Preliminary Assessment of Flooding Hazards in the Nooksack River Watershed, Washington State, and its Effect on Water Quality and the Local Shellfish Industry

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Abstract

Flooding in the Nooksack River in northwestern Washington State has predominantly been the product of heavy rains occurring between the months of October and March (Nooksack Indian Tribe, 2016). Future climate change models as well as trends observed in historic data suggest that yearly winter temperatures have increased by about 4° C over the last 50 years will continue to increase by about 3° C by 2100 under current land use conditions and fossil fuel emissions (Kremen, 2007). Increasing winter temperatures would decrease the amount of snowfall experienced along the Nooksack River floodplain and the rest of Whatcom County and replace it with rainfall. By increasing rainfall along the Nooksack River floodplain, the frequency of flood events, which are defined in this study as flow rates equal to or above 565 m^3/s, is expected to increase during the months of October to March by about three floods per year. Heavy rainfall and overland flow along the floodplain as the result of flood events has the potential to move sediment, organics, and contaminants from the floodplain to the Nooksack River (NOAA, 2015). Due to the agricultural and industrial development as well as expansive rural environments, bacterial contamination has been of concern in the Nooksack River and its discharge point in Portage Bay since testing began around 1990 (Peterson, 2011). Due to this contamination, shellfish beds in Portage Bay have experienced conditional and permanent closures since 1995 (Peterson, 2011). Shellfish beds in Portage Bay are relied on by residents as sources of food and money and understanding influences on fecal coliform concentrations in the Nooksack River can lead to preventative measures to reduce fecal coliform introduction to the Nooksack River and Portage Bay.

To investigate influences on fecal coliforms concentrations in the Nooksack River, the relationship between flood events and fecal coliforms concentrations was analyzed. Conclusions drawn from this relationship was then taken one step further to analyze how increasing temperatures and precipitation would affect the frequency of floods over the next 50 years and ultimately the potential response of the fecal coliform concentrations in Portage Bay. It is expected that flood frequency will increase over the next 50 years and as a result fecal coliform concentrations in the Nooksack River and Portage Bay will increase as well.

Introduction:

A flood event is characterized as an overflowing of water from the area meant to contain it such as rivers, oceans, and lakes. Flooding in waterways such as rivers and streams is normal with frequency and intensity being dependent on the climate (Geoscience Australia, 2017).

Due to these flooding events, most waterways have developed natural levees, deposits of sediments mounded along the banks of a river during past flood events. These levees help to constrain overflow onto the flood plain, which can lead to human settlements encroaching onto the floodplain areas behind the levees where they are perceived as being less vulnerable to flooding. To further protect their settlements, humans have constructed artificial levees intending to increase the volume of water the affected waterway could contain and mitigate flood events (KCM, 1994).

When confined by levees, streams experience what is known as aggradation: a build-up of sediment in the stream channel that would have otherwise been deposited on the floodplain during an overflow event. This can decrease the channel depth and create greater flood risks, thus requiring the levees be built higher, in a continuous feedback loop over time (KCM, 1994). An additional problem arises when levees increase the volume of water the stream channel can hold, as it means that future flood events can result in larger volumes of water breaching the levees onto developed floodplains. Changes to climate, including melting of glaciers, more intense storms, and increased rain-on-snow events, can increase the frequency of levee breaches.

Impacts and economic losses to developments in the floodplain can be great with greater risk of destruction of farmland, homes, and other infrastructure. However, apart from economic losses, the overland flooding of developed land can also affect the water quality in the watershed, depending on the type of development the area has undergone, such as farming or industrial use. Flood waters can collect nutrient and pathogenic contaminants as they move across the floodplain, with the potential to affect those inside and outside of the floodplain in both local and downstream waters. According to a NOAA publication in 2015 concerning watershed flooding and pollution the runoff generated by flood and storm events is especially detrimental in coastal areas. In coastal environments, this runoff has the potential to also enter and influence the oceans.

Effects of polluted runoff on marine and estuarine ecosystems are dependent on the contaminant that is introduced from freshwater sources and can involve excess nutrient, hydrocarbon, or bacterial loads to coastal and estuarine environments. This can create nutrient induced dead zones or the closure of beaches and harvesting zones from bacterial contamination. Dead zones are created from an excess of nutrients which trigger blooms of algae and primary producers. This bloom in primary producers attracts consumers, primary and secondary, which consume the producers and respire in the process. This depletes available oxygen preventing most, if any, biological existence (NOAA, 2017). Bacterial contamination would occur from large volumes of polluted water discharging from a polluted source. If the point of discharge is not capable to diluting the contamination faster than it is discharged, these contaminants will accumulate which is a health risk. This is common in bay and certain estuarine environments (USA EPA, 2001).

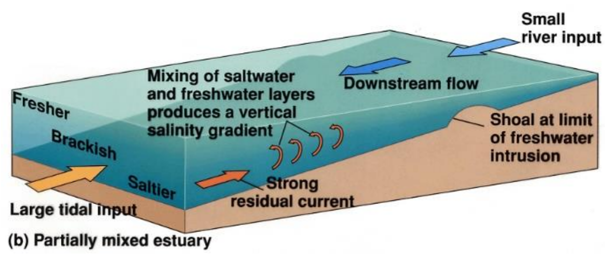

Figure 1: Illustration of estuarine mixing and the interactions of salt and fresh water in a partially mixed estuary environment (US EPA, 2001)

Estuaries are environments where fresh water and saline water mix and interact (figure 1). Due to density differences between fresh and salt water, mixing does not always occur evenly throughout but rather once the density differences are overcome, a process that generally requires some amount of kinetic energy to be introduced into the system. This is normally accomplished through wind or tidal activity. In a closed, bay environment, tidal action is limited which limits mixing and hinders contaminant dilution. (Fischer et al, 1979). These periods of reduced mixing can further exacerbate the build-up of contaminants introduced from the river upstream, and the issues caused by them (US EPA, 2001).

Study Area

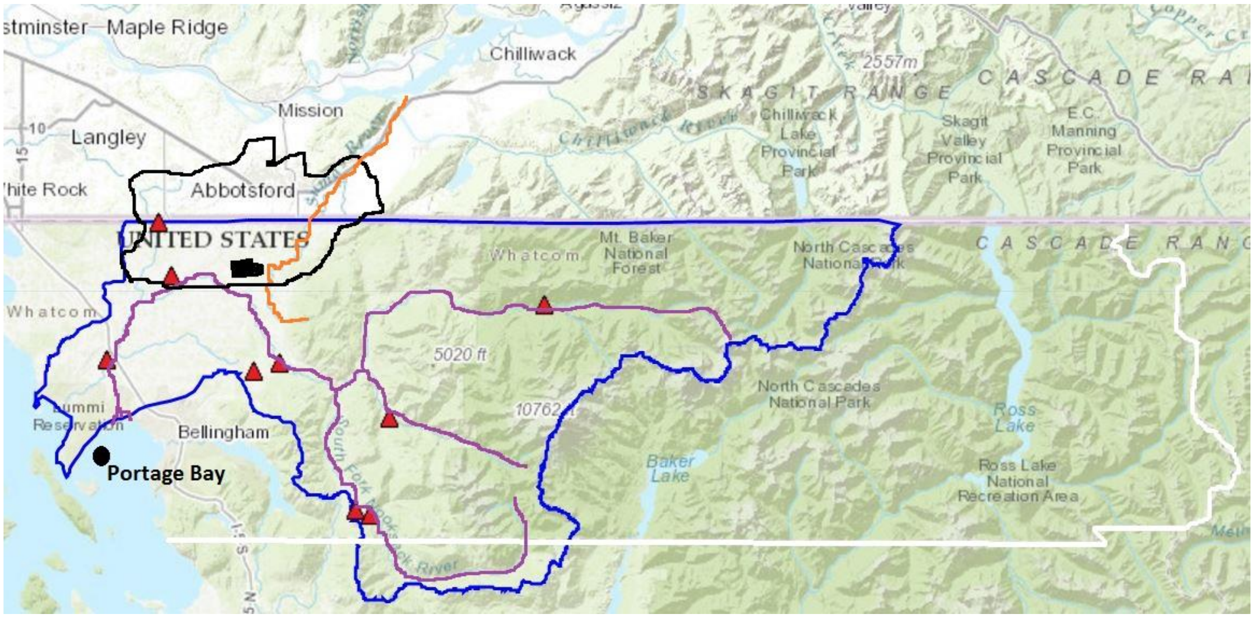

Figure 2: Map of Whatcom County and overview of the study area. Dark Blue: Nooksack River Watershed Boundary | Purple: Nooksack River | Black: Abbotsford-Sumas Aquifer | Orange: Sumas River | White: Border of Whatcom County (USGS,

This project investigated flood history and dynamics and their relationship to water quality contamination in the Nooksack River watershed, including its estuary in Portage Bay, in Whatcom County, northwest Washington State, USA.

Whatcom County is bordered by British Columbia, Canada to the north, the Pacific Ocean to the west, and the Cascade Mountains to the east. Due to its location, Whatcom County ranges in elevation from around sea level to about 3200 meters. The flat, low elevation lands are former floodplains of the Fraser River in British Columbia that once ran through creating the agriculturally productive land seen today (Washington DOT, 2017). The Nooksack River basin covers about 2,100 square kilometers originating from glacial melt in the Cascade Mountains before running west through the lowlands and eventually emptying into Bellingham Bay.

Currently, the Nooksack River flows into Portage Bay (see map in Figure 2). Portage Bay is classified as partially mixed estuary where mixing occurs as salt water freshens and fresh water becomes more saline but a salinity gradient still exists. Portage Bay's geomorphology is that of a bar-built estuary meaning that freshwater and saltwater mixing experiences periods of stagnation.

Ambient temperatures can range from 0 °C in the Winter to about 22°C in the Summer. The area experiences about 910 mm of rain and about 90 mm of snow annually.

Since 1930 there have been 150 recorded floods within the Nooksack River watershed (Khare & Sellars, 1991). Due to its location in relation to the mountains, the Nooksack River and the flooding it

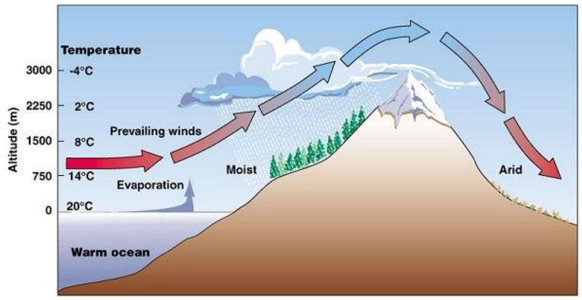

Figure 3: Illustration of Orographic lift as seen in Whatcom County (West and Howard, 2016).

experiences are influenced largely by precipitation rather than spring snow melt as defined in the 2012 Adelsman et al. report concerning Washington State's Climate Response Strategy. Due to this range in elevation, higher percentages of rain could be expected to occur along the lowlands of the Nooksack River watershed as opposed to the mountains due to a process known as orographic lift. This occurs as warm, moist air rises before being carried the prevailing winds as seen in figure 3. Changes in elevation causes the moist air to expand and release the water vapor in the form of precipitation (West and Howard, 2016). For the case of the Nooksack River basin, this precipitation is seen in the lowlands in the towns of Clearbrook, Ferndale, Bellingham where data had been obtained for this project, as well as the surrounding areas that are representative of this precipitation regime.

Khare and Sellars had not given a specific definition to flood events in the Nooksack River watershed and to analyze the frequency of flood events, a definition was derived from minimum peak flow levels based off peak flow data obtained for Ferndale, Washington. As mentioned in the Adelsman et al. report in 2012, flooding in Nooksack River was determined to be most influenced by precipitation which was also determined as non-uniform throughout the Nooksack River Watershed due to elevation changes. For this reason, peak discharge data for Ferndale, Washington were used as the data had been the most consistent compared to other sample sites and discharge and precipitation over time was determined to be representative of the conditions seen throughout other sites in the lowlands, such as Clearbrook and Deming.

Although measures have been taken to reduce the frequency of floods, Adelsmans et al. report stated that flood frequencies are projected to increase during the late fall and winter months from now until around 2080. Flood events, as defined by flow values higher than 565 m^3/s, have occurred between late October through early March as these months are characterized by periods of drastic flow increase in the Nooksack River caused by heavy rains which, apart from being a source of water, can saturate soils and melt current snowpack further adding to the amount of water and runoff. In 2007,

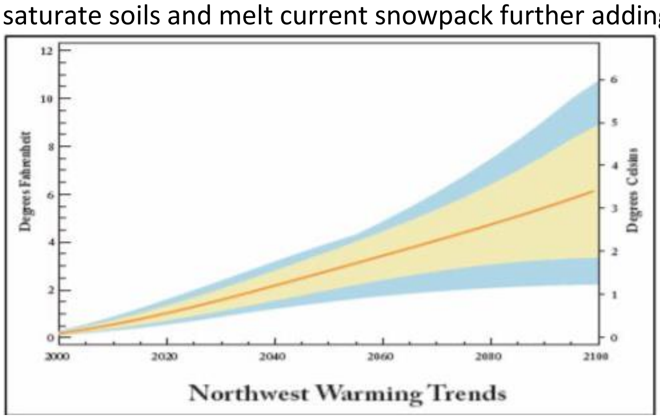

Figure 4: Northwest Warming Trends from 2000-2100 under an increased emission scenario (Kremen, 2007)

Pete Kremen of Whatcom County published the Climate Protection and Energy Conservation Action Plan in which climate data concluded snowfall has reduced between 50 and 60% over the last 50 years to present and precipitation has increased by about 75% throughout the year increasing the amount of rain on snow events. The published climate models in the action plan also provide the expected warming trends from present to 2100 provided emissions are not reduced. Further warming, as exemplified by the climate model further supports less future snowfall and more future rainfall and rain-on-snow events.

Purpose:

This project was completed as a preliminary study to report the concern of increasing flood frequency in the Nooksack River and economic and health issues that could occur as a result. An increase to flood frequency can have drastic public health and socio-economic impacts and on the residents along the Nooksack River floodplain as well as its discharge point of Portage Bay. This exploratory study analyzed how an increase to flood frequency would affect bacterial contamination in the Nooksack River and the shellfish beds in Portage Bay. Closure of shellfish beds has led to a loss of 850,000 dollars a year for the residents who rely on these beds for food sources and as a livelihood (Whatcom County Advisory Committee, 2014). This project analyzed development along the Nooksack River floodplain as well as climate and hydrological data to assess if flood frequency is to increase as well as how floods influence water quality in the Nooksack River. This preliminary study is intended to be used to identify potential problems in the Nooksack River and Portage Bay and as well as influence future studies.

History of Whatcom County:

This region of the United States is primarily forested and is classified as a temperate rainforest. Whatcom County makes up a small section of what is the world's largest temperate rainforest region that spans from Alaska to California. The forests in Whatcom County comprise mostly of Douglas Fir conifers. Numerous salmon species inhabit the inland and coastal waters including King, Sockeye, Chum, Coho, and Pink salmon, which were relied on by those who inhabited the surrounding land as a primary food source (Washington Department of Fish and Wildlife, 2017)

Development in Whatcom County began in what is currently Bellingham in 1857 as part of the Fraser River gold rush. Development extended east into present day Everson and Sumas. 1877 was the first year that the Nooksack River was used for boat travel promoting settlement along the floodplain. Farming was the main economic development with major agricultural centers in the towns of Lynden, Ferndale, Everson, and Nooksack (KCM, 1995). By 1890, railroads had reached the west coast further increasing population and the rise of the lumber industry. At the turn of the century, clear cut logging and wetland drainage had further stimulated agricultural development in Whatcom County. Whatcom County also experienced a rise in the salmon industry during the 20th century and is currently the largest producer of raspberries than any other part of the United States. The primary urban center in Whatcom County is Bellingham which houses most of the population but also contains heavy industrial activity in Cherry Point in the northwest corner of the county where oil refineries, aluminum processing, and manufacturing plants can be found (Vance-Sherman, 2015).

Influences on Water Quality in the Nooksack River:

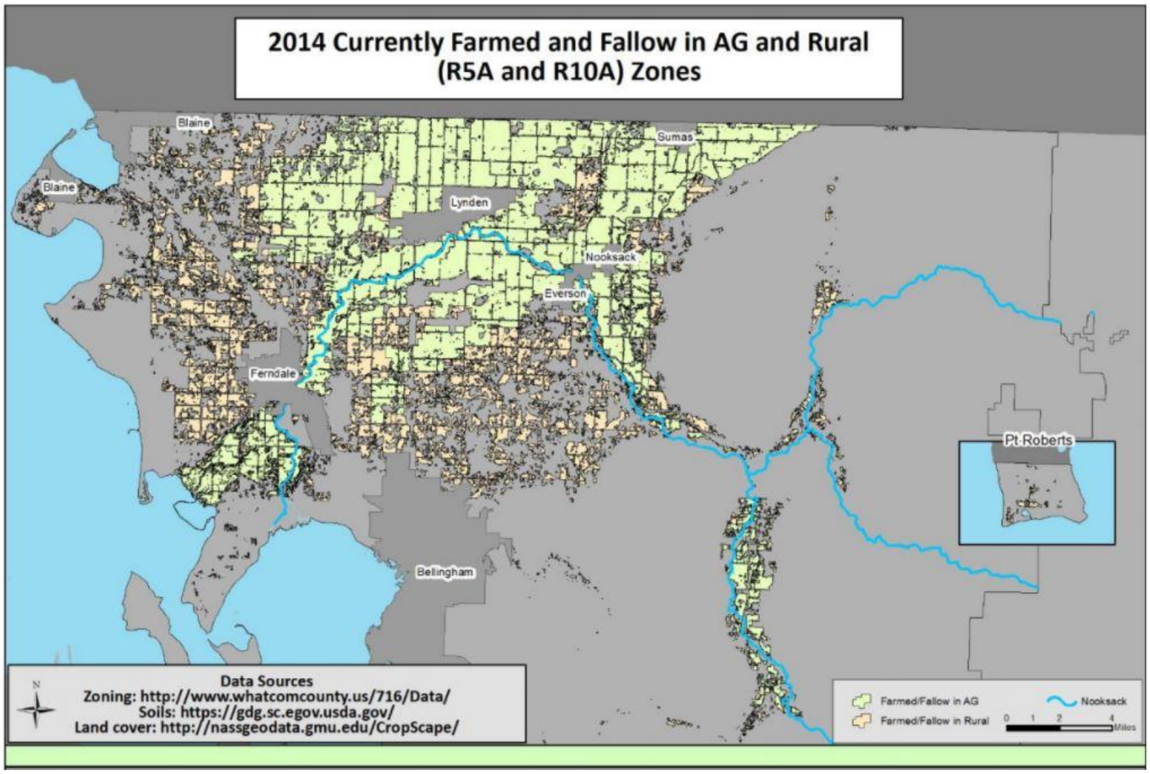

Figure 5: Distribution of farmed and fallow agricultural lands in rural and agricultural zones within the Nooksack River Watershed within the Whatcom County lowlands (Gillies and Mackay, 2016)

In 2012, there were just over 1700 farms in Whatcom County, each averaging about 28 hectares in area (Census of Agriculture, 2012), leading to an approximate agricultural area of 510 km^2. Approximately 68% of these farms are dedicated to crops such as hay, raspberries, and corn with 12% being used for about 210,000 chickens, cows, and horses. The remaining percentage comprises of orchards, nurseries, and vegetable growth. The agricultural land of Lynden, Bertrand, Laurel, just north of the Lummi reservation, nearest the Nooksack River Delta and both Bellingham and Portage Bay, comprises of about 85% crop growth and 15% dairy pasture (Bradt, 2016). Figure 5 shows the agriculture land use of the Nooksack River Watershed for zones designated as rural and agricultural for both farmed and fallow lands. Fallow lands refer to lands that are plowed but left intentionally unsown to reestablish fertility. Approximately 34,500 hectares of Whatcom County land is designated for agricultural use, however agricultural practices occur on 56,600 hectares of land as demonstrated by the differentiation in figure 5 (Whatcom County/Nooksack Watershed, 2015).

The runoff from these agricultural lands, as reported by the USGS and Department of the Interior, as well as tributary inflow carrying effluent from sewage treatment plants, and failing septic systems ultimately drain into the Nooksack River bringing suspended contaminants with it (Peterson, 2011). Portions of the unconfined Abbotsford-Sumas Aquifer, located in the Nooksack basin, were stated as being at highest risk of contamination from surface water and over 80% of samples taken from these portions were found to contain fecal coliforms. As this aquifer feeds into the Nooksack tributaries, the water quality in the aquifer has a direct impact on the water quality of the Nooksack River as well (Cox et al, 2005). While the issues of heightened nutrient and pathogen loads have been investigated on their impact on environmental and human health, the influence of future, local climate change on contaminant loads entering waterways needs consideration. Since 2000, The Washington Department of Ecology has conducted maximum daily load evaluations of the Nooksack River in the past due to its history of failing to comply with water quality standards for the presence of bacteria, specifically fecal coliforms. With multiple factors influencing the bacteria levels in the Nooksack River, the Department of Ecology recognized the importance of identifying the specific sources of contamination to reduce the amount of effluent entering the river (Washington State Department of Ecology, 2000).

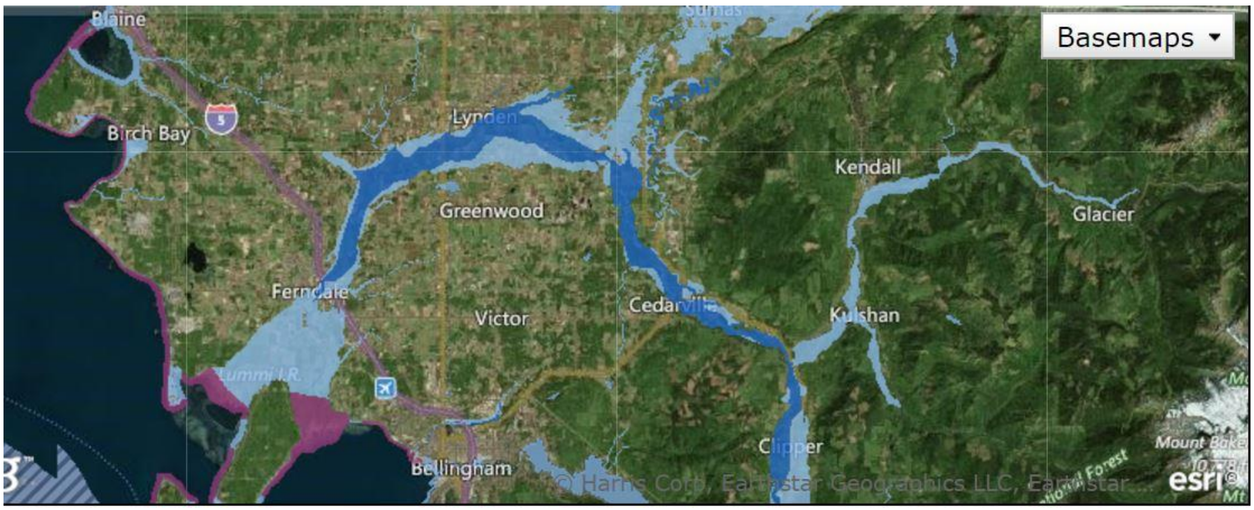

Figure 6: 100-year Floodplain (light blue) and floodway (dark blue) of the Lower Mainstem Nooksack River (Department of Ecology, 2017)

According to the Washington State of the Watershed Report published in 2010, there are municipal sewage plants that discharge directly to the Nooksack River in Everson, Lynden, and Ferndale and well as industrial discharge from Lynden. While improvements have been made to improve the disinfecting processes of these sources of sewage and industrial discharge, the discharge has yet to cease still acting as a source of bacterial contamination to the Nooksack River. Failing septic tanks were identified as major contributor to fecal coliform delivery in the Nooksack River since the initial Washington Department of Ecology report in 2000. Since then, however, inspections have been required which declare which septic systems were up to regulation, needed maintenance, or failed inspection entirely. While the percentage of failing systems with influence on the Nooksack River has been reduced to 3% in 2010, only 38 systems were tested that year with the total number of systems that could influence contamination in the Nooksack River being unknown (Peterson, 2011).

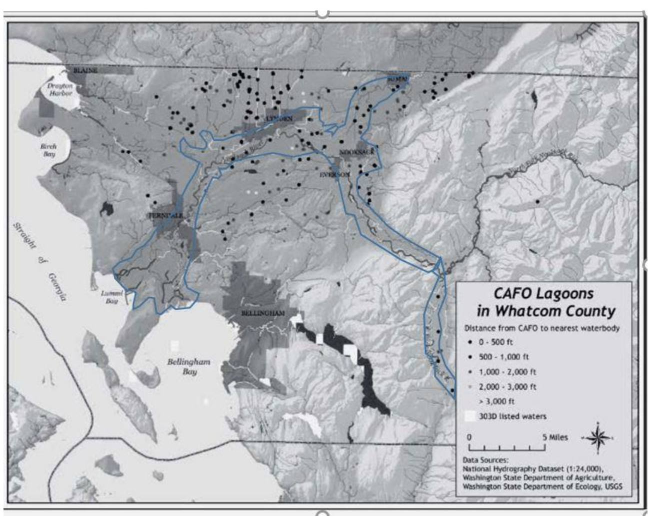

Figure 7: Map of Manure Lagoons in Whatcom County with respect to distance from bodies of water and 100-year floodplain outlined (Skagit River System Cooperative, 2015)

In 2015, the Skagit River System Cooperative published a map of manure lagoons located within Whatcom County. According to figure 6 which shows the floodway and 100-year floodplain of the Nooksack River paired with the floodplain map that has been overlain on the manure lagoon map, about 30 manure lagoons are within the Nooksack River 100-year floodplain and within 150 meters of the Nooksack River or one if its tributaries. While manure lagoons are currently strictly regulated to be placed outside of the 100-year floodplain there are leniencies that allow for the lagoon to be placed within the 25-year floodplain provided it is protected from inundation (US Department of Agriculture, 2017). These leniencies are in effect in the event that the farmer is unable to build outside of the 100-year floodplain but does not describe the criteria which would justify the inability to build outside of the 100-year floodplain. The regulations discuss placement based off the 100 and 25-year floodplains of main stem rivers but did not discuss placement near tributaries which could make it difficult to meet distance regulation from every water source. The combination of industrial, municipal, and agricultural discharge to the Nooksack River, either directly or indirectly, combined with the numerous dairy operations located within the flood plain of the Nooksack River (figure 7), all influence the water quality.

Bacterial Contamination:

Fecal coliforms are a specific genus of coliform bacteria originating from fecal matter used to indicate fecal contamination. Increased levels of these bacteria in the water can be indicative of failing domestic systems such as septic tanks, poorly treated waste water, improperly managed manure, or livestock and wildlife presence in the waterway. While high levels of fecal coliforms are not universally considered to cause direct harm when ingested, their presence tend to suggest that other pathogens are present with the potential to be life threatening. According to the United States EPA in June of 2017, water meant for consumption must not contain measurable levels of fecal coliforms. From a seafood consumption perspective, samples are measured using two different systems referred to as either Most Probable Numbers or Colonies per 100mL, both involve the multiple dilutions of samples taken to identify pathogens present in each sub-divided sample. According to the Washington Department of Health, the water quality in shellfish harvesting areas must not exceed a geometric mean of 14 colonies/100mL of water when testing for fecal coliforms with a maximum of 10% of samples permitted to exceed 43 colonies/100mL. For some perspective, recreational activity in freshwater has standards which permit a geometric mean of 100 colonies/100mL with no more than 10% of the samples permitted to exceed 200 colonies/100mL. As shellfish are filter feeding organisms and constantly filter water in and out of their systems, accumulation of toxins from the water within their bodies is of concern to those who may consume them (Fisheries and Oceans Canada, 2016).

The shellfish populations in Portage Bay are directly affected by the flow of the Nooksack River. Starting in the 1990's, portions of shellfish harvesting sites located in the Lummi reservation were closed down as it was deemed unsafe for consumption (Whatcom Advisory Committee, 2014). In 1998 increasing areas of Portage Bay were labeled as prohibited or restricted to shellfish consumption. Water quality standards were put into effect to regulate fecal contamination of the Nooksack River and Portage Bay allowing for the previously prohibited areas of the bay to be reopened in 2003. Fecal coliforms levels have fluctuated since causing further closures in 2004 and 2014-2017 and areas labeled as conditional which means it is subject to fluctuate between suitable and unsuitable for the purposes of consumption (State of our Watersheds Report, 2012).

Objectives

This project focused on two main questions: Assuming there is no future change to land use and current climate trends continue, 1) will the frequency of floods increase over time, and if they do, 2) how will this affect water quality?

Answering the first part of the question required the analysis of discharge, precipitation, and temperature data to determine how flood events will be characterized for this project. The data were analyzed for trends over time and hydrometric and water quality variables were compared to understand their relation and dynamics. These results are then discussed in the context of the published literature and local knowledge. By defining the magnitude of a flood event in the Nooksack River for this project, the total number of flood events were determined for each year giving insight on the frequency through time.

Once flood frequency was determined for the historic period of record, the next objective was to project flood frequency risk for the future. This was done with an assessment of climate models and trends observed in existing data sets.

The second objective of this project involved an assessment of watershed fecal coliform sources, indicators, and pathways into the Nooksack River, and how increased flood events would influence this. A review of fecal coliform monitoring practices and indicators in both freshwater and marine environments was conducted in the context of water quality regulatory guidelines. These data were then compared to time series and trends in river flow, flood events and associated climatic conditions.

Understanding the relationship between flood events and fecal coliform concentrations, as well as assessing risk for future flood events, allows for conclusions to be made concerning the potential future impacts of flooding on water quality in the Nooksack River and estuary.

Methods

Data Sources:

For clarity purposes, the sites where data were obtained were grouped geographically due to their location along the river as either at the headwaters, at the mid-section, or at the mouth (figure 8). These distinctions were not just geographically determined but were also representative of the conditions experienced at the specific section of the Nooksack River when compared with other data obtained from other test sites. It should also be clarified that the water data, such as water quality and discharge, were taken from the Nooksack River prior to influence from Portage Bay marine waters at all points (Brown et al., 2005).

Discharge data were obtained from the USGS National Water Information System at sites in Glacier, Deming, and Ferndale, Washington. Ferndale (mouth), Deming (mid-section), and Glacier, Washington (headwaters) discharge data were recorded up from 1967 to 2015 providing nearly 50 years of continuous discharge data. Water temperature data were also obtained from the USGS for Ferndale, Washington from 2008 to 2015.

Peak discharge data were obtained from the USGS for Ferndale, Washington (mouth) from 1967-2016. These data are representative of the highest yearly peak flows. These peak discharge data were used to derive flood events by matching up the dates of recorded flood events from the USGS and the 1995 flood report from KCM Inc with the corresponding peak discharge recorded by the USGS. The smallest recorded peak flow was identified and used to determine a minimum discharge required to cause a flood event as defined previously. With a minimum peak flow value determined, it was assumed that each daily discharge record above the minimum would be considered a flood event.

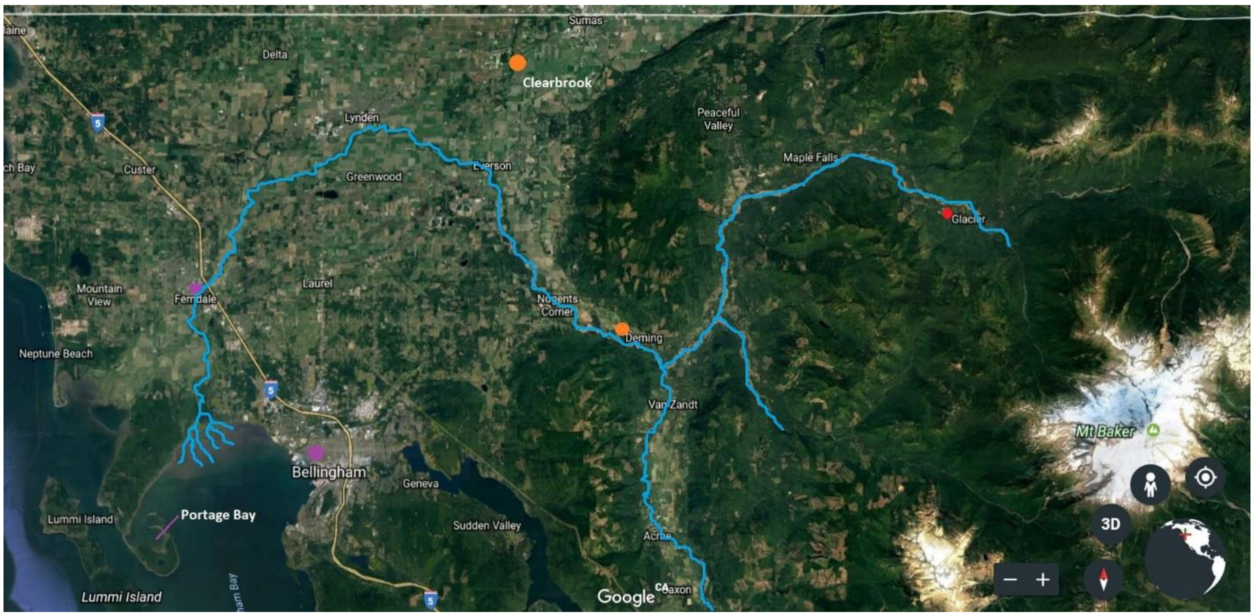

Figure 8: Map of data collection sites. Purple: "At the mouth" Ferndale and Bellingham | Orange: "At the mid-section" Clearbrook and Deming | Red "At the headwaters" Glacier | Nooksack River is outlined in blue and Portage Bay is labeled in white (GoogleEarth, 2017).

Air temperature and precipitation data were obtained from the Western Regional Climate Center historical data archives. In this case, total precipitation was recorded as the total of liquid and melted precipitation. Consistent climate data were available for two sites, Bellingham (mouth) and Clearbrook (mid-section). These data were consistent from 1949 to 2016 for total precipitation and temperature; 1935-2010 for total snowfall.

Monthly fecal coliform data for the Nooksack River were obtained from the State of Washington Department of Ecology with consistent data available from one site in Ferndale, Washington (mouth). The data range from 1982 to 2015. Whatcom County Public Works provided fecal coliform data for the Nooksack River in the form of a GIS map in which ranges of fecal coliform values were given in the form of plots on the map. These data were also presented and published in 2017 by Whatcom County Public Works focusing on the mainstem Nooksack River and its surrounding tributaries. Whatcom County Public Works also provided monthly fecal coliform data for Portage Bay from 1990-2016 as well as geometric mean and 90th percentile values. The data provided by Whatcom County Public Works were also used to imply dates of shellfish bed closures in Portage Bay.

Data on shellfish bed closures were not directly obtained but were derived from fecal coliform data from Portage Bay provided by Whatcom County Public Works. Fecal coliform levels in marine and freshwater environments must adhere to specific standards, which are outlined in the analysis portion of this report, to be accessible to the public for the respective function. If fecal coliform values for shellfish beds in Portage Bay were found to be higher than the given standards, than it could be concluded that bed was closed.

Agricultural data were obtained from the Whatcom County Census of Agriculture as well as Blue Water GIS. Agricultural data include number and size of farming operations in Whatcom County, however only the operations that were within the Nooksack River floodplain was of interest. The distribution of farms was also collected, for example the percentage of dairy or berry farms in the floodplain.

Information concerning the development on the floodplain of the Nooksack River was obtained from maps generated from Blue Water GIS, Skagit River System Cooperative, and the State of Washington Department of Ecology publication in 2000. This information includes type of agriculture, locations of dairy operations and manure lagoons, major industrial operations within the floodplain, and waste water plants that discharge to the Nooksack River.

Analysis:

For this report, a flood was characterized by any flow event above 565 m^3/s. This was derived from the recorded peak discharge from the data provided by the USGS. According to their data combined with recorded flood events, it was determined that floods were had not been observed to occur when peak flow has been less than 565 m^3/s and this report operated under the assumption that this was the minimum peak discharge required to cause a flooding event. Daily discharge data were used from 1967-2016 with data grouped into 10-year intervals. Flow data that were found to be greater than the established minimum discharge of 565 m^3/s were isolated from flow data recorded as less than the minimum peak discharge to identify the frequency of flood events. These discharge values greater than 560 m^3/s were also compared only to months with historically recorded flood events to observe the frequency these recorded flows occurred during months with reported flooding. This created a frequency of flood events over four, 10-year intervals with the purpose of identifying how flood frequency has changed over 40 years and can allow for inferences to be made for the future.

Determining the minimum peak flow operated under the assumption that overflow events in the Nooksack River occur at the same peak discharge. However, this cannot be guaranteed due to anthropogenic influence such as road and railroad construction and subsidiary levees creating points of altering topography (Franz, 2004). In 1991 the US Army Corps of Engineers published a report regarding levee breach events in the Nooksack River in 1990 determining that overflow events were thought to occur around 565 m^3/s although the exact flow could not be guaranteed. Unfortunately, determining the exact location in the river in which overflow occurs at the lowest peak discharge has created a challenge for those involved in modeling flow as it was determined in 2004 by Delbert Franz that the Nooksack River features about 1200 different points where in which a bank or levee breach could occur. It was also found that with the non-uniform micro-topography of the Nooksack River floodplain has a flow path of about 240 kilometers in a stream system with an apparent flow length of about 70 kilometers (Franz, 2004). However, combined with the information derived from the peak flow measurements, the measurements given by the Army Corps of Engineers both produced peak flows of around 565 m^3/s and supports the value previously obtained.

The data collected were used to perform linear correlation analyses to determine the statistical significance of trends seen between data sets. Correlation analyses were completed using the statistical program SPSS and were considered accurate with a p value of 0.05. Linear correlation tests were run to compare trends seen in precipitation and discharge, discharge and fecal coliforms, discharge and nitrate, discharge and water temperature, fecal coliforms and nitrate, and water temperature and fecal coliforms. Data were grouped into three-month time intervals based off the similar flow levels observed during these three-month spans. This was done to separate periods of high flow from those of low flow with the purpose of identifying potential trends over different flow regimes.

An assessment of land use was conducted, agricultural, industrial, and domestic, in Whatcom County along the Nooksack River floodplain with GIS maps created by Blue Water GIS. These maps provide a detailed depiction of agricultural land use along the Nooksack River dividing Whatcom County by individual town. These maps also outline the floodplain of the Nooksack River and the neighboring tributaries showing which agricultural sections are most likely to be affected by flood events. Locations of manure lagoons and are labeled within the generated maps noting their location in relation to the Nooksack River the floodplain. This allows for accurate conclusions to be drawn concerning the number of farms within the Nooksack River basin to investigate the risk of fecal contamination of water sources through pathogen entry either through discharge or future flood events. Other sources of pollution besides agriculture into the Nooksack River as well as its tributaries were also investigated. These other sources include industrial and municipal effluent discharge and domestic septic systems and are outlined in the Washington State Department of Ecology.

Due to the complexity of non-point sources of contamination entering the Nooksack River waterways, this study analyzed an indicator to represent pathogen contamination. This proxy was shellfish bed closures in Portage Bay. These closures are typically the result of fecal coliform concentrations above the water quality standard of 14 MPN/100ml because of polluted waters from the Nooksack River that empties into the Bay. Understanding the history of closures will be an effective representation of contamination. Human health alerts associated with contaminated shellfish in the Nooksack River estuary (Portage Bay shellfish fishery) were also obtained as these usually were issued in tandem with bed closure notices. This helped to determine what, if any, correlations exist between flood events and shellfish bed closures. This helped to further assess the potential risks of flooding associated with human health impacts and the future for shellfish bed closures.

Results

Hydrological Data:

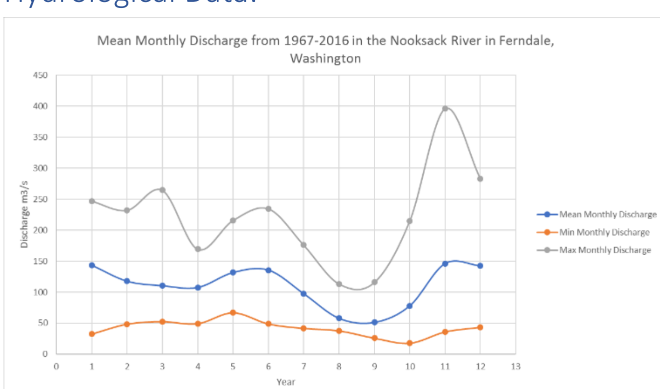

Figure 9: Average monthly discharge at the mouth of the Nooksack River from 1967-2016

The first objective was to analyze the hydrologic and climatic data in Whatcom County from mid-section and the mouth of the Nooksack River. These data from the mouth and midsection of the Nooksack River were the primary focus since waters discharged from the mouth of the river would contain the contaminants that wash in from the land and other tributaries while the mid-section would be where these contaminants would collect. Figure 9 shows the average monthly discharge at the mouth of the Nooksack River as well as

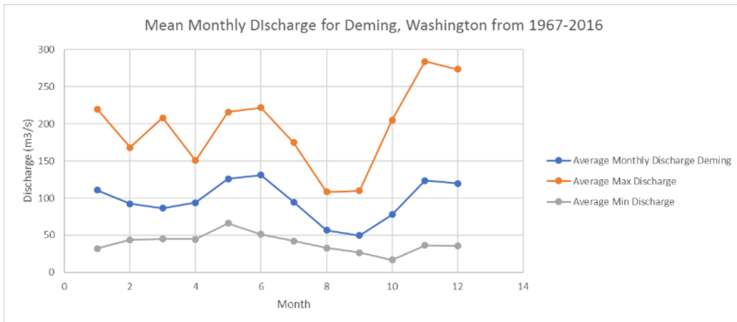

Figure 10: Mean monthly discharge at the mid-section of the Nooksack River from 1967-2016.

the average monthly minimum and maximum discharges from 1967 to 2016. This was used to determine periods of low and high flow in the Nooksack River and could be used in conjunction with known flood event dates. Periods of peak flow occur during the months of November, December, and January as well as May and June. Flow decreased between the months of February and April and then again between the months of July and September. Figure 10 shows the average monthly discharge from the midsection of the Nooksack River at Bellingham, Washington over the same interval, 1967-2016. These data show similar trends with peak discharge occurring during late autumn and early winter from November to January and again during May and June. Periods of low flow can be seen from July to October as well as from February to April. Peak discharge events for both the mouth and midsection of the Nooksack River have occurred during the months of November with minimum discharge events peaking during the month of October for both data sets.

Statistical Significance of Discharge and Precipitation in the Nooksack River												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Significant	Yes	Yes	No	Yes	No	No	No	No	No	Yes	Yes	Yes
Floods	Yes	Yes	Yes	No	No	No	No	No	No	Yes	Yes	Yes
Rainfall	AA	AA	AA	A	BA	BA	BA	BA	A	AA	AA	AA
Discharge	HF	HF	HF	HF	HF	HF	LF	LF	LF	LF	HF	HF
R^2	0.25	0.35	0.06	0.11	0.04	0.04	0.09	0.02	0.10	0.17	0.30	0.35

Figure 11: Table of statistical significance for discharge and precipitation for each month. This table also mentions if floods have occurred during each month, the amount of rainfall each month as received, discharge conditions. AA-Above Average | A-Average | BA-Below Average HF-High Flow | LF-Low Flow

Climate Data:

The climate data includes total precipitation as well as air temperature. Information used here was collected both from the mid-section and the mouth of the Nooksack River. These data were necessary to draw conclusions from the discharge data. Figure 12 shows that Clearbrook, Washington (midsection) experienced the highest total precipitation (rain and snow combined) during the autumn and winter months. October to March all exhibit precipitation amounts higher than the average monthly rainfall in Whatcom County of about 76 mm. This number is most likely skewed by the higher numbers seen during the colder months but provides a baseline when determining the relevance of the rainfall numbers over the course of a year. Snowfall was highest during the winter months peaking in January. Values seen from Bellingham, Washington (mouth) in figure 13 are slightly less than those seen at the midsection but show a similar trend to data seen in the mid-section of the

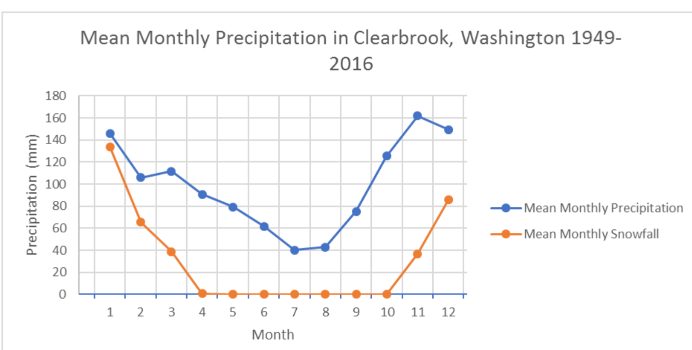

Figure 12: Average monthly precipitation at the midsection of the Nooksack River from 1949-2016

river. Precipitation is again highest during the autumn and winter months exhibiting the same range of months with above average rainfall during October to March.

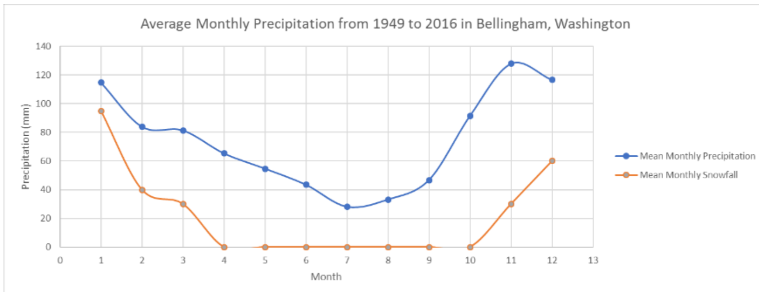

Figure 13: Average Monthly Precipitation at Bellingham, Washington of the Nooksack River from 1949-2016

Statistical correlations were performed to determine the significance of trends that were observed from the graphed data (Figure 11). Statistically significant relations for discharge and precipitation were found to occur for the months of October to February and April. Of these six months, five were found to be periods of high flow, November to February and April, and another five were found to be periods of above average precipitation, October to February. The latter five months were determined to be when floods have occurred in the past.

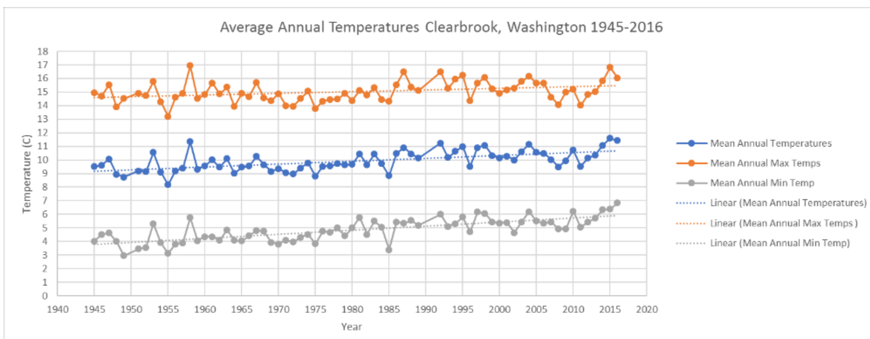

Figure 14: Average annual temperatures at the mid-section of the Nooksack River from 1945-2016

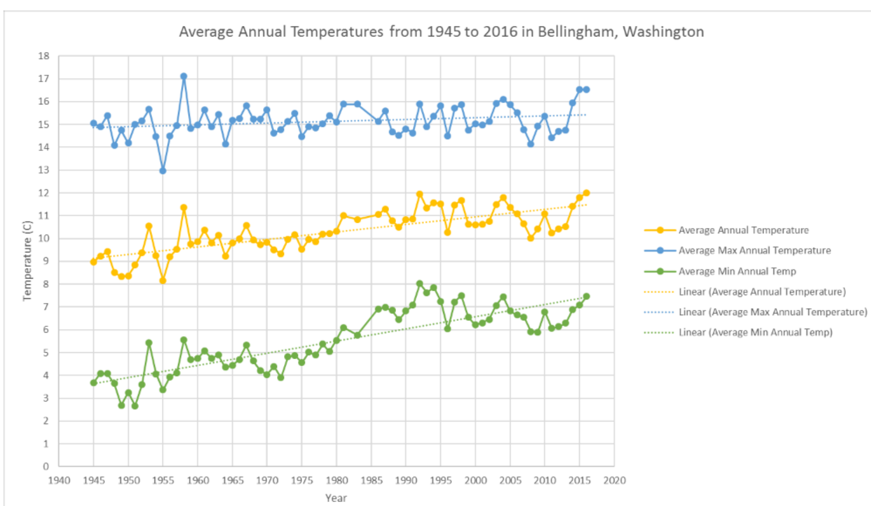

Figure 15: Mean Annual Temperatures at the mouth of the Nooksack River from 1945-2016.

Temperature data were collected from the mid-section and the mouth of the Nooksack River from 1945 to 2016 to determine how ambient temperatures have changed, on average, over the last 50 years. Minimum temperatures were of primary focus as these would affect the amount of snowpack experienced in Whatcom County. Minimum temperatures at the mid-section of the Nooksack River were found to have increased, on average, by about 2°C since 1945 (see figure 10). At the mouth of the Nooksack River, temperatures seem to have increased by a larger margin, on average, over the last 50 years. Minimum temperatures, especially, show an increase of almost 4° centigrade over the 51-year interval (see figure 15).

Flood Data

Historic Floods and Flood Frequency

Daily flow data obtained from the USGS for Ferndale, Washington was used to determine the number of floods that have occurred from 1967 through 2016. Floods here are defined as flow rates equal to or greater than 565 m^3/s. Figure 16 shows the number of floods that have occurred for each year from 1967-2016 giving an idea of the frequency of floods in Ferndale and if this frequency has changed over time. Flood frequency appears to have slightly increased, by about one or two, since 1967. Figure 17 was used to identify the specific months of flood activity. Figure 17 shows floods have been found to occur during the late fall and early spring, from October to March. November and January were found to have experienced some of the highest amounts of flooding while October and March were found to have experienced some of the least number of floods since 1967. Spring and summer months from April to September were not found to have experienced flooding based strictly off the Ferndale daily flow data. A flow duration curve was made using the discharge data to better understand the probability of flood causing peak flows occurring in Ferndale, Washington (Figure 18). According to the flow duration curve, peak flows large enough to constitute as a flood have less than a 5% chance of occurring each year or that less than 5% of all recorded data would show values higher than 565 m^3/s. These results of the flow curve are further supported by comparing the total number of floods that occurred in Ferndale since 1967 to the rest of the fall and winter months. According to figure 19, over the last 40 years, flood events have occurred between about one and two percent of the time over each 10-year span of compiled flow data. Data were broken down in to 10-year spans to observe how flow conditions resulting in flood changed over time.

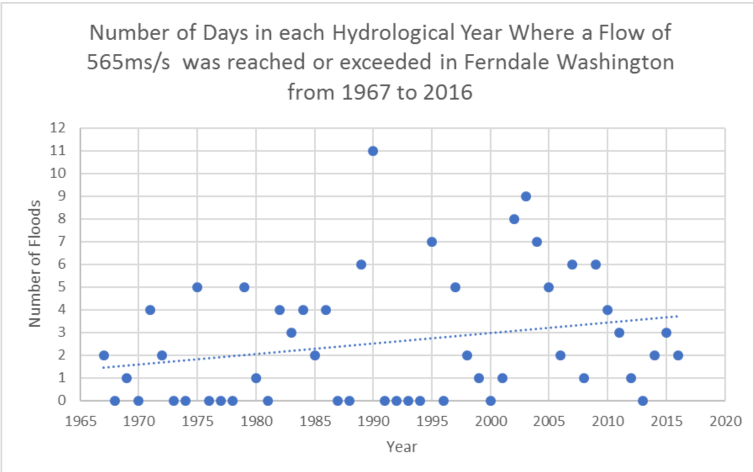

Figure 16: Number of days in each hydrological year in which a flow of 565 m3/s was reached or exceeded indicating a flood event

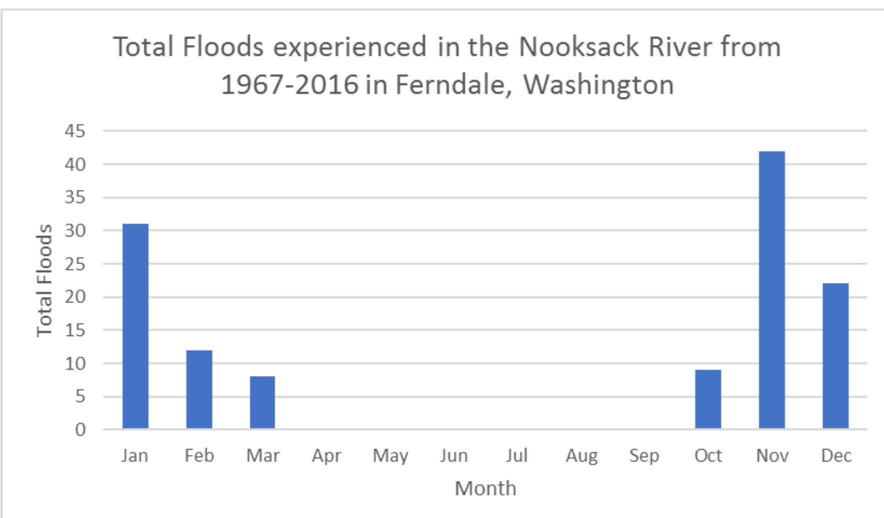

Figure 17: Total floods and the months they have occurred on the Nooksack River from 1967-2016 in Ferndale, Washington

When the data was looked at over one continuous 40-year span, it was found that flood events occurred about 1% of the total time which shows consistency with the flow duration curve in figure 18.

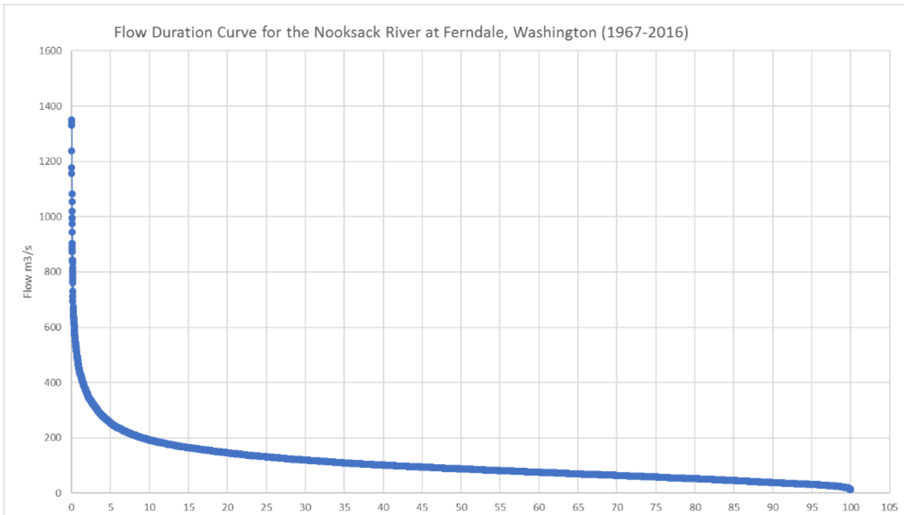

Figure 18: Flow Duration Curve for Ferndale, Washington from 1967 to 2016

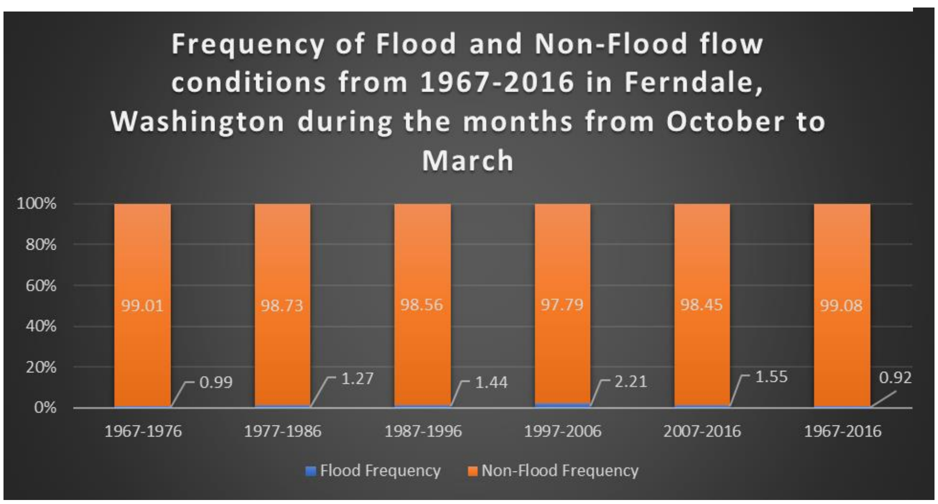

Figure 19: Frequency of Flood and Non-Flood flow conditions from October to March in Ferndale, Washington from 1967-2016.

24, 48, 72-hour precipitation

Correlations found between rainfall and discharge used rainfall data collected on the same day as the discharge data was collected. This was a bit limiting in its ability to fully explain floods since it was not certain how rainfall had influenced the discharge from the days prior, if it had at all. For this reason, antecedent rainfall was also used for statistical analysis. Days identified to have peak flows above 565 m^3/s were analyzed with rainfall records 24, 48, and 72 hours prior to the peak flow. In doing so it was found that the correlations between peak flow events and rainfall from 24 and 48 hours prior were statistically significant while the correlation between peak flow events and rainfall from 72 hours prior was not statistically significant.

Water Quality Data

Fecal Coliforms

Mainstem Nooksack River:

The second objective of this project involved the analysis of bacterial contamination in the Nooksack River by looking at the fecal coliform data collected by the Washington Department of Ecology published in 2016. The average monthly data for fecal coliform levels in Ferndale were first analyzed (figure 20). Spikes were seen both in August and November reaching levels over 200 colonies/100mL. June exhibited the lowest measured levels dipping below 50 colonies/100mL. Maximum values showed similar trends with the highest measured values occurring during the months of August and November. April and February also showed spikes in fecal coliforms but this was only observed for the maximum values. Standards were not shown on this graph as these data only show the monthly measured values for fecal coliforms before a geometric mean could be taken. While these data are not indicative of issues in the Nooksack River nor its discharge point, it does give insight as to potential months where fecal coliforms may be in larger concentrations influencing its discharge point of Portage Bay accordingly.

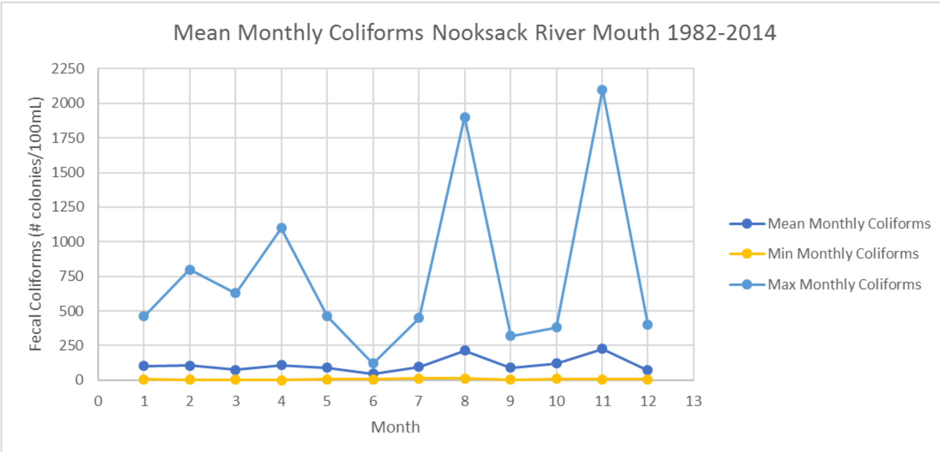

Figure 20: Average monthly fecal coliforms measured at the mouth of the Nooksack River from 1982-2014. Includes observed maximum and minimum values.

Fecal coliform data was collected monthly starting in 1982. A geometric mean of the data was taken from 1984 to 2014 and compared to freshwater and marine standards which can be seen in figure 21. Freshwater standards require a geometric mean for fecal coliforms to be less than or equal to 100 colonies/100mL whereas marine standards dictate a geometric mean less than or equal to 14 colonies/100mL. At the mouth of the Nooksack

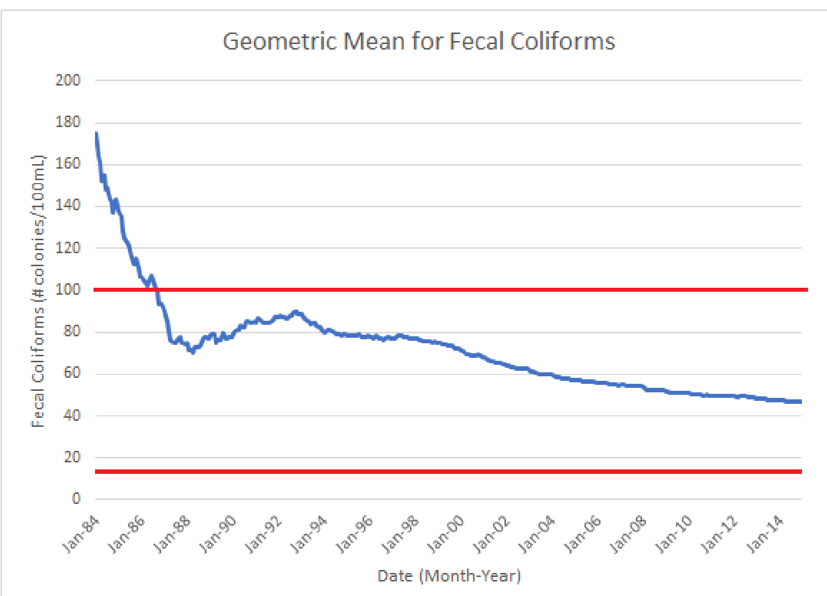

Figure 21: Geometric mean of fecal coliforms measured at the mouth of the Nooksack River from 1982-2014. The line at 100 represents freshwater standards while the line at 14 represents marine standards.

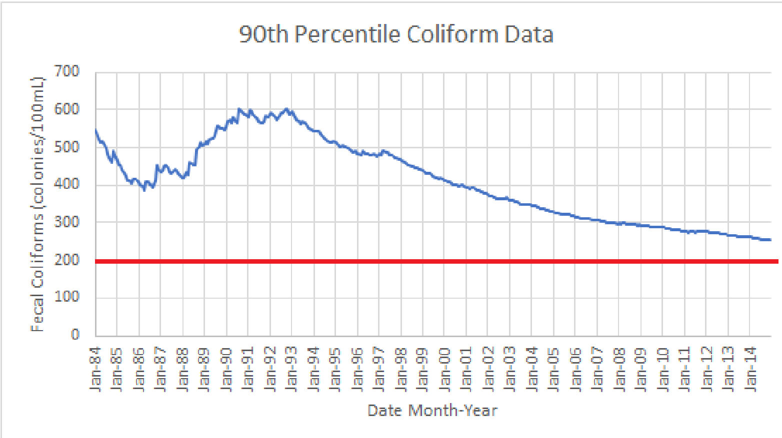

Figure 22: 90th percentile values for fecal coliforms at the mouth of the Nooksack River from 1982-2014

River, the geometric mean of fecal coliforms has met the freshwater standard since around 1987 but has yet to reach the marine standard since sampling began despite emptying directly into Portage Bay, a marine environment. The 90th percentile standard value for fecal coliforms in freshwater is set at 200 colonies/100mL. Here it was found that the measured 90th percentile values for fecal coliforms measured at Ferndale of the Nooksack River from 1982-2014 was perpetually above the standard directly before discharging into the ocean (figure 22).

Nooksack River Fecal Coliforms in the Winter:

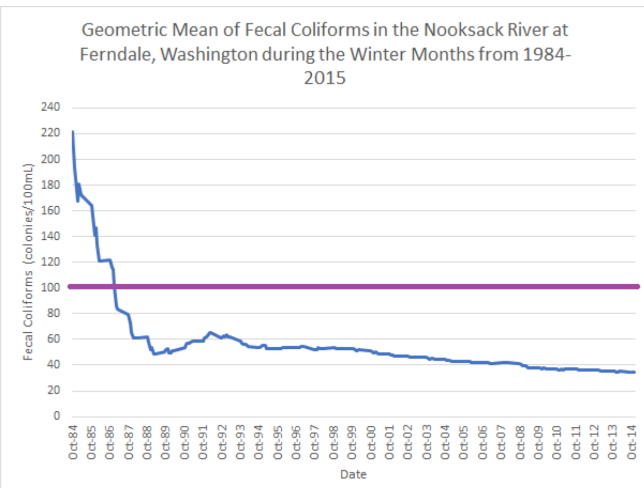

Figure 23: Geometric Mean of Fecal Coliforms in the Nooksack River at Ferndale, Washington during October-March from 1984-2015

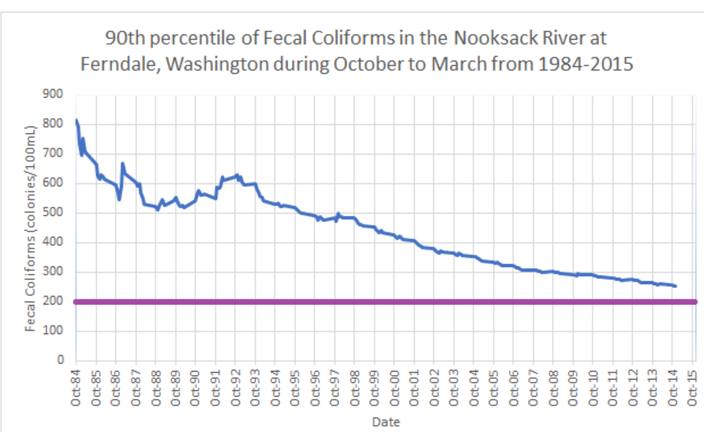

Figure 24: 90th percentile values for Fecal Coliforms from October to March in the Nooksack River at Ferndale, Washington

The dates of the recorded floods showed that the late fall and winter months of October through March were the only ones to experience high enough flows to be classified as flood events. For this reason, the geometric mean and 90th percentile values for fecal coliforms in the Nooksack River and Portage Bay were investigated. During these fall and winter months, the geometric mean and 90th percentile values of fecal coliforms in the Nooksack River followed a similar trend as the seen the when data was used throughout the year. Geometric mean values (figure 23) failed to meet the freshwater standard of 100 colonies/100mL up until the transition between 1986 and 1987. From these, the freshwater standard for the geometric mean of fecal coliforms was met. Geometric mean values were higher by about 40 colonies/100mL in the years prior to 1986 when compared to the geometric mean of values taken throughout the entire year. The 90th percentile values for the Nooksack River during the fall and winter months (figure 24) failed to meet the freshwater standard as was seen with the values calculated throughout the year. These values were also higher than those calculated from yearly data, as seen in figure 20, peaking at 800 colonies/100mL rather than 600 colonies/100mL. Although the geometric means and 90th percentile values were found to be higher initially in the winter months, similar trends were exhibited by both data sets and ending values were similar.

Tributaries of the Nooksack River:

Water quality data for tributaries were provided by Whatcom County Public Works and were primarily taken at the midsection of the river while the mainstem samples were taken from the midsection and at the mouth. M1 at the mainstem was sampled nearest the mouth of the river and M5 was sampled nearest the headwaters, relative to the others and was used as a standard (figure 25). In figure 26 over the last three years, about one half of the tributaries at the midsection of the Nooksack River are failing to meet health standards for calculated geometric mean of fecal coliforms. The black dot above the bars, in this case SD, COU2, DDW, M5, and M4, indicate that the geometric mean of bacteria levels has increased over the last year. Even though M1 and M2 are below the standard for geometric mean values, figure 27 shows that these two sites fail to comply with standards for 90th percentile values. In fact, for the case of S1, F4, and F1, over 50% of the samples were over 200 FC/100mL. Every sampled tributary of the Nooksack River was found to be above the accepted standard value for the 90th percentile each failing the freshwater health standard. The black dot that is shown above the bar, such as those seen in SD, COU2, and S1, indicated that bacteria levels have been increasing over the last year.

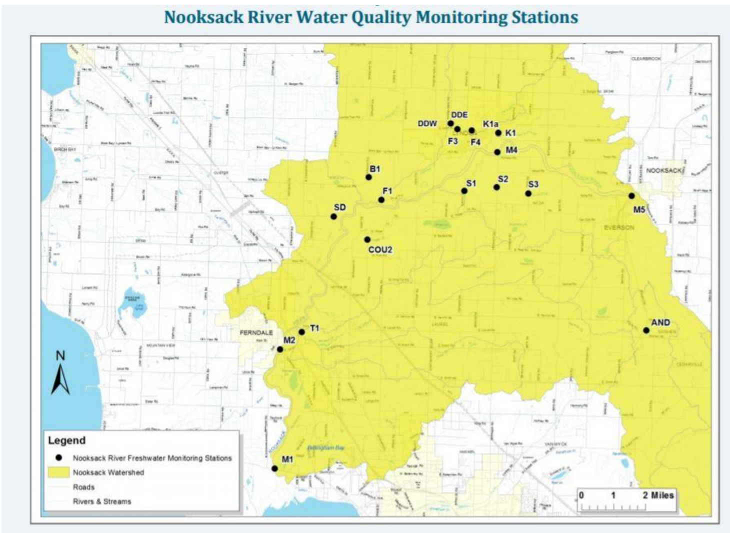

Figure 25: Nooksack River Water Quality Monitoring Stations for the Mainstem and Tributaries. M#-Mainstem, Others-Tributaries (Whatcom County Public Works, 2017)

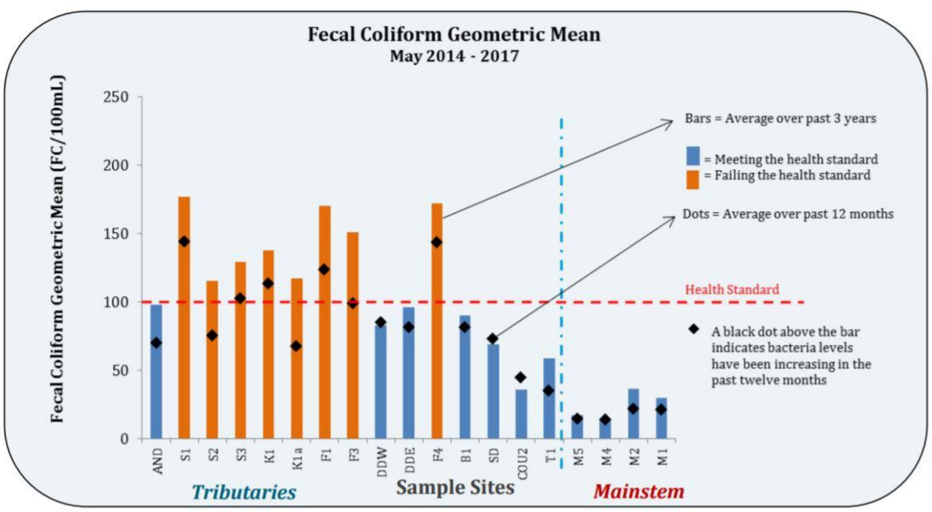

Figure 26: Geometric Mean for Fecal Coliform in the Mainstem of the Nooksack River and its surrounding tributaries from 2014-2017 (Whatcom County Public Works, 2017)

The standards displayed on these graphs are for freshwater and should be expected to all fail health standards if these levels were seen in a marine setting.

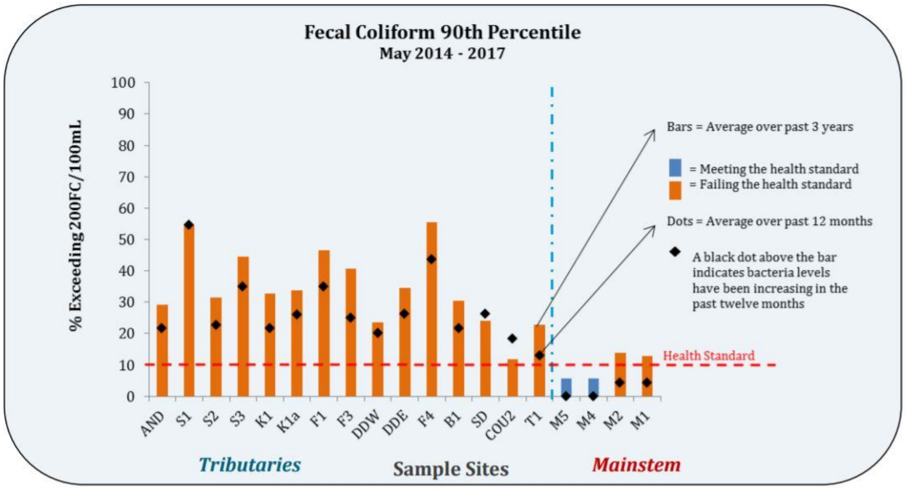

Figure 27: 90th percentile values for Fecal Coliform in the Mainstem of the Nooksack River and its surrounding tributaries from 2014-2017 (Whatcom County Public Works, 2017)

Portage Bay:

Marine fecal coliform data for Portage Bay was obtained from Whatcom County Public Works published in 2017 providing information from monthly sampling, calculated geometric means, and 90th percentile values from 1990 to 2016 (Figures 28 and 29). Calculation for the geometric mean of fecal coliforms involved using every recorded value, including the value measured for the current month. Each month a new geometric mean was calculated to include that month's measurement. The purple line shows the standard that the geometric mean cannot exceed for shellfish harvesting and consumption to occur. Since Portage Bay is a marine environment, the marine standard for fecal coliforms of 14 MPN/100mL or 14 colonies/100mL was used. These data were collected from Station 51 in Portage Bay, which is labeled as conditionally closed. This means fecal coliforms levels have been observed to fluctuate to levels above and below the accepted standard. The geometric mean for these data dips over the accepted standard once around 1996 and has not been observed to do so prior to or after this date. These data pair with the calculated 90th percentile values

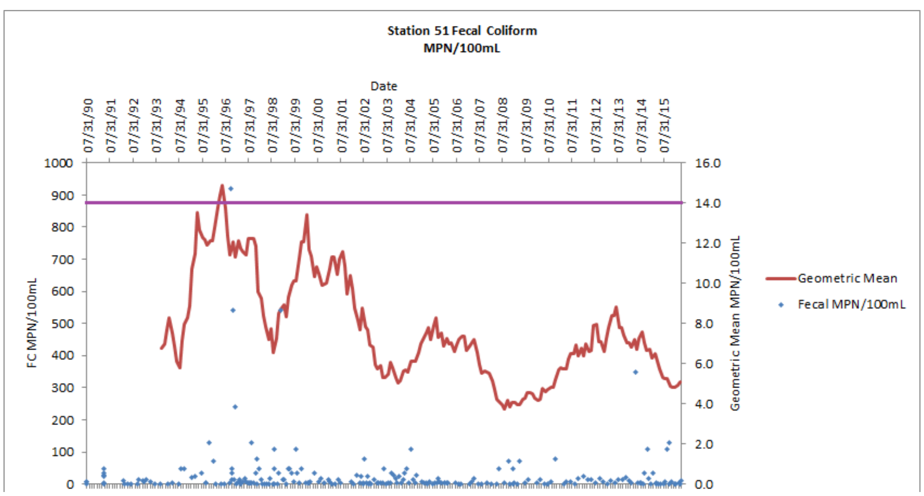

Figure 28: Measured levels and calculated geometric mean of fecal coliforms from Station 51, Portage Bay from 1990 to 2016.

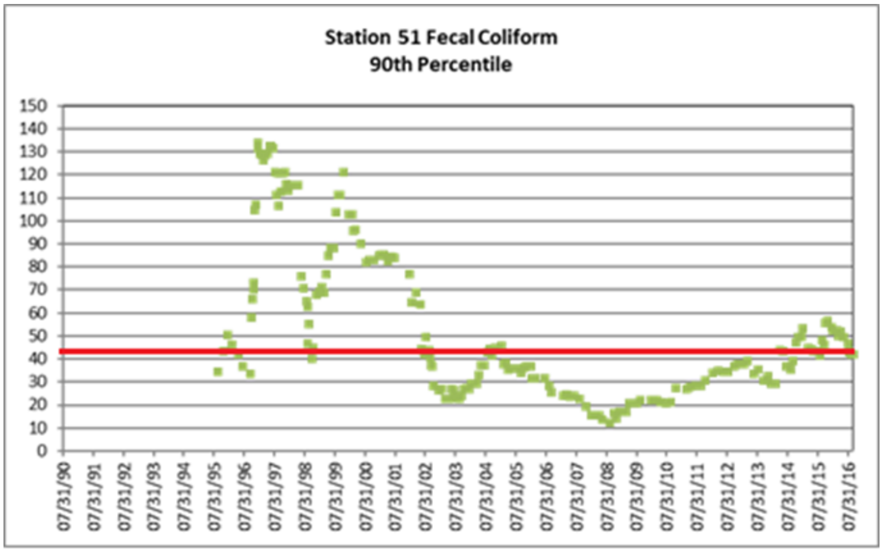

Figure 29: Calculated values for the 90th percentile values for fecal coliform levels at Station 51, Portage Bay from 1995-2016. The red line shows the standard that 10% of samples may not exceed.

for fecal coliforms measured at Station 51 in Portage Bay. A new value was calculated each month to include that month's collected measurement. The standard for the 90th percentile mandates that 10% of the total samples taken to that point in time cannot exceed 43 MPN or colonies/100mL. The graph shows that over 10% of the samples were above the standard for shellfish consumption from 1995 to about 2003 before peaking again in 2004 and again around 2014.

Portage Bay Coliforms in the Winter

Faecal coliforms in Portage Bay were analyzed during exclusively winter months as these months were found to be the only ones to experience peak flows large enough to classify as floods. By limiting values to just winter months (figure 30), the geometric mean values were found to exceed the marine standard of 14 colonies/100mL from about 1995 to the end of 1999. Annual geometric mean values shown in figure 28, the standard was only found to exceed the standard once in 1996. Both winter and yearly geometric mean values were found to remain below the standard from the year 2000 to present. 90th percentile values during the winter in Portage Bay, figure 31, were found to exceed the standard of 43 colonies/100mL more frequently than the annual 90th percentile data had (figure 29). 2003 and the range of 2008-2013 were all years that demonstrated 90th percentile values below the standard however these years were found to be above the standard when using just the winter data. Winter 90th percentile values were also observed to be almost twice as high between 1995 and 1997 when compared to annual 90th percentile data.

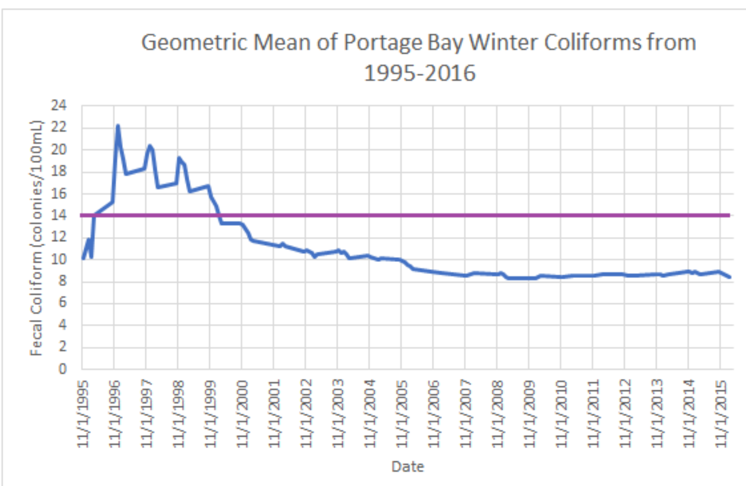

Figure 30: Geometric Mean of Portage Bay Coliforms from 1995-2016 from October to March

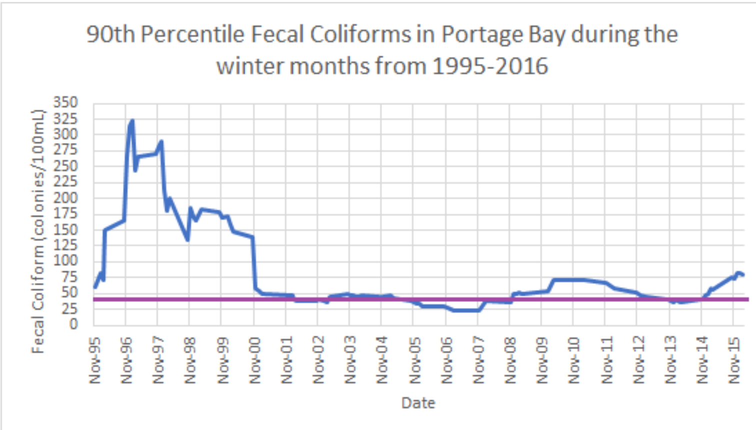

Figure 31: 90th percentile values for fecal coliforms in Portage Bay from October to March from 1995-2016

Water Temperature:

Water temperature data was collected in Ferndale, Washington (figure 32). Water temperature for July and August are presented here as these two months represent periods of low flow compared to the rest of the year. It was found that both of these months demonstrate a negative correlation when comparing discharge and water temperature, or that as discharge decreases temperature increases. It was also found that these two months were the only two where the correlations between discharge and water temperature were found to be statistically significant (figure 33). Other months either showed little to no correlation at all and others that did show correlations were found proved not to be significant. It should also be noted that August demonstrated average fecal coliform values that were above nearly every other month of the year.

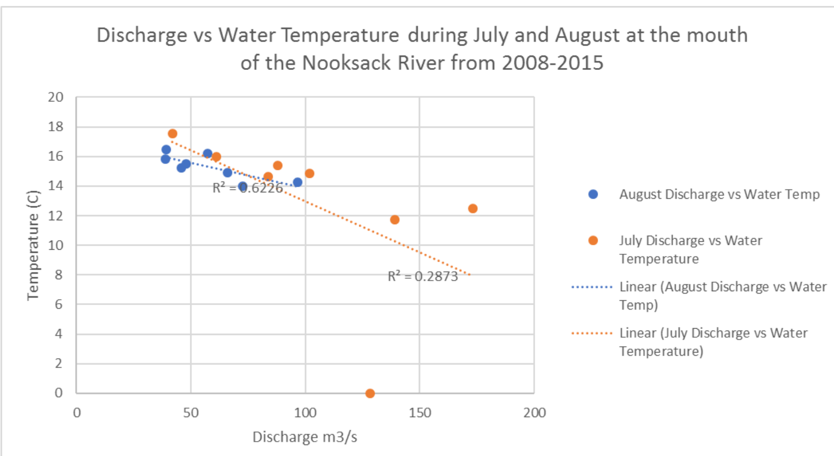

Figure 32: Discharge vs Water Temperature at the mouth of the Nooksack River during July and August from 2008 to 2015. R^2 values: July- 0.2873 August-0.6226

Statistical Significances of the Correlations between Discharge and Water Temperature												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Significant	No	No	No	No	No	No	Yes	Yes	No	No	No	No

Figure 33: Table showing statistical significance between discharge and water temperature at the mouth of the Nooksack River from 2008-2015

Peak Flow Events and Fecal Coliform Values:

To interpret if peak flows greater than or equal to 565 m^3/s were influencing coliforms in Portage Bay, the two were compared (figure 34). The comparison was a bit limited by lack of coliform data compared to discharge data and was not able to start until 1995. It should also be noted that these flow values were the peak flow values taken for each year, however this does not mean that each peak flow value is indicative of a flood events. Peak flow values below 565 m^3/s were not considered flood events. The geometric mean of fecal coliforms has been decreasing since the mid 1990's remaining above the accepted standard of 14 colonies/100mL until around 1999. This is consistent with the plot of geometric mean values over time seen in figure 28. Peak flow and faecal coliform data was kept exclusive to the winter months as they were indicative of flood events and relations between the two were the aim of this comparison. Each year between 1995 and 1999 was also found to be a time when peak flow was greater than 565 m^3/s except for 1997 where peak flow maxed out at about 370 m^3/s. This pattern of fecal coliform values being above the accepted standard seen in 1995, 1996, 1998, and 1999 was not seen anywhere else as the geometric mean values for fecal coliforms remained consistently below the standard between about 12 and 8 colonies/100mL despite peak flows exceeding 565 m^3/s. When comparing the winter peak flow and peak 90th percentile values for fecal coliforms (figure 35), flood events did not show consistency with coliform standard exceedance of 200 colonies/100mL. As previously stated, from 1995 until 2005 the standard was exceeded as well as from 2008 to present day. Flow events exceeding 565 m^3/s occurred from 1995-1996, 1998-2000, 2001, 2003-2004, 2006-2010, and 2014-2015.

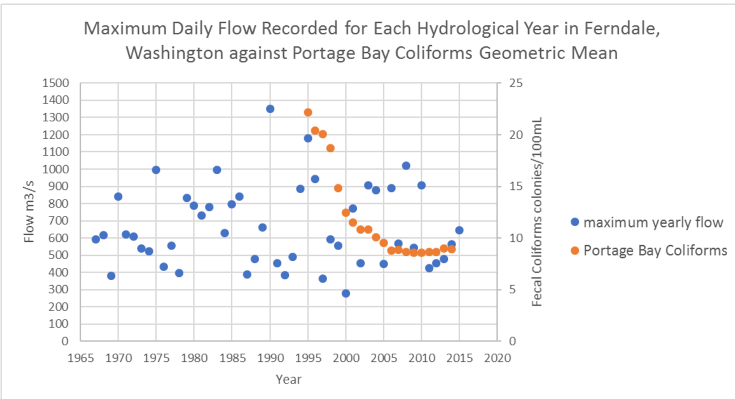

Figure 34: Maximum Daily flow recorded for each hydrological year in Ferndale, Washington against Portage Bay Coliforms

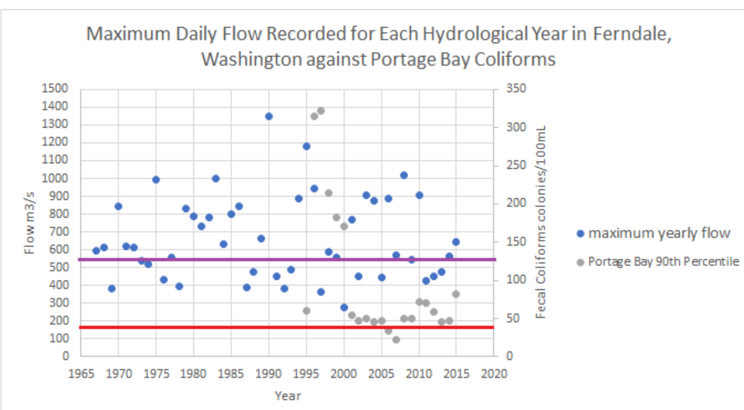

Figure 35: Maximum daily flow recorded for each hydrological year against 90th percentile values of fecal coliforms in Portage Bay

1997 not showing a recorded flows values over 400 m^3/s

Shellfish Bed Closures:

Based on fecal coliform data obtained for Portage Bay as well as Health Advisories from Fisheries Canada pertaining to locations where shellfish collection was deemed unsafe, historic closure dates for shellfish beds were determined. It can be seen here that these dates typically spanned multiple years except for a closure in 2004. Geometric means and 90th percentile values were calculated monthly to determine if a shellfish bed was safe for public use. It can be assumed that the years indicating closures of shellfish beds refer to these closures lasting for the entire year and not just a portion of it (figure 36).

Derived Shellfish Bed Closure Dates based on Fecal Coliform Data and Health Advisories											
Years of Closure	1996 all year	1997 all year	1998 all year	1999 all year	2000 all year	2001 all year	2002 all year	2004 all year	2014 all year	2015 all year	2016 all year

Figure 36: Derived Shellfish Bed Closure Dates based on Fecal Coliform Data and Health Advisories

Discussion

Hydrologic and Climate Data:

The discharge data exhibited two specific peaks during the winter late spring/early summer months. The spike in winter discharge is most likely caused by precipitation during the months of October to January which is supported by the collected precipitation data. The second peak in discharge during May and June are most likely the result of snow melt creating the spring freshet. This, again, is supported by the precipitation data for these months where precipitation is marginally lower than it is during the winter months.

Current climate models, as published in 2007 as part of the Whatcom County Climate Protection and Energy Conservation Action Plan, show widespread increases in annual precipitation with widespread decrease in April snowpack. This includes a decrease in snowpack and glacial accumulation in the Cascade Mountains where the Nooksack River originates. Temperature models for Northwestern Washington are expecting yearly temperatures to increase by about 3° Celsius, with a one degree confidence interval in both directions, by the year 2100. If these published models are the best available information depicting scenarios for future temperature and precipitation, increasing minimum temperatures suggest a reduction in snowfall during the winter months resulting in more liquid precipitation during storm events as well as rain-on-snow scenarios. Temperature data from Bellingham and Clearbrook have shown increases in minimum temperatures of 4° and 2° Celsius respectively over the last fifty years further supporting the climate models predicting warmer winter and yearly temperatures.

Periods of high flow, discharge above 100 m3/s, occur between November and June. Periods of time that experience above average monthly precipitation, in this case 76 mm, are between October and March. Historically, floods in Whatcom County have been recorded during the months from October to March rather than April to June suggesting that floods in Whatcom are caused by heavy precipitation during autumn and winter rather than the spring freshet in spring and summer caused by snowmelt.

While October has not exhibited average discharge levels consistent with other months that experience flooding, the data show that October is a time where precipitation is increasing and higher than average levels are not unexpected. In 2003, for example, Whatcom County experienced a record rainfall of 279 mm in Clearbrook and 210 mm in Bellingham. The flood occurred between the days of October 17th and 18th however, about twenty-five percent of the total rainfall experienced throughout the entire month occurred on October the 16th which brought 58 mm to the mouth of the Nooksack River and the surrounding area. While October the 17th experienced about 24 mm, the previous precipitation had created saturated conditions leading to the two-day flood. Historically, this is not the only occurrence of sustained rainfall leading to flooding of the Nooksack River. Similar conditions led to floods in both 1989 and 1990 during November as well as in December of 1975. The longest flood occurred in 1990 and lasted for 5 days caused by the heavy rains experienced the day prior. Other floods, such as the December 1975 and November 1989 flood occurred during periods of sustained rainfall over the days leading into and during the flood (Brakenridge and Kettner, 2017). This is further supported by the statistical significance between discharge and 24 or 48-hour rainfall conditions.

Past Flood Events and Flood Frequency

After determining a minimum flow value to represent flood events, the number of days per year to experience these flood events were summed. This was done to determine if the number of flood events have changed over time since 1967. The data show that since 1967 the number of floods have increased by about three. This information does not indicate the most probable month that these events would occur if they were to increase however, based off the total number of flood events given in figure 15, it can be inferred that an increase in flood events would most likely occur in November or January.

The flow duration curve shows the percentage of specific flow events occurring for each year. Currently the flow duration curve reads that peak flows high enough to cause flooding have between a 1 and 2% chance of occurring each year. This is also shown in figure 17 in which the data were split into 10 year groups to observe if flood frequencies were increasing compared to non-flood frequencies. The percentages remained around about 1 to 2 % for each ten-year cluster as well as all 40 years analyzed at once. While the values were similar, an overall increase in flows equal to or greater than 565m^3/s compared to flows less than this value occurred over time. Based on the number of flood level flows per year outlined in figure 14, an increase of about 3 flood events per year over the course of 40 years given the changes to the climate regime did not appear to have a large impact on the flow duration curve seen. This would imply that the number of floods per year would have to increase substantially to notice an increased probability in floods for the future. It cannot be guaranteed how flood frequency will increase over another 40 years, however assuming future climate models are correct and there is no change to the current land use, the number of floods should increase by at least 3 per year but this number would be expected to be higher due to an increase in rainfall and minimum temperatures compounding on the changes that have already been observed. The 2016 Nooksack State of the Watersheds report predicted an increase in maximum flow of about 12% by 2080 which would increase peak flows by an additional 6-10m^3/s, on average, per year.

Water Quality Data

Fecal Coliforms

Mainstem Nooksack River:

The fecal coliform data collected at the mouth of the Nooksack River was taken once per month over 25 years. Data gaps during the year limited the data set provided as did the sampling technique. Rather than continuous data, the value measured at the start of the month was used to represent the water quality of that given month. This could have led to dramatic shifts in measured values between months and made drawing definitive conclusions difficult. Conclusions that could be drawn could also create controversy as to whether there even is an issue with fecal coliforms. At the current moment, the Nooksack River meets the freshwater standard for the geometric mean of fecal coliforms. This standard was created around the purpose of recreational uses of freshwater focusing more on indirect contact rather than ingestion. If one were to look exclusively at these data, the Nooksack River would appear to contain acceptable levels of bacteria.

However, there are two standards that need to be met and while the data show the geometric mean for fecal coliforms sits below the freshwater standard, the calculated 90th percentile values for the fecal coliform data are perpetually above the standard. Since this standard is not met, the Nooksack River, at least at the point it was sampled, is considered unsafe for any activity that does not involve direct ingestion of the water. The point of sampling occurred at Ferndale, Washington of the river and it can be implied that the river will then discharge directly into Portage Bay, a location where direct ingestion of harvested shellfish is depended on by the residents.

It can still be observed that the current geometric mean and 90th percentile values of fecal coliforms in the Nooksack River have yet to produce a value less than the standard for shellfish harvesting. Even with the Shellfish Sanitation Decree in 1994 and the Portage Bay Shellfish Protection District Shellfish Recovery Plan in 1998, which intended to manage fecal coliform levels in the Nooksack River and protect the shellfish industry in Portage Bay. While the Nooksack River is a freshwater body and thus not dictated by marine standards, it does discharge into a saline body of water, Portage Bay. The partially mixed estuarine environment in Portage Bay has previously been stated to limit mixing of the water while the storm protected bay environments limit wind action and ocean inflow further inhibiting mixing and hindering dilution of contaminants (Conomos, 1979). Conomos continues to discuss similar scenarios have been observed in the San Francisco, Hudson, and Chesapeake Bays. In 1982 the USGS published another study on San Francisco Bay and the inflowing, nearby delta determining that the impacts of the freshwater depend almost entirely on the circulation and mixing of the marine environment it enters as well as the amount of discharge given off by the freshwater source. Despite having strict standards in place for fecal coliforms in the marine setting, the less strict regulations on freshwater inflows from the Nooksack River, coupled with circulatory dynamics of bay environments, would negatively influence fecal coliform count in Portage Bay preventing shellfish harvesting.

Monthly data demonstrated a similar situation in which the fecal coliform standard for shellfish consumption is not met by the water discharging from the Nooksack River into Portage Bay. This conclusion is not definitive however as monthly values recorded only once and are not an ideal depiction of actual conditions. Monthly data analysis was intended to determine if there specific months were of influence for driving the high levels of fecal coliforms seen in Portage Bay and if these months coincided with the shellfish harvesting season. The shellfish harvesting season in Washington State is open all year provided health standards are met which, based off the available data, are exceeded throughout the entire year. Spikes are seen during the months of August and November where measured levels averaged above 200 colonies/100mL. August was found to be a period of low flow, warmer water temperatures, and below average rainfall creating conditions that would allow for higher concentrations of fecal coliforms to accumulate without being flushed through the river and into the bay. November, however, exhibited opposite trends of high flow conditions and above average precipitation. This could be caused by a few reasons. One of which would be due to the inconsistencies with sampling previously mentioned creating an unreliable depiction of the water quality. Another explanation could be unrelated to the discharge and rather be caused by the heavy precipitation experienced during the month of November. The heavy November rains would collect agricultural, industrial, and domestic contaminants, manure and effluent included. This would runoff back into the Nooksack River influencing the water quality as stated in the previously mention 2015 NOAA publication concerning watershed flooding and pollution. However, this would also suggest that other months experiencing heavy rainfall such as October, December, and January would also be expected to see spikes in fecal coliform levels rather than sharp decreases. This could be explained by lower concentrations of contaminants remaining to be collected by heavy rains and overland flow during the later months compared to those present in November.

This is further supported by factoring in farmers use of excess manure on their fields during the month of October to make space for manure storage during the winter. In Whatcom County, it is understood that fertilizing during known flood periods, November to March can increase the potential for pollutant runoff and fertilizing during these months is either prohibited or requires the approval of a governing body such as the Natural Resources Conservation Service (Grusenmeyer and Peterson, 1995). This further explains why fecal coliform values showed a spike in November as the fields would be covered in excess manure during mid-October to make room for winter storage and to avoid the cutoff date for manure application. These data can be compared to the nitrate data observed at the mouth of the Nooksack River. If October manure applications did contribute to the observed November fecal coliform levels, then nitrate levels during November could also be expected to have shown a spike as it would also indicate increased levels of manure. Based off the nitrate data observed at the mouth of the Nooksack River, November did not exhibit average nitrate levels higher than other months but rather November exhibited average nitrate levels less than four other months'.

Nooksack River fecal coliform geometric mean and 90th percentile values from October to March showed similar trends to values taken over the twelve months. Geometric mean values were above the accepted standard until 1986. From 1987 to present the geometric mean values were below the standard of 100 colonies/100mL. 90th percentile values were above the standard of 200 colonies/100ml for the duration that calculations were made at the test site in Ferndale, Washington. A key difference between the geometric mean and 90th percentile fecal coliform values calculated over 12 months compared to the 6 months during the winter was that values were higher during the winter months during the first three months of calculations. Geometric mean values during the winter peaked at 220 colonies/100mL compared the 180 colonies/100mL seen over the 12-month period. 90th percentile values during the winter were almost one and half times as high as the values seen over a 12-month period peaking at just over 800 colonies/100mL. While these values for winter months were initially higher than those seen over the course of the year, both data sets were found to follow similar trends in that the geometric mean of fecal coliforms still dipped below the standard, as previously stated, while 90th percentile never reached the standard. For these reasons looking at the fecal coliform data during the winter did not provide much insight towards the influence of winter conditions on fecal coliforms in the Nooksack River given the current regime. It cannot be determined if the calculated geometric mean and 90th percentile values for Nooksack River coliforms have reached an asymptote in their current values, however based on this data set values do not seem as if they would increase for the future years. Even if 90th percentile values don't increase, if they plateau at their current state values will still remain above the accepted freshwater standard.

Tributaries of the Nooksack River:

Compared to the mainstem of the Nooksack River, the surrounding tributaries were found to contain levels of fecal coliforms consistently above accepted standards over the last three years. This could be explained by the locations these tributaries happen to travel through before reaching the mainstem of the Nooksack River. For instance, fecal coliform levels were found to be above the accepted standard in a tributary that flows through the town of Lynden at the mid-section of the Nooksack River floodplain. As previously mentioned, discharge from a wastewater treatment located in Lynden enters directly into a nearby tributary of the Nooksack River. The Washington Department of Ecology in 2000 determined that the waste water had not been properly disinfected before being discharged and while measures have been taken since to correct this, fecal coliform levels have continued to demonstrate values above the accepted standard. Another hotspot for fecal coliforms can be seen within a 10-kilometer radius of the Cherry Point Refinery, as seen in figure 37, which was previously mentioned as being an oil refinery and aluminum processing plant. Discharge from this plant has potential to reach the Nooksack River further affecting the fecal coliform levels observed at the mouth. A final influence on fecal coliforms in tributaries can be seen by using figure 37 alongside a map of the manure lagoons located in Whatcom County with relation to their distance from the Nooksack River (figure 7). This map was created by the Skagit River System Cooperative and illustrates that a majority of these manure lagoons are within 150 meters of a body of water. In this case the bodies of water are clustered near the tributaries above Lynden as well as those to the Northeast of Cherry Point Refinery which, according to figure 37, are locations where fecal coliforms were found to be in abundance. However, based off of figure 37, manure lagoons along the mainstem Nooksack River have not shown the same influence on water quality as the development along the tributaries and in some locations these lagoons have not proven to influence water quality to any extent. The location of these municipal, industrial, and agricultural operations all further influence the fecal coliforms discharged from the Nooksack River into Portage Bay and help to explain the reason why fecal coliforms counts are still as high as they are currently observed despite events to manage them.

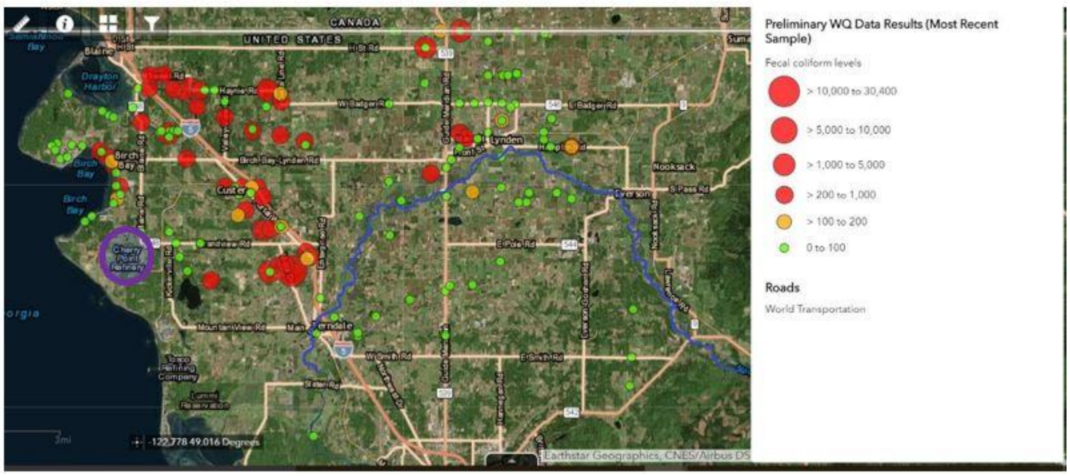

Figure 37: Map of Fecal Coliforms measurements from the stations located around Whatcom County. The Nooksack River flows through the center of the map and is highlighted in blue. Cherry Point Refinery is in the Northwest of the county and is circled (Whatcom County Public Works, 2017).

Portage Bay:

Portage Bay fecal coliform measurements were taken once per month from 1990 to present. Station 51 provided the most consistent data set of the information provided from Whatcom County

Public Works including values for fecal coliforms levels, the geometric mean of the collected data, and 90th percentile values. The data for monthly fecal coliform collection was used to determine the geometric mean of the measure monthly values which cannot exceed 14 MPN/mL or 14 colonies/mL. Both standards are the same despite the measurement processes being different. At station 51 it was found that the geometric mean of samples only exceeded the permitted standard once around 1996 and has remained below the standard in year prior and following. This location of Portage Bay is still considered conditionally closed for public harvesting as the 90th percentile values seen at Station 51 have been fluctuating above and below the permitted standard since 1995. This means that over 10% of the samples taken have exceeded the standard value for fecal coliforms of 43 MPN/100mL or 43 colonies/100mL. For the case of Station 51, over 10% of the samples exceeded the permitted standard numerous times justifying the conditional status given to the location. This could be the result of inflow of fresh, contaminated water from the Nooksack River inhibiting ocean mixing as well as limited circulation created by a bay environment. In order for a shellfish harvesting station to be opened to the public, both criteria must meet the standard for fecal coliform values. Even though the geometric mean for fecal coliforms had not exceeded the accepted standard since the md-1990's, the 90th percentile values fluctuated above and below the marine standard. It can be implied then that every time one of these standards were exceeded, harvesting in that location was closed. For that reason, it was determined that Station 51 had be closed from 1995 to 2002, again in 2004, and currently has been closed since 2014 for the entire 12-month period of each year.

Comparatively, Portage Bay faecal coliforms value for the winter did not demonstrate similar trends. Geometric mean values were found to exceed the accepted marine standard from 1995 to 1999 before falling to accepted levels in 2000 and remaining there until present day. 90th percentile values fluctuated less between the standard and producing values above the standard for most of the years since testing began. The marine standard for 90th percentile values of fecal coliforms above the standard from 1995-2002, 2003-2005, and from 2008 to present. On the contrary, the standard was only met from 2005 to 2007. Increased values for fecal coliforms seen during the winter months on Portage Bay could be attributed to increased discharge to the Nooksack River via increased precipitation. Geometric mean values for the Nooksack River during the winter months were found to be higher when compared to yearly data which could have led to the increased concentrations of fecal coliforms in Portage Bay. Other 6 month spans were not isolated so it cannot be determined if fecal coliforms concentrations in Portage Bay would have also shown similar values of spring and summer were analyzed during periods of glacial melt and the warming of the water. However, isolating winter months did show increased concentrations of fecal coliforms in both the Nooksack River and Portage Bay supporting the idea that these months have some degree of influence on bacterial contamination.

Water Temperature:

Water temperature data were used to support fecal coliform data. Due to the data gaps and limits of monthly testing of fecal coliforms, water temperature of the Nooksack River could be used to support or dispute potential trends demonstrated by monthly coliform data. Water temperature would be indicative of water quality, in this case bacterial contamination and proliferation, as bacteria prefer specific temperatures to live and reproduce. Low flow conditions, as seen in July and August, paired with warmer temperatures associated with the summer months, raise water temperature and create conditions conducive to bacterial growth (Palmer et al., 2009). This would help to support why August was sampled to have some of the highest values for fecal coliforms compared to any other month. The fact that the correlation between water temperature and discharge observed during the month of August also proved to be statistically significant further supports the idea that the Nooksack River during the summer months, specifically August, is subjected to conditions ideal for bacterial contamination and transport despite not being known to experience high levels of precipitation, discharge, or flood events. Since extreme climatic events such as high levels of precipitation and discharge have not been recorded for the months of July and August it cannot be concluded that increased concentrations of fecal coliforms because of rising water temperatures due to a changing climate would be affected by the flood events and potential affects to water quality that could come from such. While this is still an issue for water quality, increased frequency in flood events would not affect the trends seen.

Flood and Shellfish Bed Closure Events:

The fecal coliform data for the winter months had been superimposed on the peak flow data from each hydrological year to identify if one had influenced the other. The geometric mean for fecal coliform values were found to be above the standard from 1995-1999 despite each of these years not experiencing peak flows indicative of flood events. Irregularities were also seen during between 2003 and 2004, 2006-2010, and 2014-2015. Each of these years exhibited flood events based off their peak flows for that year but fecal coliform geometric mean values remained below the standard for closures of 14 colonies/100mL. This would suggest that peak flow events over 565 m^3/s do not influence coliform levels in Portage Bay. However, as previously mentioned, two standards must be met for shellfish beds to remain open. For this reason, fecal coliform values for the 90th percentile were also compared to peak flow events. 1997, 2000, 2002, and 2011-2013 were all years in which flow events were not high enough to be considered a flood yet all exhibited 90th percentile values that were above the standard. 2006 and 2007 were also years that did experience flood level flows yet did not show 90th percentile values above the standards nor were years in which Station 51 in Portage Bay was closed. Of the 11-years derived as shellfish bed closures, three of these years were without peak flows high enough to be considered floods. For this reason, it cannot be concluded that peak flows of 565 m^3/s or greater, flood events, are of direct influence on shellfish bed water quality or their closure.

Statistical Significance

Discharge and Precipitation:

Significant correlations between discharge and precipitation were found for each month that has experienced flooding in the past along the Nooksack River and surrounding floodplain. April was also found to be significant despite having no flood history. October, despite being a period of low flow, showed statistical significance for discharge and precipitation suggesting that floods that occur during October could be the result of heavy, abrupt rainfall as opposed to prolonged, sustained storms experienced later in the winter months. While flooding was not seen during the months of April the correlation was still significant. Despite lower observed values for both discharge and precipitation during this month, it is still entirely possible that the two are correlated and, according to the results, increased precipitation during the month of April has also led to higher discharge. These lower values seen for discharge and precipitation help to explain why floods have not occurred during the month of April.

Discharge and 24, 48, and 72-hour Precipitation

Significant correlations between yearly peak discharge events above 565 m^3/s and 24 and 48-hour prior rainfall were found. Peak discharge and 48-hour rainfall was found to have a greater R^2 value than peak discharge and 24-hour rainfall. Investigating rainfall only on the day of flood events does not take prior conditions into account that could have influenced the outcome of the statistical correlation. Determining the statistical significance for prior rainfall further supports the idea that rainfall is a primary influence on discharge in the Nooksack River. It also helps to support the idea that periods of sustained rainfall as well as abrupt 24-hour rainfall can cause flood events in the Nooksack River. However, it is not the only contributor to peak discharge in the Nooksack as floodplain development and an increase in impervious surfaces would also influence discharge and runoff into the River.

Discharge and Fecal Coliforms:

Significant correlations were not seen for monthly discharge and monthly fecal coliform data despite the data suggesting increases in monthly coliforms during August and November compared to the rest of the year. Originally it was thought that the statistical tests were being affected by high variability in the data by using discharge and fecal coliform data from all twelve months. For this reason, statistical correlation analyses were performed again, this time by grouping the data into periods of low flow and periods of high flow. These groups broke down the data over a range of months, August to October and November to January. These groups were based off average discharge data observed during these months from both the midsection and mouth of the Nooksack River and each group represented a continuous three-month span representative of the lowest lows and highest highs. The intention was to see if observed trends for low/high flow discharge data and fecal coliform data for the respective months were statistically significant to attempt to identify months of concern for coliform discharge from the Nooksack River. These analyses were also not statistically significant.

It is not unexpected to have not seen any linear correlation between discharge and fecal coliforms. This is because discharge is not the single influence on observed levels of fecal coliforms in a body of water but rather one of many that includes water temperature, sunlight, farm size, manure management practices (Wilkinson, 2000). With so many factors influencing fecal coliform count in the Nooksack River at any given time, it cannot be certain that discharge has the largest influence on observed values. This is supported in figure 14 which displays mean monthly coliform data at the mouth of the Nooksack River. Spikes in fecal coliforms were seen during August and November which were found to be periods of dissimilar flow with August exhibiting one of the smallest discharge volumes and November showing one of the largest discharge volumes compared to every other month. This would suggest that discharge is not the only influence on fecal coliform counts in the Nooksack River.

Water Temperature and Discharge:

Even though trends for fecal coliform data were found to show no significance when analyzed with discharge data, trends for water temperature data compared to discharge data were found to be statistically significant for the months of July and August. Water temperature data can be used to represent water quality to an extent as water temperatures influence the propagation of bacteria (Palmer et al., 2009). Warmer temperatures associated with the low flow conditions seen in the months of July and August would be more conducive to bacterial growth in the waterway which supports the fecal coliform data analysis seen for the month of August. However, this significance is not associated with flood events despite its indication to issues with water quality.

Conclusions

Changes in climate have shown limited effect on the water quality in the Nooksack River. This also suggests that flood events have shown inconsistent effects on the water quality in the Nooksack River and Portage Bay. Water quality in the Nooksack River has shown consistent influence from land development along the floodplain of the Nooksack River with that largest contributor of contamination being the tributaries of the Nooksack rather than the mainstem river.

Fecal coliform concentrations in the Nooksack River are not just influenced by peak flow events along a developed floodplain. Water temperature and turbidity were also found to influence high concentrations in the Nooksack River further supporting that flood events and an altering climate are not the sole contributors to water quality concerns.

These conclusions are limited by the amount of available fecal coliform data. Fecal coliform data was obtained over the last 15 years with concentrations being recorded once per month. These data were limiting in determining if flood events had direct impact water quality in Portage Bay as sampling had no occurred following flood events. The time between samples created a possibility that fecal coliform values could have been above an accepted standard for the duration of a month that had experienced a flood but remained undetected.

To determine the influence that floods are having on fecal coliform concentrations, future sampling in Portage Bay would need to be done directly after a flood rather than just once per month. Determining the largest contributors of bacterial contamination in the Nooksack tributaries is also an important next step in limited the concentrations of fecal coliforms to Portage Bay.

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References

1. Adelsman, H. and Ekrem, J. (2012). Preparing for a Changing Climate: Washington State's Integrated Climate Response Strategy. Washington State Department of Ecology.
2. Bandaragoda, C., J. Greenberg, M. Dumas and P. Gill. (2012). Lower Nooksack Water Budget Overview. In C. Bandaragoda, J. Greenberg, M. Dumas and P. Gill, (eds). Lower Nooksack Water Budget, (pp. 3-35). Whatcom County, WA: WRIA 1 Joint Board. Retrieved [Date], from http://wria1project.whatcomcounty.org/. Bronson, A. (2009, January 8, 2009). Whatcom flooding 2009. *The Bellingham Herald*
3. Bradt, S. (2016). Blue Water GIS Map@Syst: Whatcom County Watershed Improvement District's Story Map
4. Brakenridge, R. & Kettner, A. (2017). Space-based Measurement, Mapping, and Modeling of Surface Water: Active Archive of Global Large Floods. Dartmouth Flood Observatory, Boulder, Colorado.
5. Brown, M., Maudlin, M., Hansen, J. (2005). Nooksack River Estuary Habitat Assessment. Report for: Salmon Recovery Funding Board, Office of the Interagency Committee. Lummi Nation Department of Natural Resources.
6. Conomos, T. J. (1979). Properties and Circulation of San Francisco Bay Waters. San Francisco Bay: The urbanize estuary. Investigations into the Natural History of San Francisco Bay and Delta with Reference to the Influence of Man (47-84). Pacific Division of the American Association for the Advancement of Science c/o California Academy of Sciences Golden Gate Park San Francisco, California 94118
7. Cook, K. (October- 1995). *Historical floods in the Sumas prairie, British Columbia*. Victoria, B.C.: UBC: Resource Management and Environmental Studies.

8. Cox, S.E., Simonds, F.W., Doremus, Llyn, Huffman, R.L., and Defawe, R.M. (2005). Ground Water/Surface Water Interactions and Quality of Discharging Ground Water in Streams of the Lower Nooksack River Basin, Whatcom County, Washington: U.S. Geological Survey Scientific Investigations Report 2005-5255, 46 p.

9. Department of Ecology State of Washington. (2017). Washington State Coastal Atlas: Flood Hazard Area in Whatcom County

10. Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J., Brooks, N.H. (1979). Mixing in Inland and Coastal Waters. Chapter 7: Mixing in Estuaries. Academic Press.

11. Fisheries and Oceans Canada. (2016). Shellfish contamination in the Pacific Region. Government of Canada

12. *Franz, D.*D. (2004). Lower Nooksack River Unsteady-Flow Model and Analysis of Initial Scenarios Near Everson. Linsley, Kreagar Associates, LTD. Whatcom County, Washington.

13. Geoscience Australia. (2017). Applying Geoscience to Australia's most important challenges and hazards. Australian Government: Commonwealth of Australia.

14. Gillies, J. and MacKay, H. (2016). Preliminary Assessment of Drivers of Agricultural Land Conversion in Whatcom County, Washington. Whatcom County Agriculture-Watershed Project

15. Grusenmeyer, D. and Peterson, B. (1995). Manure Management Guidelines for Western Washington. WSU Cooperative Extension-Whatcom County.

16. *KCM Inc.* (1995). Lower Nooksack River Comprehensive Flood Hazard Management Plan: Nooksack River Flood History. Whatcom County Transportation Service Department

17. *Kremen, P.* (2007). Climate Protection and Energy Conservation Action Plan. Whatcom County, Washington. Local Governments for Sustainability for the Northwest Clean Air Agency and Whatcom County.

18. Khare, P., & Sellars, C. D. (April 1991). *Flooding of west Sumas prairie November 9-12 1990.* (No. PB 5174 02). BC Environment Water Management.

19. *Lower Nooksack river CFHMP: Flood history task.* (1994). KCM.

20. *Lummi Nation Chapter.* (2012). State of Our Watersheds Report. Whatcom County, United States

21. Luoma, S. N. and Cloern, J. E. (1982). The Impact of Waste-Water Discharge on Biological communities in San Francisco Bay. US Geological Survey, 345 Middlefield Road, Menlo Park, CA

22. Mellor, A. F. P., & Cey, E. E. (2015). Using generalized additive mixed models to assess spatial, temporal, and hydrologic controls on bacteria and nitrate in a vulnerable agricultural aquifer. *Journal of Contaminant Hydrology, 182*, 104-116

23. Morgan, D. (2015). Nooksack valley nostalgia: A virtual museum covering the history of Sumas, Nooksack, and Everson in Whatcom county, Washington. Retrieved

from http://nooksackvalleynostalgia.blogspot.ca/2015/01/floods-of-sumas-part-1-of-1-featuring.html

24. Mercure, J. (2017). Office of the Washington State Climatologist. OWSC.

25. National Oceanic and Atmospheric Association. (2017). What is a dead zone? National Ocean Service, U.S. Department of Commerce

26. National Oceanic and Atmospheric Association. (2015). Watersheds, flooding and pollution. U.S. Department of Commerce

27. Nooksack Indian Tribe. (2016). 2016 State of our Watersheds Report: Nooksack River Basin.

28. Nooksack Salmon Enhancement Association. (2017).

29. Palmer, M.A., Lettenmaier, D.P., Poff, N.L., Postel, S.L., Richter, B., Warner, R. (2009). Climate Change and River Ecosystems: Protection and Adaptation Options. Environmental Management Volume 44, Issue 6, pp 1053-1068.

30. Peterson, B., Gill, P., Fleishmann, J. (2011). 2010 State of the Watershed Report, WRIA1 Watershed Management.

31. Ramírez-Castillo, F.Y.; Loera-Muro, A.; Jacques, M.; Garneau, P.; Avelar-González, F.J.; Harel, J.; Guerrero-Barrera, A.L. Waterborne Pathogens: Detection Methods and Challenges. *Pathogens* **2015**, *4*, 307-334.

32. Skagit River System Cooperative (2015). CAFO Lagoons in Whatcom County. Whatcom Watch.

33. S.S. Sumioka, D.L. Kresch, and K.D. Kasnick. (1998). *Magnitude and frequency of floods in Washington.* (Water-Resources Investigations). Tacoma, Washington: U.S. Geological Survey.

34. United State Environmental Protection Agency, Narragansett Bay Commission, University of Rhode Island. (2001). Discovery of Estuarine Environments: Water Properties.

35. United States Environmental Protection Agency. (2017). Ground Water and Drinking Water: National Primary Drinking Water Regulations

36. United States Department of Agriculture. (2017). Natural Resources Conservation Service: Conservation Practice Standard Waste Treatment Lagoon Code 359

37. USGS. (2016). National water information system: Web interface. Retrieved from https://nwis.waterdata.usgs.gov/

38. US Army Corps of Engineers (1991). *Flood summary report Nooksack, Skagit, and Snohomish river basins: November 1990 events*. (No. 911104004)..

39. US Department of Agriculture: National Agricultural Statistics Service. (2012). Census of Agriculture, County Profile for Whatcom County, Washington. www.agcensus.usda.gov

40. Vance-Sherman, A. (2015). Whatcom County Profile: Employment Security Department of Washington State.

41. Washington Department of Fisheries and Wildlife. (2017). Salmonscape

42. Washington State Department of Ecology. (2000). Lower Nooksack River Basin Bacteria Total Maximum Daily Load Evaluation. Olympia, Washington. No. 00-03-006.

43. Washington State Department of Ecology. (2017). River and Stream Water Quality Monitoring

44. *Washington State Department of Transportation. (2017).* Climate and Area Geography of Whatcom County.

45. *West and Howard.* (2016). *UBC ATSC 113 - Weather for Sailing, Flying & Snow Sports.* University of British Columbia.

46. Western Regional Climate Center. (2016)

47. Whatcom County Advisory Committee. (2014). Portage Bay Shellfish Protection District Shellfish Recovery Plan: A community Effort for Clean Water.

48. Whatcom County Agriculture-Watershed Pilot Project (2016). Agriculture-Watershed Characterization and Mapping Report for the South Lynden Watershed Improvement District. Whatcom County Planning and Development Services, August 2016.

49. Whatcom County/Nooksack Watershed (WRIA 1). (2015). The 2014/2015 Action Agenda for Puget Sound: How Local Areas are Working to Protect and Recover Puget Sound.

50. Whatcom County Public Works (2017). Nooksack River Watershed. Water Quality Status: Fecal Coliform Bacteria. Whatcom County Washington

51. Wilkinson, J. (2000). Modelling Faecal Coliforms Dynamics in Streams and River. Doctoral thesis, University of Wales, Aberystwyth.