IPassAug<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 8Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotAug<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 8Industrial',])
IFailAug<-ITotAug-IPassAug
IPropAug<-IFailAug/ITotAug

IPassSep<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 9Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotSep<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 9Industrial',])
IFailSep<-ITotSep-IPassSep
IPropSep<-IFailSep/ITotSep

IPassOct<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='10Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotOct<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='10Industrial',])
IFailOct<-ITotOct-IPassOct
IPropOct<-IFailOct/ITotOct

IPassNov<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='11Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotNov<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='11Industrial',])
IFailNov<-ITotNov-IPassNov
IPropNov<-IFailNov/ITotNov

IPassDec<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='12Industrial' & subyrsFCgeodf$BothStand=='Pass
ITotDec<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='12Industrial',])
IFailDec<-ITotDec-IPassDec
IPropDec<-IFailDec/ITotDec

#Marine Sites

MarPassJan<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 1Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotJan<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 1Marine',])

```

```

MarFailJan<-MarTotJan-MarPassJan
MarPropJan<-MarFailJan/MarTotJan

MarPassFeb<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 2Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotFeb<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 2Marine',])
MarFailFeb<-MarTotFeb-MarPassFeb
MarPropFeb<-MarFailFeb/MarTotFeb

MarPassMar<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 3Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotMar<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 3Marine',])
MarFailMar<-MarTotMar-MarPassMar
MarPropMar<-MarFailMar/MarTotMar

MarPassApr<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 4Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotApr<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 4Marine',])
MarFailApr<-MarTotApr-MarPassApr
MarPropApr<-MarFailApr/MarTotApr

MarPassMay<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 5Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotMay<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 5Marine',])
MarFailMay<-MarTotMay-MarPassMay
MarPropMay<-MarFailMay/MarTotMay

MarPassJun<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 6Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotJun<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 6Marine',])
MarFailJun<-MarTotJun-MarPassJun
MarPropJun<-MarFailJun/MarTotJun

MarPassJul<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 7Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotJul<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 7Marine',])
MarFailJul<-MarTotJul-MarPassJul
MarPropJul<-MarFailJul/MarTotJul

MarPassAug<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 8Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotAug<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 8Marine',])
MarFailAug<-MarTotAug-MarPassAug
MarPropAug<-MarFailAug/MarTotAug

MarPassSep<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 9Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotSep<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 9Marine',])
MarFailSep<-MarTotSep-MarPassSep
MarPropSep<-MarFailSep/MarTotSep

MarPassOct<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 10Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotOct<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 10Marine',])
MarFailOct<-MarTotOct-MarPassOct
MarPropOct<-MarFailOct/MarTotOct

MarPassNov<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 11Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotNov<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType==' 11Marine',])
MarFailNov<-MarTotNov-MarPassNov
MarPropNov<-MarFailNov/MarTotNov

```

```

MarPassDec<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='12Marine' & subyrsFCgeodf$BothStand=='Pass B
MarTotDec<-nrow(subyrsFCgeodf [subyrsFCgeodf$IDMonthType=='12Marine',])
MarFailDec<-MarTotDec-MarPassDec
MarPropDec<-MarFailDec/MarTotDec

```

#Add proportions to dataframe

```

monPropdf [nrow(monPropdf) + 1,] <-c(1,yearVar, 'Residential', resPropJan)
monPropdf [nrow(monPropdf) + 1,] <-c(2,yearVar, 'Residential',resPropFeb)
monPropdf [nrow(monPropdf) + 1,] <-c(3,yearVar, 'Residential',resPropMar)
monPropdf [nrow(monPropdf) + 1,] <-c(4,yearVar, 'Residential',resPropApr)
monPropdf [nrow(monPropdf) + 1,] <-c(5,yearVar, 'Residential',resPropMay)
monPropdf [nrow(monPropdf) + 1,] <-c(6,yearVar, 'Residential',resPropJun)
monPropdf [nrow(monPropdf) + 1,] <-c(7,yearVar, 'Residential',resPropJul)
monPropdf [nrow(monPropdf) + 1,] <-c(8,yearVar, 'Residential',resPropAug)
monPropdf [nrow(monPropdf) + 1,] <-c(9,yearVar, 'Residential',resPropSep)
monPropdf [nrow(monPropdf) + 1,] <-c(10,yearVar, 'Residential', resPropOct)
monPropdf [nrow(monPropdf) + 1,] <-c(11,yearVar, 'Residential',resPropNov)
monPropdf [nrow(monPropdf) + 1,] <-c(12,yearVar, 'Residential',resPropDec)

```

```

monPropdf [nrow(monPropdf) + 1,] <-c(1,yearVar, 'Rural', agPropJan)
monPropdf [nrow(monPropdf) + 1,] <-c(2,yearVar, 'Rural', agPropFeb)
monPropdf [nrow(monPropdf) + 1,] <-c(3,yearVar, 'Rural', agPropMar)
monPropdf [nrow(monPropdf) + 1,] <-c(4,yearVar, 'Rural', agPropApr)
monPropdf [nrow(monPropdf) + 1,] <-c(5,yearVar, 'Rural', agPropMay)
monPropdf [nrow(monPropdf) + 1,] <-c(6,yearVar, 'Rural', agPropJun)
monPropdf [nrow(monPropdf) + 1,] <-c(7,yearVar, 'Rural', agPropJul)
monPropdf [nrow(monPropdf) + 1,] <-c(8,yearVar, 'Rural', agPropAug)
monPropdf [nrow(monPropdf) + 1,] <-c(9,yearVar, 'Rural', agPropSep)
monPropdf [nrow(monPropdf) + 1,] <-c(10,yearVar, 'Rural', agPropOct)
monPropdf [nrow(monPropdf) + 1,] <-c(11,yearVar, 'Rural', agPropNov)
monPropdf [nrow(monPropdf) + 1,] <-c(12,yearVar, 'Rural', agPropDec)

```

```

monPropdf [nrow(monPropdf) + 1,] <-c(1,yearVar, 'Commercial', IPropJan)
monPropdf [nrow(monPropdf) + 1,] <-c(2,yearVar, 'Commercial', agPropFeb)
monPropdf [nrow(monPropdf) + 1,] <-c(3,yearVar, 'Commercial', IPropMar)
monPropdf [nrow(monPropdf) + 1,] <-c(4,yearVar, 'Commercial', IPropApr)
monPropdf [nrow(monPropdf) + 1,] <-c(5,yearVar, 'Commercial', IPropMay)
monPropdf [nrow(monPropdf) + 1,] <-c(6,yearVar, 'Commercial', IPropJun)
monPropdf [nrow(monPropdf) + 1,] <-c(7,yearVar, 'Commercial', IPropJul)
monPropdf [nrow(monPropdf) + 1,] <-c(8,yearVar, 'Commercial', IPropAug)
monPropdf [nrow(monPropdf) + 1,] <-c(9,yearVar, 'Commercial', IPropSep)
monPropdf [nrow(monPropdf) + 1,] <-c(10,yearVar, 'Commercial', IPropOct)
monPropdf [nrow(monPropdf) + 1,] <-c(11,yearVar, 'Commercial', IPropNov)
monPropdf [nrow(monPropdf) + 1,] <-c(12,yearVar, 'Commercial', IPropDec)

```

```

monPropdf [nrow(monPropdf) + 1,] <-c(1,yearVar, 'Marine', MarPropJan)
monPropdf [nrow(monPropdf) + 1,] <-c(2,yearVar, 'Marine', MarPropFeb)
monPropdf [nrow(monPropdf) + 1,] <-c(3,yearVar, 'Marine', MarPropMar)
monPropdf [nrow(monPropdf) + 1,] <-c(4,yearVar, 'Marine', MarPropApr)
monPropdf [nrow(monPropdf) + 1,] <-c(5,yearVar, 'Marine', MarPropMay)
monPropdf [nrow(monPropdf) + 1,] <-c(6,yearVar, 'Marine', MarPropJun)
monPropdf [nrow(monPropdf) + 1,] <-c(7,yearVar, 'Marine', MarPropJul)

```

```

monPropdf[nrow(monPropdf) + 1,] <-c(8,yearVar, 'Marine',MarPropAug)
monPropdf[nrow(monPropdf) + 1,] <-c(9,yearVar, 'Marine',MarPropSep)
monPropdf[nrow(monPropdf) + 1,] <-c(10,yearVar, 'Marine',MarPropOct)
monPropdf[nrow(monPropdf) + 1,] <-c(11,yearVar, 'Marine',MarPropNov)
monPropdf[nrow(monPropdf) + 1,] <-c(12,yearVar, 'Marine',MarPropDec)
}

#Dateframe conversions
monPropdf$Month<-as.numeric(monPropdf$Month)
monPropdf$PropFail<-as.numeric(monPropdf$PropFail)
monPropdf$PropFail<-format(round(monPropdf$PropFail, 3), nsmall = 3)
monPropdf$PropFail<-as.numeric(monPropdf$PropFail)
monPropdf$Year<-as.numeric(monPropdf$Year)

```

Graphs

Figure 5: Overall Proportion of Failed Sites

```

#Calculate the overall proportion of failed sites for each land use type

globprop<- monPropdf %>%
  group_by(Type)%>%
  drop_na(PropFail) %>%
  summarize(mean=mean(PropFail), sd=sd(PropFail), n=n(), se=sd/sqrt(n))

#Box plot of overall proportions

ggplot(data=globprop, aes(x=Type, y=mean, color=Type))+
  geom_point()+
  geom_errorbar(aes(ymin=mean-se, ymax=mean+se), width=0.2)+
  theme_classic()+
  guides(color="none")+
  #theme(legend.position = "none")+
  labs(x='Land Use Type',y="Proportion of sites that failed at least one state standard")+
  theme_bw() +
  theme(axis.line = element_line(colour = "black"),
        panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        panel.border = element_blank(),
        panel.background = element_blank())

```

Figure 6: Yearly average of yearly proportion of failed sites (included all years)

```

#Calculate global yearly average of yearly proportion of failed sites (included all years)

yrPropdfAvg_Mar<-monPropdf %>%
  group_by(Year, Type) %>%

```

```

drop_na(PropFail) %>%
summarize(mean=mean(PropFail), sd=sd(PropFail), n=n(), se=sd/sqrt(n))

#Proportion of fails over all years
ggplot(data=yrPropdfAvg_Mar, aes(x=Year, y=mean, color=Type)) +
  geom_line()+
  geom_ribbon(data=yrPropdfAvg_Mar, aes(x=Year, ymin=mean-se, ymax=mean+se, group=Type,fill=Type), alpha=
  labs(fill='Land Use Type')+
  guides(color="none")+
  ylab("Proportion of sites that failed at least one state standard")+
  scale_x_continuous(breaks=seq(1990,2021,5))+
  scale_y_continuous(breaks=seq(0,1,0.25))+
  theme_bw() +
  theme(axis.line = element_line(colour = "black"),
        panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        panel.border = element_blank(),
        panel.background = element_blank())

```

Figure 7: Monthly Average of Proportion of Failed Sites

```

#Calculatel monthly average of monthly proportion of failed sites

monPropdfAvg<-monPropdf %>%
  group_by(Month, Type) %>%
  drop_na(PropFail) %>%
  summarize(mean=mean(PropFail), sd=sd(PropFail), n=n(), se=sd/sqrt(n))

## 'summarise()' has grouped output by 'Month'. You can override using the
## '.groups' argument.

#Seasonal Graph with Rainy Season shading
ggplot(data=monPropdfAvg, aes(x=Month, y=mean, color=Type)) +
  geom_line()+
  geom_ribbon(data=monPropdfAvg, aes(x=Month, ymin=mean-se, ymax=mean+se, group=Type,fill=Type), alpha=
  labs(fill='Land Use Type')+
  guides(color="none")+
  ylab("Proportion of sites that failed at least one state standard")+
  scale_x_continuous(breaks=seq(1,12))+
  scale_y_continuous(breaks=seq(0,1,0.25))+
  theme_bw() +
  theme(axis.line = element_line(colour = "black"),
        panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        panel.border = element_blank(),
        panel.background = element_blank())+
  annotate("rect", xmin = 1, xmax = 4, ymin = 0, ymax = Inf,
         alpha = 0.1, fill='blue')+
  annotate("rect", xmin = 10, xmax = 12, ymin = 0, ymax = Inf,
         alpha = 0.1, fill='blue')

```

Anova and Tukey HSD for overall proportion of fails

```
aov1<- aov(PropFail ~ Type, data=monPropdf)
summary(aov1)
TukeyHSD(aov1)
```

Timeseries

General timeseries

```
#General Time series for all land use types
model_gen_month<-lm(PropFail~Month, data=monPropdf)
gen_acf<-acf(model_gen_month$residuals, type='correlation', lag.max=12)

gen_ts<-ts(monPropdf$PropFail, start=c(1990, 1), frequency=12)
plot(gen_ts, ylab='Proportion of sites that failed at least one state standard')

plot(gen_acf, main='')
```

Marine Time Series

Figure 10 and Figure A3

```
#Subset Marine data
MarMonPropdf<-monPropdf[monPropdf$Type=='Marine',]
model_Mar_month<-lm(PropFail~Month, data=MarMonPropdf)

#Marine Time series and ACF
mar_ts<-ts(MarMonPropdf$PropFail, start=c(1990, 1), frequency=12)
mar_acf<-acf(model_Mar_month$residuals, type='correlation', lag.max=12)

plot(mar_ts, ylab='Proportion of sites that failed at least one state standard')

plot(mar_acf, main='')
```

Rural Time Series

Figure 8 and Figure 9

```
#Subset Rural data
RuralMonPropdf<-monPropdf[monPropdf$Type=='Rural' & monPropdf$Year>2002,]

#Rural time series and ACF
model_Rur_month<-lm(PropFail~Month, data=RuralMonPropdf)
rur_ts<-ts(RuralMonPropdf$PropFail, start=c(2003,1), frequency=12)
rur_acf<-acf(model_Rur_month$residuals, type='correlation', lag.max=12)
```

```
plot(rur_ts, ylab='Proportion of sites that failed at least one state standard')
```

```
plot(rur_acf, main='')
```

Residential Time Series

Figure 11 and Figure A1

```
#Subset Residential data  
ResMonPropdf<-monPropdf[monPropdf$Type=='Residential'& monPropdf$Year>2002,]  
  
#Residential Time Series and ACF  
model_Res_month<-lm(PropFail~Month, data=ResMonPropdf)  
Res_ts<-ts(ResMonPropdf$PropFail, start=c(2003,1), frequency=12)  
res_acf<-acf(model_Res_month$residuals, type='correlation', lag.max=12)
```

```
plot(Res_ts, ylab='Proportion of sites that failed at least one state standard')
```

```
plot(res_acf, main='')
```

Commercial Time Series

Figure 12 and Figure A2

```
#Subset Commercial Data  
CommMonPropdf<-monPropdf[monPropdf$Type=='Commercial'& monPropdf$Year>2002,]  
  
#Commercial time series and ACF  
model_Comm_month<-lm(PropFail~Month, data=CommMonPropdf)  
com_ts<-ts(CommMonPropdf$PropFail, start=c(2005,1), frequency=12)  
com_acf<-acf(model_Comm_month$residuals, type='correlation', lag.max=12)
```

```
plot(com_ts, ylab='Proportion of sites that failed at least one state standard')
```

```
plot(com_acf, main='')
```