FECAL BACTERIA MANAGEMENT IN PACIFIC NORTHWEST WATERSHEDS:

A comparison methodology to determine significant sources and best management practices for fecal bacteria, using the Amazon Creek basin in Eugene, Oregon as a case study.

by

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Abstract

Fecal bacteria are one of the most common pollutants of urban waterways, and cause illness in humans and animals. Laboratory tests such as microbial source tracking (MST) are increasingly used to determine the sources of fecal bacteria. However, MST can be prohibitively expensive, which slows communities' efforts to develop best management practices and reduce bacterial loads. In 2006, the EPA listed Amazon Creek in Eugene, Oregon as impaired by *E. coli*. This project examined whether the MST results from 25 previously studied basins in the region can inform Eugene's environmental planners about the likely sources of fecal bacteria in the Creek. To compare already studied basins to the Amazon Creek Basin, this project used analyses of land use and impervious surfaces, estimates of domestic and wild animal densities, and expert information on sewage systems and unsheltered homeless people. The results from these interviews and comparisons are used to recommend specific management practices for water planners in the Eugene area and general practices for all environmental managers tasked with reducing fecal bacteria loads in urban waterways.

Abbreviations

ACB	Drainage area of the upper Amazon Creek and its tributaries
BMP	Best management practice
BLM	Bureau of Land Management
CWA	Clean Water Act
EPA	Environmental Protection Agency
MST	Microbial source tracking
NLCD	National Land Cover Database
OR DEQ	Oregon Department of Environmental Quality
OSU	Oregon State University
TMDL	Total Maximum Daily Load
TNC	The Nature Conservancy
USGS	U.S. Geological Survey

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Chapter I: Introduction

By the 1950's, many American creeks and rivers were experiencing increasing and extreme pollution. In response, Congress passed the Clean Water Act (CWA) in 1972 and the Safe Drinking Water Act in 1974. These acts enabled national regulations that limited water pollutants and improved water quality. First aimed at point sources of pollution, CWA requires that a permit be obtained to discharge any pollutant from a point source into navigable water. Permits can be obtained only if discharged pollutants are below certain thresholds. The Act originally exempted storm and urban runoff from meeting water quality criteria. However, these sources are now included in municipal water policy that falls under Federal regulations. Cities and states are responsible for meeting water quality standards and reporting water quality levels to the Environmental Protection Agency (EPA). Water planners managing any impaired waters must write a TMDL, or Total Maximum Daily Load for that waterbody. Under a TMDL, sensitive species are monitored to determine the maximum level of allowable pollutants before such species are threatened, and pollution controls are implemented in an effort to restore water quality in that area.

Since Congress passed the Clean Water Act, American communities experienced significant success in reducing sources of pollution. However, many communities are still faced with urban waterways that do not meet water quality standards set under the CWA (Novotny *et al*. 2010). These standards are designed to reduce environmental degradation and promote human health. Water pollution poses many threats to communities. First, polluted surface and ground water is a health risk for local residents, other members of the community further downstream, and local pet and wildlife populations (Burres 2009, Marks *et al*. 2011, Rhind 2009). Anthropogenic pollution impairs natural functions of a stream, through mechanisms such as eutrophication and heavy metal poisoning (Henne *et al*. 2002, Paul and Meyer 2001). Further, pollutants have an adverse effect on all animal species so far studied (Rhind 2009). The presence of multiple pollutants in a localized area can have a cumulative effect that is particularly damaging to physiological processes, even if individual pollutants are present at relatively low levels. Lastly, polluted surface water can be unsightly or odoriferous. This may discourage tourists from visiting communities, decrease nearby property values, and discourage local residents from recreating near the water (Novotny *et al*. 2010).

Problems caused by fecal bacteria pollution

Fecal bacteria include pathogenic bacteria, and are one type of pollutant for which water quality standards are set. Organisms that take in water polluted with pathogenic fecal bacteria or protozoans can develop a suite of illnesses. These illnesses are usually expressed in the digestive system or mucous membranes, and include gastroenteritis, giardiasis, pneumonia, typhoid, cholera, salmonella, tuberculosis, and hepatitis (Bellack *et al*. 2006, Burres 2009, U.S. EPA 2013, Krause *et al*. 2005, U.S. Dept. Ag. 1992). In severe cases, infection caused by water-borne pathogens is fatal. Infection of some types of fecal bacteria can also lead to illnesses in domestic dogs and cats (Marks *et al*. 2011).

In humans, infection is usually facilitated by recreating in or drinking contaminated water, or by eating undercooked, contaminated fish. A study on the polluted lower Passaic River in New Jersey estimated that annually, a homeless person living along the shore of this river has an 88% chance of infection with fecal *Streptococcus* or *Enterococcus* bacteria and a 100% chance of infection with *Giardia* (Donovan *et al*. 2008). High levels of bacteria can also lead to depleted levels of dissolved oxygen in waterways. This reduces the oxygen available for native aquatic plants and animals, inhibiting the natural functioning of the waterways (Burres 2009).

Eugene, Oregon is one community that faces the challenge of polluted surface water. The community's main waterway, Amazon Creek, and its two main tributaries have experienced fecal bacteria pollution for several decades. Bacteria levels are often above the Total Maximum Daily Load, as designated by the EPA. This adversely impacts the Eugene community. First, people and pets who recreate along the waterways are at a relatively higher risk of contracting illnesses from waterborne fecal bacteria. There are many access points to and paths along the creek, such as the Fern Ridge bike path, which parallels the creek for nearly seven miles. Amazon Creek or its tributaries bisect five parks, including the large and heavily used Amazon Park, and run adjacent to five other City parks. Second, many business and houses are situated close to the creek. These residents and people who use these businesses may have increased exposure to fecal pathogens when parts of the creek overflow the banks, which currently occurs about every three years. Lastly, a sizeable population of transient and homeless people lives near Amazon Creek during at least part of the year, which puts them at risk for contracting illnesses. The January 2013 count of homeless people in Lane County found over 1,000 unsheltered homeless (Lane County 2013), and this number increases during warmer months.

Fecal bacteria in the ACB also affects the area outside of Eugene. About 2/3 of the Amazon Creek flow enters the Fern Ridge Reservoir west of Eugene. The reservoir is a popular spot for fishing, boating, and swimming, and recreators can take in pathogenic bacteria during these activities. About 1/3 of the creek's flow enters the Long Tom River, where fecal bacteria can affect the health of livestock in the surrounding area, and then enters the Willamette River, where untreated fecal bacteria can potentially enter the drinking water of communities such as Corvallis and Wilsonville.

Methods to determine sources of pollution

The first step in addressing water quality problems is to determine the types of pollution present in the impacted waterway. This is usually evaluated through basic water sampling. However, determining the pollutant *source* can be difficult because most communities have at least several and sometimes all of the common causal factors and nonpoint sources of pollution are difficult to trace (Duda *et al*. 1982, Ellis 2004, Young and Thackston 1999). With respect to fecal bacteria specifically, potential nonpoint sources are sewer leaks, septic system failures, wastewater plant overflows, agricultural activity, and raw sewage, domestic pets, and wildlife (Bellack *et al*. 2006, Morato *et al*. 2009, Whitlock *et al*. 2002, Zhu *et al*. 2011). The Amazon Creek basin in Eugene is possibly polluted by a combination of the above sources and efforts to single out one chief source of fecal bacteria have been unsuccessful thus far (Burr 2013).

To determine the origin of fecal pollution (human, avian, canine, etc.), communities can pay for microbial source tracking of water samples. Fecal bacteria coming from a particular host group, such as canines, comprise a particular species or genus or carry unique characteristics, such as "markers" on their DNA (Scott *et al*. 2002). These traits are identified in bacteria in water samples and then compared to traits of bacteria from known hosts. This process is generally termed "microbial source tracking," or MST. Depending on the method of testing and specificity of results, laboratory analysis costs between $10,000 and $20,000 per sampling site (U.S. EPA 2011), with at least several sites per study. The City of Eugene currently monitors the bacteria load of nine different sub-basins at 18 locations within the Amazon Creek basin. If the City were to perform an MST analysis at one site in each of these sub-basins, it would cost at least $90,000 in laboratory analyses alone. This level of cost is prohibitive for such a study in many communities. Therefore, there is a need for a less costly method to determine the likely sources of bacterial pollutants. This project was designed to determine if the MST results already obtained for other basins could be informative to environmental planners working with water quality in the Eugene community. To this purpose, I compared metrics related to hydrology and sources of fecal bacteria between Eugene and MST-studied basins.

Profile of the Amazon Creek Basin

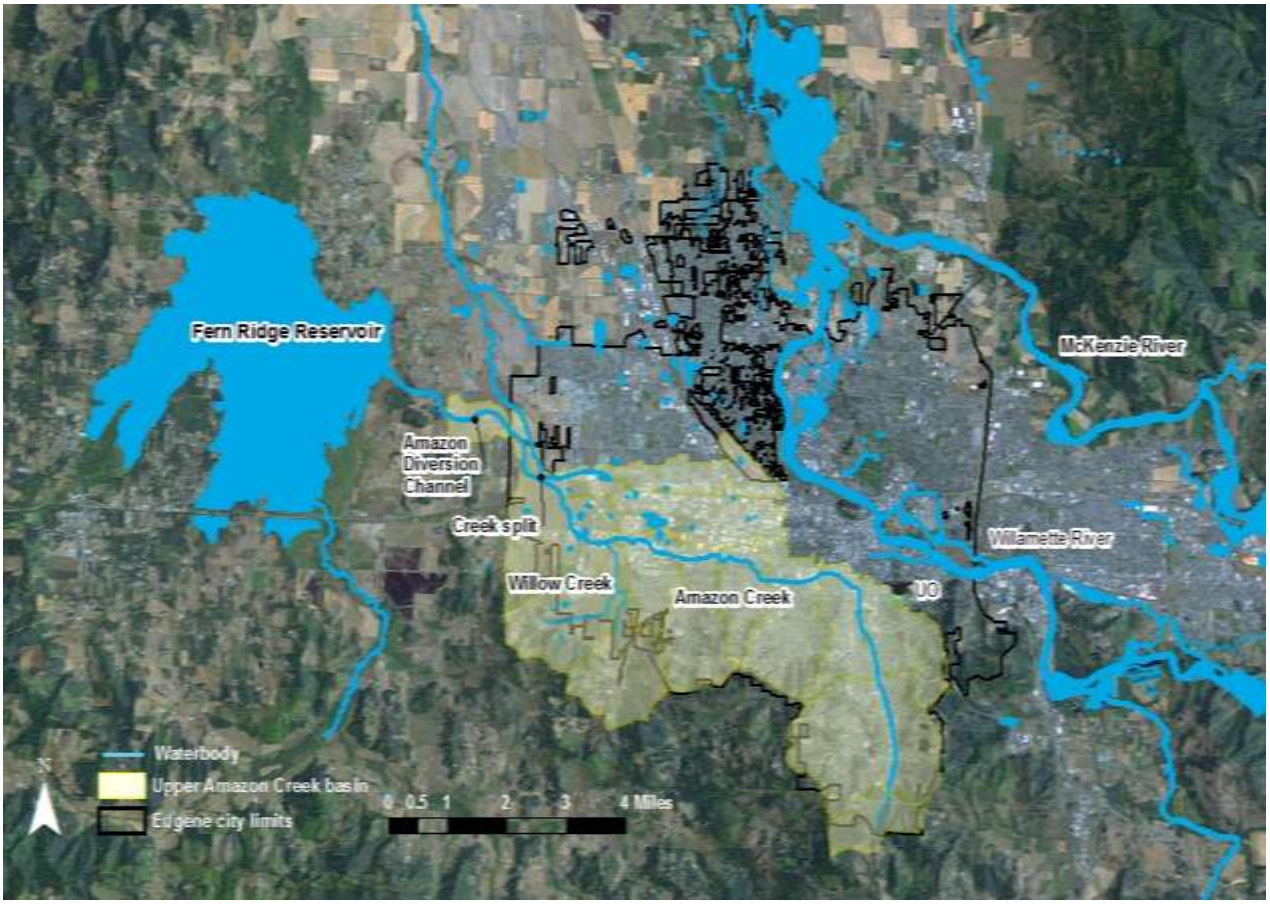
The Amazon Creek drainage, part of the Long Tom basin (Figure 1.1), is separated into two sub-basins, the upper Amazon and the lower Amazon. The portion of Amazon Creek north of the split drains the lower Amazon sub-basin, which is not analyzed in this study. The upper Amazon sub-basin contains the drainage area of Amazon Creek and its tributaries up to the creek's junction with Fern Ridge Reservoir, and does not include any of the lower Amazon. The upper Amazon Creek is the subject of this study, and is hereafter abbreviated as the ACB.

Figure 1.1. Upper Amazon Creek Basin (outlined in red) within the Long Tom River Basin.

Source: Long Tom Watershed

The headwaters of upper Amazon Creek lie in Spencer Butte Park just south of Eugene, Oregon. The creek flows north into downtown Eugene, and then turns west, paralleling 11th Avenue/Hwy 126 for about seven miles (Figure 1.2). Near the intersection of Hwy 126 and Green Hill Road, the creek splits. From this point, most of the water in the creek flows northwest through the Amazon Diversion channel, emptying into the Fern Ridge Reservoir. A portion of the water (the lower Amazon) continues northward to fulfill the water rights of downstream users. This portion of Amazon Creek empties into the Long Tom River, which empties into the Willamette River north of Junction City.

Figure 1.2. Amazon Creek course through the Eugene-Springfield, Oregon area.



Map by Scarlett Philibosian

Amazon Creek and its tributaries drain 25.3 square miles. Much of this area lies within the City of Eugene, with smaller portions to the south and west of the city limits. Over the last 100 years, the City and federal government have significantly altered the Creek's channel and flows. At the time of European settlement, the creek south of downtown flowed through a shallow, natural channel less than six feet deep (Long 1992). This portion flooded almost every year, and alterations of the creek began in 1912. At this time, the City dredged the creek, then enlarged pieces of the channel in 1925 and 1928 (Long Tom 2000). Between 1951 and 1958, the Army Corps of Engineers deepened and widened the creek further, installed a concrete channel to convey water flowing between Jefferson and 24th Street, and constructed the Amazon diversion channel. Most of these projects were part of an effort to reduce flooding within Eugene and in the lower portion of the Long Tom basin. Today, 15.6 miles, or 36% of upper Amazon Creek have been channelized (Figure 1.3).

The Eugene community has monitored water quality in the ACB and in the Willamette River for decades. The City's Public Works Department issues annual updates to its Comprehensive Stormwater Management Plan. In the comprehensive plan, water quality is monitored monthly at 12 sites within the City, and several strategies are implemented to enhance water quality, including green piping, bank stabilization, and catch basin cleaning (City of Eugene 2012).

Figure 1.3. A portion of the channelized Amazon Creek.

Photo by Scarlett Philibosian

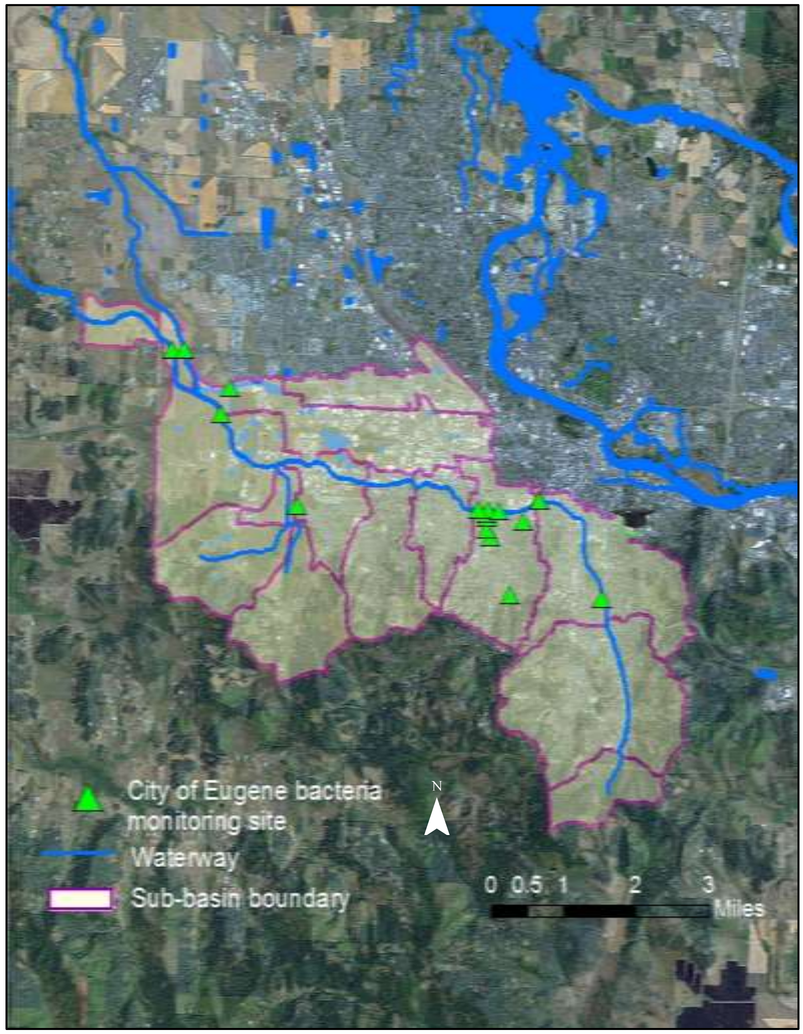
In a 1981 water quality study by the Lane Council of Governments, Amazon Creek showed levels of fecal coliform bacteria that exceeded standards set by the Oregon Department of Environmental Quality (DEQ) (Long Tom 2000). Starting in 1996, the City of Eugene and the U.S. Army Corps of Engineers regularly monitor the water quality in different parts of the ACB. Current state criteria are set at mean values of 126 or fewer *E*. *coli*/100 mL, and no one sample above 406 *E*. *coli*/100 mL. These are the maximum standards that determine whether a stream is listed as "impaired by pollution of fecal bacteria." In 2002 and 2003, DEQ intensively studied the water quality at nine sites in the Amazon Creek and in its tributaries. Seven of the stations violated at least one DEQ criterion for *E*. *coli* during at least one season (OR DEQ 2006). Water at one site violated the threshold for acceptable *E. coli* density for nearly every sample. A 1999-2006 study by the Long Tom Watershed Council found that water samples from the ACB exceeded the state bacteria limits over 40% of the time (Long Tom 2007). In 2012, the ACB's sampled *E*. *coli* exceeded state criteria 30% of the time (City of Eugene 2012). In contrast, the fecal bacteria concentrations in the Willamette Basin monitoring sites rarely exceed state criteria.

In 2006, a TMDL was completed for the Upper Willamette sub-basin, which includes the ACB. Waterways within the basin were listed as impaired for bacteria, dissolved oxygen, lead, arsenic, mercury, and two volatile organic compounds (OR DEQ 2006). The TMDL analysis called for a reduction of up to 84% of the Creek's fecal bacteria to meet state criteria. During the 2011-2012 monitoring period, all six ACB sub-basins monitored by the City of Eugene exceeded Oregon water quality standards for bacteria (City of Eugene 2012).

The City of Eugene is working to determine the most significant sources of fecal bacteria within the ACB. Currently, the City measures densities of fecal bacteria at 18 different creek and piped sites within the ACB (Figure 1.4). Point sources of bacteria pollution are unlikely. There are only two entities with NPDES permits for direct discharge within the ACB, and they are limited to bacteria concentrations that meet water quality criteria (Oregon DEQ 2006). The receiving water body is the Amazon diversion channel, which lies downstream of Eugene. For these reasons, current bacteria studies, including this one, are focusing on non-point sources of fecal bacteria, which are more difficult to determine. The City's stormwater plan includes the following goals, which this study addresses:

- Develop and implement appropriate strategies that will help further identify or rule out potential sources of bacteria to the stormwater system.
- Evaluate alternative investigative methods including microbial source tracking (City of Eugene 2012).

Figure 1.4. City of Eugene fecal bacteria monitoring sites within the upper Amazon Creek basin, Oregon.



Map by Scarlett Philibosian

Overview of Microbial Source Tracking

Because MST is a new science field, emerging in the early 1990's, the knowledge behind best MST methods is rapidly evolving. In addition, improved technology and comprehensive microbial "libraries" have improved accuracy and precision of these studies, especially since 2005 (Stabach 2013). There are currently 10 common methods of microbial source tracking, broadly divided into two categories: library-dependent and library-independent (EPA 2011).

Library-dependent methods compare certain traits of bacteria from water samples in question to the same traits of bacteria from known hosts, which are collectively compiled into laboratory "libraries." This method is possible because the commonly found *Escherichia coli* and *Enterococcus* spp. from different host taxa (canine, human, avian, etc.) have different "fingerprints," such as antibiotic resistance or unique markers on their DNA.

Library-independent methods rely on known traits of bacteria that identify the original host, and these methods do not require a comparison library database. For example, presence of species in the genus *Bifidobacteria* indicates a close and recent source of human fecal contamination, while presence of the bacterium *Rhodococcus coprophilus* indicates fecal contamination from pasture animals (Timm 2013*a*).

Library-dependent microbial source tracking is often more expensive and takes longer than library-independent methods (EPA 2011). Also, the database of bacterial traits for known hosts can be geographically specific to one basin, which makes library-dependent MST studies more challenging. However, library-dependent methods lead to more specific findings of probable bacteria sources, as well as relative proportions. For example, a library-dependent MST study within a watershed may find that 30% of the sampled bacteria are sourced by birds, 30% by other wildlife, 20% by humans, 10% by canines, 5% by felines, and 5% are not matched to sources. This is referred to as a “fecal bacteria portfolio,” or fecal portfolio. This is important information for planners to know when deciding which management practices are likely to be effective at reducing bacteria pollution within a watershed.

Chapter II. Methodology and Data Sources

This project addressed two specific questions related to current issues in urban water planning:

1. Can the microbial source tracking results of 25 other, nearby watersheds be used to determine the most likely significant sources of fecal bacteria pollution in Amazon Creek?
2. What are the best management practices local planners can employ to reduce the fecal bacterial loading in the Amazon Creek basin, and in other regional basins listed as impaired for bacteria?

To determine if results from an MST-studied basin could potentially inform the City of Eugene, the analysis was divided into three sections:

1. Compiling and documenting MST studies within a defined study area,
2. Conducting an initial comparison analysis, and
3. Conducting in-depth analyses for MST-studied basins that showed initial similarity to the Amazon Creek basin.

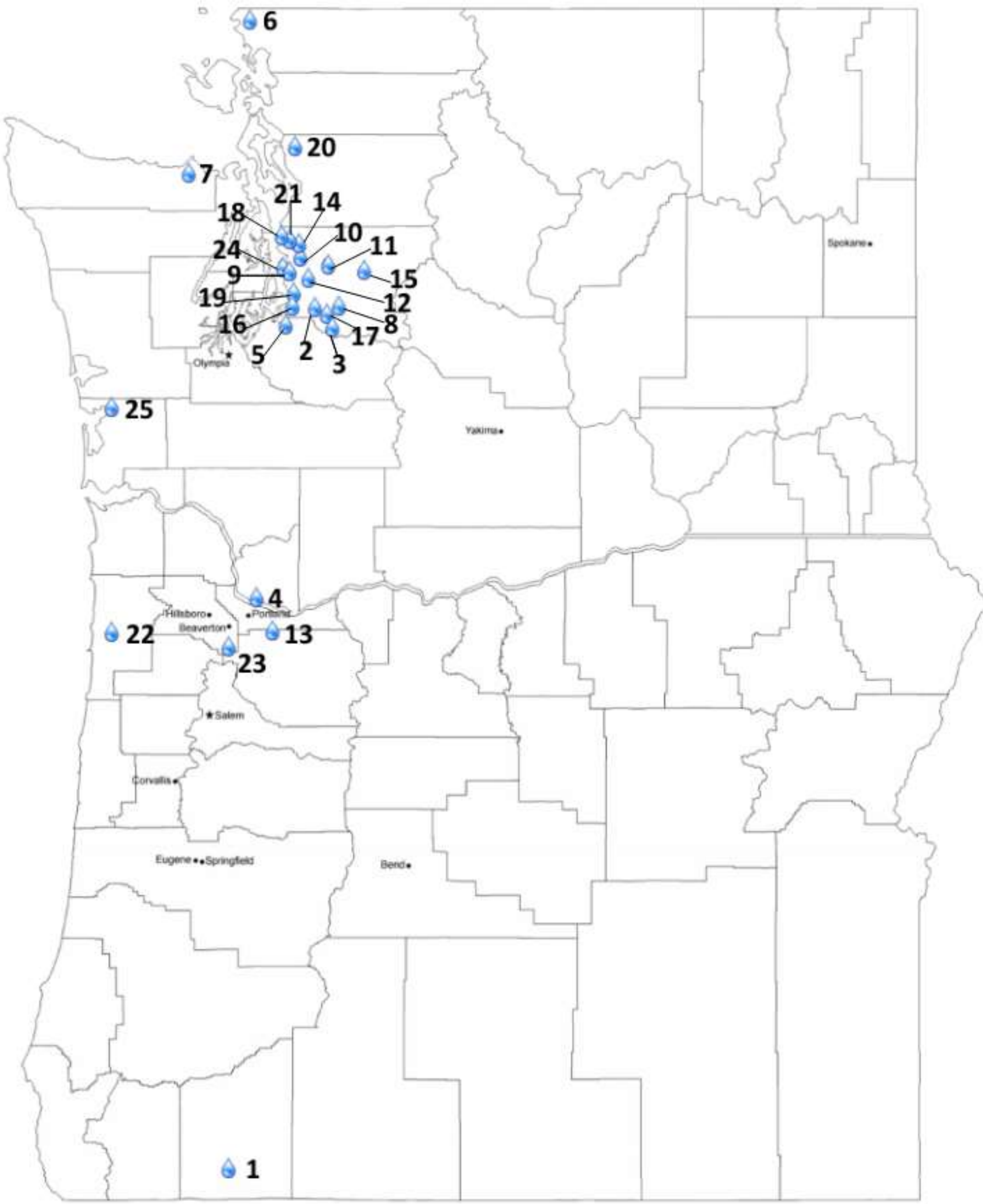
This study uses data from consultations with planners and water scientists working to reduce fecal bacteria loads in waterways. The objective is to determine which management practices would be most effective in reducing fecal bacteria levels in the ACB.

Sample pool of MST-studied communities

Region-specific characteristics such as geology, soil type and structure, and presence of burrowing animals including worms, insects, and small mammals affect the underlying hydrology of that area (Hendriks 2010). For these reasons, and in the interest of time, only American basins west of the Cascades that have been studied using MST methods were investigated as potentially comparable areas to the Amazon Creek basin.

Although MST studies occur across the U.S., there are no national or statewide databases that list communities which performed this type of study. I consulted state water quality agencies in California (Environmental Protection Agency), Oregon (Dept. of Environmental Quality), and Washington (Dept. of Ecology) about locations of MST studies. Through further discussions with water planning staff at state, regional, and community levels, I learned of 25 areas within the sample region that were studied for MST (Figure 2.1). Four of the basins are in Oregon and 21 are in Washington. By contacting planners and engineers in these different areas through the snowball method, using online document databases, and using city and county record offices, I collected documents on characteristics of each basin, the MST study description, and related documents such as TMDL programs, for each of the 25 watersheds. Although I contacted water planners in Arcata, Chico, Eureka, Redding, and at California regional water quality control boards, I was unable to find any communities west of the Cascades in California that performed MST studies.

Figure 2.1. Map of 25 MST-studied basins west of the Cascade Mountains. Numbers correspond with numbered areas in Table 3.1.



Initial comparison

There are many metrics within a basin that influence the production and transportation of fecal bacteria. I initially compared the Amazon Creek basin to each of the MST-studied basins by using the following three metrics:

1. **Percent of basin used as pasture land**. Most MST studies were able to track fecal bacteria sources only to the “ruminant” category, which could be sourced by either domestic livestock or wild animals. The ACB has no significant land parcels designated as pasture land. Therefore, it was important to eliminate MST-studied basins that had a significant (greater than 10%) portion of the land used by livestock, because ruminant-sourced bacteria in these watersheds would not necessarily be comparable to the Amazon Creek basin.

   Unless otherwise noted, pasture land percentages were calculated in ArcMap 10.1 using the USGS National Land Cover Database (NLCD) together with watershed boundary data. Either 2001 or 2006 (the year closest to the year of the MST study) data were used for each basin. Other land use percentages were calculated for some basins in Washington. To generate data in these cases, I used the Washington Dept. of Ecology’s 2010 Statewide Landuse GIS files together with watershed boundary data.

2. **Percent of basin covered by impervious surfaces**. Basins with relatively high impervious surfaces have relatively high rates and volumes of surface water runoff. This leads to relatively greater loads of pollutants, including pathogenic bacteria (Arnold and Gibbons 1996, Espy 1966, Leopold 1968). One study found that, among a host of other anthropogenic factors, the percentage of impervious land within a watershed was most strongly correlated with abundance of fecal coliforms (Mallin *et al*. 2000). MST-studied basins were eliminated from further comparison if their impervious surface coverage was more than 15 percentage points different from the ACB’s impervious surface coverage.

   Unless otherwise noted, impervious percentages were calculated in ArcMap 10.1 using USGS NLCD Percent Developed Imperviousness files together with watershed boundary data. Either 2001 or 2006 (the year closest to the year of the MST study) data were used for each basin.

3. **Type of sewage and stormwater systems in the basin**. In a combined sewer system, stormwater runoff and human effluent travel through the same system of pipes to a wastewater treatment plant. In this situation, much of the fecal bacteria from stormwater runoff will not enter waterways. The percentage of the basin served by septic systems will also influence the sources and proportions of human fecal bacteria that live in water bodies. These data were gathered through document research and through speaking with engineers and water planners in communities within the MST-studied basins. MST-studied basins were eliminated from further comparison if their waste system(s) were different from the ACB: if the basin was served by a combined sewer-stormwater system, if the basin was served by septic systems, and/or if portions of the basin retained stormwater runoff outside of flowing waterbodies or stormwater systems.

Further comparison

I further analyzed the basins that were similar to the ACB for the three initial metrics listed above. Metrics for more comprehensive similarity to the ACB were soil permeability, sewer system integrity, and data on domestic dogs, homeless populations, aquatic birds, landfills, and backyard farm animals. For each metric, data were gathered for the year closest to the date of the MST study, and for the Amazon Creek basin, the most recent data available were used.

1. **Soil permeability**. Soil permeability and size of bacterium influences bacteria dispersal into the soil layer, as well as its subsequent movement (Lindqvist and Bengtsson 1990). Sandy and loamy soils (relatively permeable to water) can slow movement of bacteria, either by mechanically trapping larger microbes, or by providing an attachment site for smaller organisms (Balkwill and Ghiorse 1985, Corapcioglu and Haridas 1984, Harvey *et al*. 1989). Relatively impermeable soils are likely to yield a high rate of surface water runoff, in which fecal bacteria on the surface are rapidly transported into water bodies.
2. **Leaks, infiltration, and inflow of sewer systems, and cross-connections between sewer and stormwater systems**. In a sewer system separate from the stormwater system but with multiple cross-connections or high levels of inflow, much of the fecal bacteria from stormwater runoff may not enter waterways (Novotny *et al*. 2010). Conversely, fecal bacteria sourced by humans can enter waterways by leaking out of sewer pipes. Changes in these metrics will change the fecal portfolio of a basin. These data were gathered through document research and through speaking with engineers and water planners in communities within the MST-studied basins.
3. **Dog influences**. Domestic dogs contribute to a waterway's fecal bacteria when owners leave dog waste to be washed into creeks or stormwater drainages. To estimate the density of domestic dogs in each basin I combined statistics from U.S. Census household data, GIS files of watershed boundaries, and American Veterinary Medical Association (2013) data on state-specific rates of dog ownership. Although dog fecal pollution can occur anywhere in a watershed, dog parks are one area where dogs are highly concentrated. For this reason, the size and proximity to flowing waterways of dog parks within each basin at the time of the MST study contributed to the estimate of canine contribution to fecal pollution.
4. **Count of unsheltered homeless.** Unsheltered homeless people and transients contribute to waterways' fecal bacteria by defecating outside of designated facilities. Population estimates and locations of these groups were estimated by contacting community organizations for the homeless and managers of vacant or park land.
5. **Density of aquatic birds**. Among bird groups, ducks, gulls, and geese are especially significant contributors to levels of *Giardia* and fecal bacteria in water, including virulent strains of *Salmonella* and *E*. *coli* (Alderisio and DeLuca 1999, Graczyk *et al*. 1998, Hudson *et al*. 2000). These disease-causing organisms enter waterways when birds defecate in the water or near its banks. I contacted local Audubon Societies and managers of park and vacant land to obtain the results from bird counts within the basins. These survey results were used to estimate densities of ducks, geese, and gulls at the time of the MST study.

In the Amazon Creek basin, none of the managing agencies perform exact and systematic bird counts on their parcels. Along three sections of the Creek, the City does perform general counts of ducks, but only ranges of birds are estimated, such as "20-50 ducks"

(City of Eugene 2013). Therefore, in October 2013, I performed one informal reconnaissance survey and one formal count survey next to waterways in the Amazon Creek basin.

During the informal reconnaissance survey, I made general notes about wildlife, buildings, parks, and the creek. On my formal count survey, I counted the total number and location of ducks, geese, and gulls observed anywhere in the air, in the creek, or along its banks as I slowly biked or walked along the Creek or around ponds. On my informal reconnaissance survey, I biked the entirety of the Fern Ridge bike path, from its intersection with Green Hill Road in west Eugene to its terminus east of the Lane Events Center; continued along the channelized portion of the creek; and continued through Amazon Park and south to the bike path's terminus at Frank Kinney Park. When on paths that did not provide a view into the creek, I walked along the creek bank. On my formal count survey, I repeated this route, except I also performed walking surveys of the Willow Creek Natural Area, Bertelsen Nature Park, Willamette Daisy Meadow, Danebo Pond, and the Amazon Creek Headwaters trail (from Frank Kinney Park to the trail's junction with Fox Hollow Road).

6. **Other influences on sources of fecal bacteria**. The number and location of landfills was analyzed as an additional possible source of fecal bacteria. I also enquired with community planners and local backyard farming organizations about the prevalence of hobby farm animals and farm animal ordinances at the time of the MST study.

Assumptions

This study assumes that point sources of fecal bacteria, such as meat-packing plants would not contribute significantly to a basin's fecal portfolio. Such industries are required to discharge waste that meet NPDES water quality standards, and/or discharge into sewer systems.

I did not collect data on domestic or feral cat densities. I analyzed the library-dependent MST results from 18 different basins, many of which are urbanized like the ACB and some of which contained many feral cats (Bailey 2013, City of Renton 2013, Halela 2013, Sorensen 2013). Of these 18 sets of results, 2.8 was the highest percentage of isolates sourced to felines, and several basins had none of the isolates matched to felines. Therefore, in comparable areas where feline contributions were measured, cats were a minor source of the fecal bacteria. It was presumed, therefore, that they would also be a minor source in the ACB, and I did not investigate this source further.

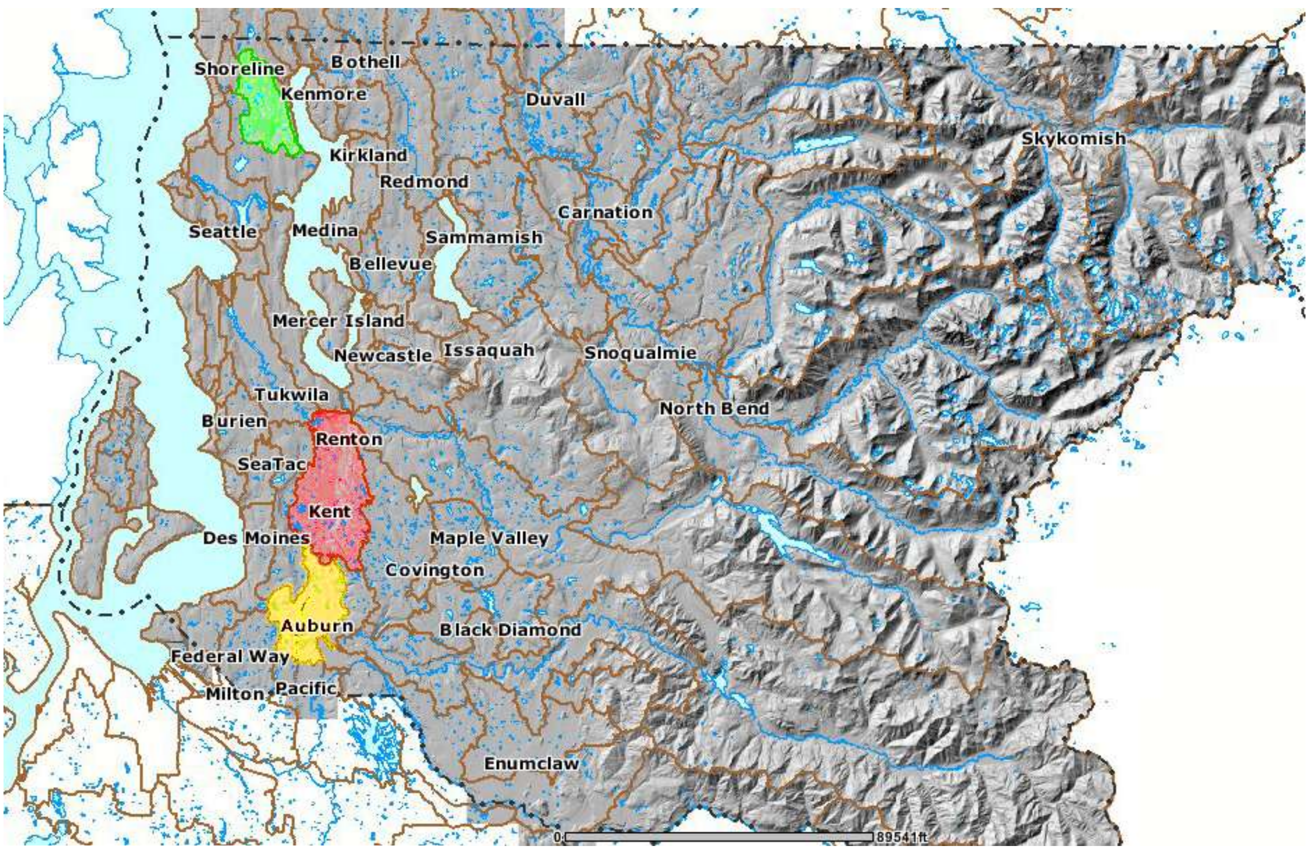
The nutria (*Myocastor coypus*) is a large, aquatic rodent that has expanded its range into the Pacific Northwest in recent decades. Its density in the different basins is unknown. However, nutria feces contain low densities of coliform bacteria relative to feces of dogs, ducks, and humans (Presnell and Miescier 1971, Wright *et al*. 2009). Therefore, unless the population of nutria is especially dense, these animals are probably not a main contributor to a basin's fecal bacteria.

Chapter III. Analyses of Comparison Basins

A description of each basin, its MST study, and data collected to determine initial similarity is provided in Appendix A. Of the 25 study areas, eight were eliminated from further analysis because the studies showed inconclusive results, or because detailed information about the study was unavailable. Pasture land use, impervious surfaces, and sewage systems in the remaining 17 basins were analyzed for initial similarity to the Amazon Creek basin. The findings are summarized in Table 3.1 on pages 18-19.

Mill Creek, Springbrook Creek, and Thornton Creek basins were similar to the ACB in terms of pasture animal land use, impervious surfaces, and type of sewer systems. Therefore, I analyzed these basins for further similarity to the upper Amazon Creek basin. Coincidentally, all three of these basins are in King County, Washington (Figure 3.2).

Figure 3.2. Study areas compared to the Amazon Creek basin:
Mill Creek basin (yellow), Springbrook Creek basin (red), and Thornton Creek basin (Green).



Source: King County Hydrographic iMap

Table 3.1. Summary of initial characteristics of MST-studied basins within the sample area[1].

Area[2]	Basin	Drainage area (sq mi)	Nearest community	Date of MST study	% Unmatched bacteria isolates[3]	% Pasture land	% Impervious surface	Sewage / stormwater system
-	Amazon Creek	25.3	Eugene, OR	N/A	N/A	0.0[4]	33.0[5]	Separate
1	Bear Creek sub-basins	Various	Ashland, OR	2004-2005	38.0	0.0	-	-
2	Big Soos basin (Big Soos Creek) [6]	65.6	Kent, WA	2003-2004	4.0	0.0	10.2	Separate, Septic
2	Big Soos basin (Little Soos Creek)	3.6	Covington, WA	1993-1995	29.0	-	-	-
3	Boise Creek	17.7	Enumclaw, WA	2011, 2012	N/A	11.7	5.1	Separate
3	Boise sub-basin (lower)	1.0	Enumclaw, WA	2011, 2012	N/A	14.0	40.4	Separate
3	Boise sub-basin (upper)	0.4	Enumclaw, WA	2011, 2012	N/A	34.8	23.7	Separate
4	Burnt Bridge Creek	28.0	Vancouver, WA	1996-1999	32-46	-	-	-
5	Clarks Creek	10.3	Puyallup, WA	2002-2003	9.0	1.1	30.5	Separate, Septic
6	Drayton Harbor (Cain Creek)	1.2	Blaine, WA	1998, 2008, 2009	N/A	7.1	30.3	Separate, Septic
6	Drayton Harbor (California and Dakota Creeks)	50.1	Blaine, WA	1998, 2006-2007, 2008	10.0	31.2	4.1	Separate
7	Dungeness River	198.5	Sequim, WA	2006-2009	11.8	3.8	1.5	Septic, separate
7	Dungeness West basin	4.7	Sequim, WA	2006-2009	11.0	9.5	9.1	Primarily septic
7	Dungeness East basin	14.2	Sequim, WA	2006-2009	4.8	9.6	17.9	Primarily septic
8	Green-Duwamish River (lower)	399.5	King County, WA	2003-2004	5.3	3.9	4.1	Separate, Septic
8	Green-Duwamish River (upper)	221.0	N/A	2003-2004	5.6	0.0	0.6	Septic
9	Hamm Creek	1.9	South Park, WA	2003-2004	9.0	0.0	38.4	Combined
10	Idylwood Creek	0.6	Redmond, WA	2011-2012	N/A	-	-	-
11	Issaquah Creek	61.0	Issaquah, WA	2011-2012	N/A	-	-	-
12	Johns Creek	1.9	Renton, WA	2005-2006	6.6	0.0	58.2	Separate
13	Johnson Creek (lower)	26.6	Milwaukie, OR	2012	N/A	17.0	15.0	Separate, Combined, and Storm retention
13	Johnson Creek (upper)	54.0	Milwaukie, OR	2012	N/A	9.4	29.6	Separate, Combined, and Storm retention
14	Juanita Creek	6.6	Kirkland, WA	2011-2012	N/A	-	-	-

Table 3.1, contd. Summary of initial characteristics of MST-studied basins within the sample area[1].

Area[2]	Basin	Drainage area (sq mi)	Nearest community	Date of MST study	% Unmatched bacteria isolates[3]	% Pasture land	% Impervious surface	Sewage / stormwater system
15	Kimball Creek	8.7	Snoqualmie, WA	2003-2004	4.8	1.1	8.8	Separate, Septic, and Storm retention
16	Mill Creek	13.1	Auburn, WA	2003-2004	0.0	0.0	37.1	Separate, Limited septic
17	Newaukum Creek[6]	27.5	Auburn, WA	2003-2004	5.2	45.2	5.0	Separate, Septic
18	Pipers Creek	2.9	Seattle, WA	1991	57.0	-	-	-
19	Springbrook Creek	23.5	Kent, WA	2003-2004	7.1	0.0	48.4	Separate
20	Stillaguamish River	702.2	Arlington, WA	Unk	N/A	-	-	-
21	Thornton Creek	11.6	Seattle, WA	2007	6.3	0.0	42.8	Separate
22	Tillamook Bay	561.5	Tillamook, OR	2001-2003	N/A	2.9	0.9	Separate
23	Tualatin River(Fanno and upper Rock Creeks)	58.0	Tualatin, OR	2004-2005	9.0	11.0	28.1	Separate, Septic
24	White Center	-	Seattle, WA	2011-2012	N/A	-	-	-
25	Willapa River (upper)	58.0	South Bend, WA	2005	2.0	5.3	0.5	Separate
25	Willapa River (middle)	251.9	South Bend, WA	2005	8.4	4.7	0.5	Separate

[1]Unless otherwise noted, land cover data were calculated in ArcMap 10.1 using the USGS National Land Cover Database (NLCD) files together with watershed boundary data. Impervious data were calculated the USGS NLCD Percent Developed Imperviousness files together with watershed boundary data. All data are from years closest to the time of the MST study.

[2] Corresponds to mapped location in Figure 2.1.

[3]Data from MST reports. See Appendix A for individual citations.

[4]Source: City of Eugene 2013.

[5]Source: City of Eugene 2002.

[6]Source: King County 2006.

Following are descriptions of fecal bacteria metrics in the ACB and in the three comparison basins. For the comparison basins, I also provide an overview of the watershed and the MST study methodology and results.

Amazon Creek

Soil permeability

The soils within the ACB are chiefly comprised of different forms of deep clays and silty loam soils (City of Eugene 2006, Long Tom 2000). Together, these traits characterize the basin as hydric (with poorly drained soils) with low permeability to water infiltration or waterborne pollutants.

Sewer Systems

The City CCTVed and smoke tested the sewer system at least as early as the 1960's (Farthing 2013). The sewer lines were smoke tested twice in the last 10 years. These methods detect cross-connections between the stormwater and sewer system, and leaks where groundwater enters the system (such as through root intrusions). Any issues such as these are reported and repaired immediately. Although sewage can also leak out of sewer lines and into soil water, this is not usually the case in Eugene. Because the pressure outside the City sewer pipes is much greater than the pressure within, any cracks found are usually areas where groundwater is flowing into the pipes. There are no septic systems or sewage treatment plants within the basin.

Dog influences

I estimated that there were 701 dogs/mi^2 in the ACB at the time of the MST study. The ACB contains three off-leash dog areas. Two parks, Little Dog Corner and Amazon Dog Park are adjacent to Amazon Creek and total 3.5 acres. A smaller off-leash area inside Wayne Morse Ranch City Park is 0.6 acres. This park is 0.9 miles away from Amazon Creek.

Count of unsheltered homeless

Figure 3.3. Transients in Eugene frequently camp next to water, such as at this two-tent campsite.

Photo by Scarlett Philibosian

The January 2013 count of homeless people in Lane County found 1,102 unsheltered homeless people (Lane County 2013). Although most of these people are within Eugene, and much of Eugene is within the Amazon Creek basin, not all of those counted live within the basin. By contacting agencies who manage open space in the Eugene area (Bureau of Land Management, City of Eugene Parks & Recreation Dept., The Nature Conservancy, and Oregon Dept. of Transportation), I determined that in recent years, at least 130 unsheltered homeless live on park or vacant land within the basin, often next to waterways (Figure 3.3). Using the higher estimates of ranges that area staff quoted, this number increases to over 300 people during the summer. This averages to between 5.5 and 12.5 unsheltered homeless people per square mile. These are likely underestimates, because not all homeless people on these lands are detected and because these calculations do not include people living in vehicles or along city streets and alleys (there were no estimates available for these groups). A more detailed description of unsheltered homeless and transients within the ACB is described in Appendix B.

Density of aquatic birds

The City of Eugene, Bureau of Land Management, Oregon Department of Transportation, and The Nature Conservancy all own park or vacant lands adjacent to Amazon Creek or its tributaries. These parcels are often, though not always, attractive to aquatic birds including ducks, geese, and gulls, which together may significantly contribute to the basin's fecal bacteria. In general, ducks and geese tend to be most dense in Bertelson Nature Park and nearby wetland areas (Baitis 2013). There are very few ducks or geese in the Willow Creek Natural Area, which The Nature Conservancy manages (Knuckles 2013). Within the natural area, the forks of Willow Creek, an Amazon tributary, are heavily vegetated, and sections of prairie often contain tall grasses; these habitats are not ideal for ducks or geese.

On both my informal reconnaissance day and my formal survey day, I observed that most of the ducks were concentrated downstream of where Chambers Street intersects the creek. This is a sampling site already downstream of the City's highest fecal bacteria counts. From my formal survey, for each square mile in the basin there was an average of 14.5 ducks, 13.9 geese, and 0.4 gulls. Notably, only two ducks and no geese or gulls were observed upstream of the creek's intersection with 29th Street, but bacteria sampled at this site already violates state bacteria criteria much of the time.

Steve Gordon, a community planner and local birdwatcher with 38 years of birdwatching experience in Eugene, and Tom Mickel, a bird counter in part of the ACB, corroborated this relative pattern of waterfowl distribution. Mr. Gordon did count many flocks of geese in the Willow Creek sub-basin, which I did not observe. This is probably because portions of this sub-basin were not yet flooded at the time of my own October count, but have at least some water in December, during the Audubon Society count. However, Willow Creek empties into the lower portion of Amazon Creek, and Mr. Gordon observes geese dispersing to farmland and fields during the day—most of this land is outside of the upper Amazon basin. Thus, large geese concentrations in this portion of the basin still do not explain the high fecal bacteria loads in the majority of the watershed.

Consistent data on birds within the ACB is not readily available but is available in the future if an agency were to retrieve it from the Lane County Audubon Society. This chapter counts and identifies all birds seen along a comprehensive system of routes in Lane County. The survey, known as the Christmas Bird Count, is performed on one day every year in late December and is conducted by teams of trained volunteer birdwatchers. The routes are the same each year and there is small variability in effort and counters from year to year. The routes comprise a circle with a 15-mile radius, with the center in West Eugene. The area surveyed includes the Amazon Creek basin, but the counts of bird species solely from within the basin are kept for only a few months after December. (The Audubon Society retains only the total counts for the entire area of the chapter's count for each bird species as permanent records.) Therefore, the data on numbers of different bird species within the basin are collected every year, but the City would need to communicate with the Audubon Society to obtain relevant records before this data is discarded.

Other influences on sources of fecal bacteria

There are no landfills within the ACB. The Eugene Backyard Farmer organization reports that chickens are the most popular backyard farm animals, followed distantly by ducks and goats (2013). They estimate that between 26,000 and 36,400 backyard chickens live in the Eugene-Springfield area. Within the ACB, chickens are especially popular in the Friendly and South Eugene neighborhoods. Most farmers use the droppings as garden fertilizer (2013) (Figure 3.4).

Figure 3.4. Many homes abut Amazon Creek. Farm animals kept in backyards can contribute to fecal bacteria within the creek.

Photo by Scarlett Philibosian

Mill Creek, Auburn, WA

Mill Creek, also known as Hill Creek, drains 13.1 mi^2 of suburban Seattle (Figure 3.2, yellow). Lake Doloff and Lake Geneva form the headwaters of the drainage (Figure 3.5). The upper sub-basin includes portions of Federal Way, Lakeland North, and Lakeland South. From there, the 8.3-mile creek flows through Peasley Canyon into Auburn, then turns north and empties into the Green River in south Kent. In 2004, the state listed the creek as impaired for temperature, dissolved oxygen, and fecal coliform. In 2003, a water quality analysis conducted on the Green River and five of its sub-basins found that the Mill Creek drainage was the most polluted for fecal bacteria. Mean fecal coliform concentrations (CFU/100 mL) were 177 during base flows and 2,200 during storm flows (King County 2006). Mean *E. coli* concentrations (CFU/100 mL) were 127 during base flows and 1,708 during storm flows. Although bacteria loads in Mill Creek have decreased overall since 1979, the drainage is still one of the most polluted for bacteria within the Green-Duwamish River watershed (King County 2009*e*).

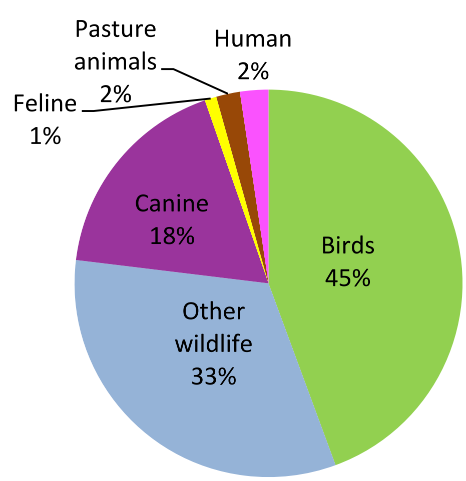
Figure 3.5. Lake Geneva, headwaters of Mill Creek.

Photo by King County, WA

Study summary

Out of concern for Mill Creek's water quality, King County hired a consulting firm to perform an MST study. Conducted between 2003 and 2004, the study used library-dependent methods to track *E. coli* isolates to known hosts (King County 2006) (Figure 3.6). Assuming that bacteria matched to "avian" sources were from wild birds, wildlife were responsible for 77.6% of all the fecal bacteria (44.9% avian and 32.7% other wildlife). Canine and feline (likely domestic pets because the basin is so developed) comprised 18.2% of the fecal bacteria sources. Humans sourced 2.4% of the isolates and pasture animals sourced 1.8%. This basin is the only one analyzed that matched all isolates to a source. In this respect, this MST study provides the most comprehensive picture of proportionate sources of fecal bacteria within a drainage.

Figure 3.6. Fecal bacteria portfolio of Mill Creek (2004).



Initial comparison

Neither the Amazon Creek nor Mill Creek basins have substantial fractions of pasture land. Impervious surfaces comprised about 37.1% of Mill Creek's watershed, a value that is higher but still similar to impervious cover in the ACB. When the study was conducted, sewer lines separate from a stormwater system serviced 82.5% of the basin, and there were a limited number of septic systems in the rest of the basin (King County 2006). Because the two basins match for initial similarity, Mill Creek was analyzed for further similarity to the ACB.

Further analyses

Soil permeability

The soils within the Mill Creek basin are chiefly comprised of eroded glacial sediments. Together, these deposits characterize the basin as poorly drained and with low permeability to water infiltration or waterborne pollutants (Water Resource Inventory 2005) (Figure 3.7).

Figure 3.7. Exposed soil along Mill Creek.

Photo by Washington State Recreation and Conservation Office.

Sewer systems

Within the Mill Creek basin, no cross-connections or major sewer leaks were detected around the time of the MST study (2003-2004) (Osborne 2013, Wharton 2013, VanDenBergh 2013). The basin is served by Soos Creek Water & Sewer District, Lakehaven Utility District, and King County Wastewater Treatment. The Soos District investigated its sewage pipes in 2003 for leaks and cross-connections, and found that the system was in generally good condition. Seattle Public Utilities, which regularly monitors its pipes, found some root intrusions. However, root intrusions usually do not result in sewage leaking out of the pipes, so it is unlikely that much bacteria entered soil water through those cracks. Overall, the sewage systems in the basin were closely monitored for leaks and stormwater connections. The only exception found was the Lakehaven Utility District, which began a comprehensive study of infiltration and inflow only in 2008, several years after the MST study. However, this district serves a small portion of the Mill Creek basin and the district also monitored its sewers for leaks around the time of the study, without detection. There are no sewage treatment plants within the drainage basin.

Dog influences

I estimated the density of dogs in the basin at 490 dogs/mi^2 at the time of the MST study. There were no dog parks within the basin.

Count of unsheltered homeless

An exact count of unsheltered homeless within the basin at the time of the MST study is not available. In 2008 (the earliest record available), 50 unsheltered homeless were counted in a portion of the City of Auburn (Seattle/King County 2008). However, data is not available on where this count took place, and it may have been outside of the basin entirely. In addition, there were probably more homeless in the area during 2008 than in 2003 or 2004, when the economy was stronger and there were fewer homeless people in general. There were no data available on unsheltered homeless within Federal Way, Lakeland North, or Lakeland South, portions of which are within the basin.

Density of aquatic birds

The Rainier Audubon Society conducts an annual bird survey, in which all birds are seen and identified along a comprehensive system of routes within different areas of King County. The survey, known as the Christmas Bird Count, is performed on one day every year in late December and conducted by teams of trained volunteer birdwatchers. The routes are the same each year and there is small variability in effort and counters from year to year. In the December 2003 count of birds in areas that coincide with Mill Creek basin, for each square mile there was an average of 30.4 ducks, 5.8 geese, and 4.3 gulls (data analyzed from Rainier Audubon Society datasets).

Other influences on sources of fecal bacteria

There are no landfills within the basin. In Auburn, at the time of the study, no urban fowl or livestock were allowed. In Federal Way, up to 20 fowl were allowed on properties larger than 20,000 ft^2. Two or fewer “large livestock” (horse, cow, sheep, pig, goat) were permitted on properties of at least 1.6 acres, with additional animals permitted larger properties. No data were available on how prevalent these animals were at the time of the MST study, but these ordinances were more restrictive than regulations in Eugene, so it is possible that farm animals were less prevalent in Mill basin than they are in the ACB.

Springbrook Creek, Kent, WA

Springbrook Creek drains 23.5 mi^2 of suburban Seattle (Figure 3.2, red, and Figure 3.8 to the right). The creek's main tributaries are Panther Creek, which drains Panther Lake in the East Hill Meridian neighborhood and Mill Creek on the north side of the Kent neighborhood (not to be confused with the different, MST-studied Mill Creek to the south). Springbrook Creek flows through the southern portion of the City of Renton before entering the lower Green River. In 2004, the state listed the creek as impaired for fecal bacteria and dissolved oxygen. A 28-year trend analysis indicated that fecal bacteria loads had decreased significantly since 1979, but the mean load was about 500 CFU/100mL, far above water quality standards, and peaked as high as 34,000 CFU/100 mL (King County 2009*g*). In contrast, the neighboring watersheds of Big Soos Creek and Newaukum Creek had higher water quality than did Springbrook Creek during the MST study.

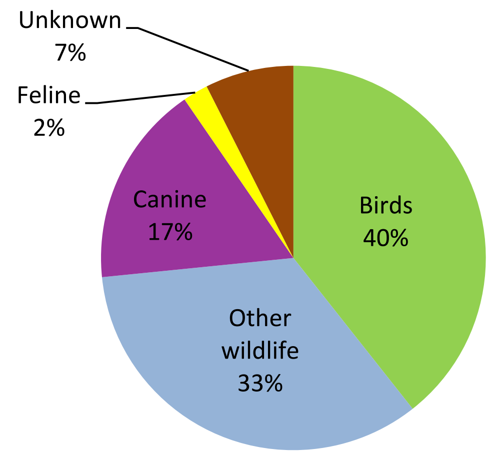
Figure 3.8. A stretch of Springbrook Creek in winter.

Photo by Washington State Dept. of Transportation

Study summary

King County hired a consulting firm to investigate the sources fecal bacteria in Springbrook Creek. The study, conducted between 2003 and 2004, used library-dependent methods to track *E. coli* isolates to known hosts (King County 2006) (Figure 3.9). Assuming that bacteria matched to "avian" sources were from wild birds, wildlife were responsible for 73.8% of all the fecal bacteria (40.4% avian and 33.4% other wildlife). Canine and feline (likely domestic pets because the basin is so developed) comprised 19.1% of the fecal bacteria sources. The final 7.1% of the isolates were not matched to a source. Notably, none of the isolates were matched to humans or pasture animals. The basin is the only one analyzed that did not find evidence of human fecal contamination.

Figure 3.9. Fecal Bacteria Portfolio of Springbrook Creek (2004).



Initial comparison

As in the Amazon Creek basin, the Springbrook Creek basin is fully sewered on a system separate from stormwater (King County 2006). Neither basin has substantial fractions of commercial pastureland. In addition, impervious surfaces comprise 48.4% of Springbrook's watershed, a value that is more than but still similar to impervious cover in the ACB. Therefore, this basin was analyzed for further similarity to the ACB.

Further analyses

Soil permeability

Soil permeability varies somewhat within the Springbrook Creek basin. About half of the basin is comprised of moderately well drained topsoil, with relatively impermeable glacial deposits at a lower depth, starting between 20 and 40 inches beneath the soil surface (U.S. Dept. Ag. 1972). Soils in the other half of the basin are either poorly drained or very poorly drained.

Sewer Systems

Although data was not available for all portions of the basin, the sewer system in much of the area has been in good condition for a relatively long period of time (Christensen 2013). Data were not available for the East Hill Meridian neighborhood, but this makes up a small portion of the basin. When the study was conducted (2003-2004), city departments were already performing regular checks for inflow and infiltration. There were no records of cross connections between sewer and storm systems or significant leaks of sewage (Gilbertson 2013). There are no sewage treatment plants within the drainage basin.

Dog influences

There were 761 dogs/mi^2 estimated at the time of the MST study. There were no dog parks within the basin.

Count of unsheltered homeless

An exact count of unsheltered homeless within the basin at the time of the MST study is not available, but was probably fairly low. In the Renton and Kent portions of the basin, homeless populations were likely insignificant, because most of that area is industrial and lacks services and amenities typically sought by the homeless (Gilbertson 2013). Counts of unsheltered homeless in portions of the City of Kent (from 2002) and the City of Renton (from 2008) total 138 (Seattle/King County 2003, 2008). However, only parts of the cities were counted, and data is not available on where these areas were. Therefore, these areas may have been outside of the basin, a likely scenario if only areas known for a homeless presence were counted. In addition, there were probably more homeless in the area during 2008 (the earliest record available) than in 2003 or 2004, when the economy was stronger and there were fewer homeless people in general.

Density of aquatic birds

Figure 3.10. Waterfowl such as these Canada Geese next to the creek are likely sources of some of Springbrook's fecal bacteria.

Photo by Washington State Dept. of Transportation

The Rainier Audubon Society conducts an annual bird survey, in which all birds along a comprehensive system of routes within different areas of King County are identified and counted (Figure 3.10). The survey, known as the Christmas Bird Count, is performed on one day every year in late December and conducted by teams of trained volunteer birdwatchers. The routes are the same each year and there is small variability in effort and counters from year to year. In the December 2003 count of birds in areas that coincide with the Springbrook Creek basin, for each square mile there was an average of 33.8 ducks, 16.3 geese, and 6.9 gulls (data analyzed from Rainier Audubon Society datasets).

Other influences on sources of fecal bacteria

There are no landfills in the basin. In the Renton and Kent portions of the watershed, hobby farm animals are not commonly kept as pets (Gilbertson 2013). In the remaining portion of the basin (East Hill Meridian and Cascade Fairwood neighborhoods), urban livestock regulations are fairly lenient, but the portion of the basin within these areas is small.

Thornton Creek, Seattle, WA

The Thornton Creek basin drains 11.6 mi^2 of the cities of Seattle and Shoreline (Figure 3.2, green and Figure 3.11 to the right). The basin's chief waterways are the north and south forks of Thornton Creek, along with the mainstem. The headwaters lie near North Seattle Community College and Shoreline's Ronald Bog Pond. The forks and their tributaries flow past several ponds, joining to form the Thornton Creek mainstem near Meadowbrook Pond. From there, Thornton Creek continues to its terminus at Matthews Beach Park, where the creek empties into Lake Washington.

Figure 3.11. A section of ponded water along Thornton Creek.

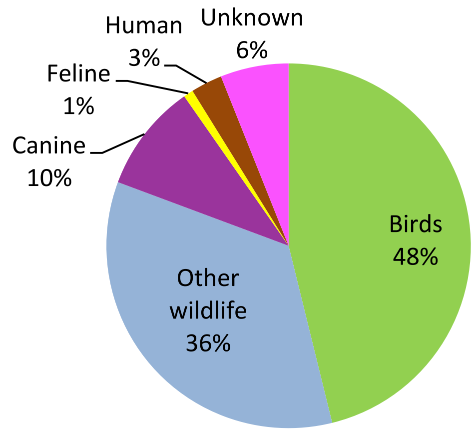
Photo by SvR Design Company

Since 1996, the state has listed Thornton Creek as impaired for fecal bacteria and in 2004, the state also listed the creek as impaired for temperature and dissolved oxygen. Historically, the creek supported several native salmonids, but most of the species have severely declined (City of Seattle 2000). Water samples collected during base flows between 1990 and 2001 showed mean values of 827 CFU/100 mL (state criterion is fewer than 50 CFU/100 mL) and a maximum concentration of 31,000 CFU/100 mL (Seattle Public Utilities 2007). During times of especially high bacteria concentrations, the city closes Matthews Beach to swimming. Due to concerns about bacteria loads and its impact on the watershed, King County and the City of Seattle funded three MST studies in the basin.

Study summary

The first two MST studies used library-dependent methods to match *E. coli* isolates to known hosts. The first study, funded by the county in 2001, was designed to determine if human sewage was a significant source of the fecal bacteria. The study found that only 4% of the isolates were from humans, with wildlife contributing 73%, pets 11%, and 12% of the samples having unknown hosts (King County 2001*a*). Seattle funded a subsequent MST study of the basin in 2007, which found similar proportions (Seattle Public Utilities 2007) (Figure 3.12). Assuming that bacteria matched to "avian" sources were from wild birds, wildlife were responsible for 83.9% of all the fecal bacteria (48.0% avian and 35.9% other wildlife). Canines (probably domestic dogs) sourced 10.0% of the bacteria; felines (probably domestic cats) sourced 0.9%; humans sourced 2.9%;

Figure 3.12. Fecal Bacteria Portfolio of Thornton Creek (2007).



and 6.3% could not be matched to sources. None of the isolates were matched to pasture animals.

The final study, conducted five years later in 2012, used library-independent methods to determine if humans were a significant source of fecal bacteria in the watershed. Presence of the species *Bacteroides thetaiotaomicron* was interpreted as evidence of a recent human source. Results indicated that human fecal bacteria from multiple sources in the basin are in fact entering the waterways at a cumulatively significant level. This change could be explained by 1) a changing dynamic in homeless populations or sewer leaks over the last several years; 2) incorrectly identified *E. coli* isolates in the 2007 study; or 3) incorrectly using *B. thetaiotaomicron* as an indicator of human sources.

Initial comparison

As in the Amazon Creek basin, the Thornton Creek basin is fully sewered, on a system separate from stormwater. There are no septic systems in the basin. Neither basin has commercial pasture land. In addition, impervious surfaces comprise 42.8% of Thornton's watershed, a value that is more than but still similar to impervious cover in the ACB. Therefore, this basin was analyzed for further similarity to the ACB.

Further analyses

Soil permeability

Almost all of the soils in the basin are Alderwood gravelly sandy loam. This soil is characterized as poorly-drained and is often associated with relatively high rates of water runoff during heavy rains (City of Shoreline 2004).

Sewer Systems

The sewer system was in generally good condition at the time of the study. Seattle Public Utilities, which regularly monitors main trunks in the sewer system, found some root intrusions. However, root intrusions usually do not result in sewage leaking out of the pipes, so it is unlikely that much bacteria entered soil water through those cracks (Wharton 2013). Leaks are repaired immediately and illegal connections are removed within four weeks of detection. In 2010, Seattle Public Utilities screened all discharge points from the City's stormwater system into Thornton Creek (Frodge 2013). From this effort, two residential illicit connections were detected and eliminated. There are no sewage treatment plants within the drainage basin.

Dog influences

I estimated that there were 1,951 dogs/mi^2 at the time of the MST study. The basin had one dog park, the 0.7 acres Northacres off-leash area. There is no direct watercourse between the park and Thornton Creek, about 0.4 miles away.

Count of unsheltered homeless

Within the basin, transients camp in tents and along greenbelts (Frodge 2013). An exact count of unsheltered homeless within the basin at the time of the MST study is not available, but may be denser than the homeless population within the Amazon Creek basin. Much of the city of Seattle is counted every year for unsheltered homeless. In 2007, the year the MST study was conducted, there were at least 1,589 unsheltered homeless within the City (Seattle/King County 2007). However, data were not available on unsheltered homeless solely within the basin. Assuming that the 2007 count represented the entire city, and that the people were evenly distributed, there were about 18.9 unsheltered homeless per square mile. The actual density comparable to the ACB would be higher, because not all parts of the City were counted in January, and the homeless population greatly increases during the summer. However, the density of unsheltered homeless within the ACB during the summer is estimated at only between 5.5 and 12.5 people per square mile.

Density of aquatic birds

Because the local Audubon Society counts birds only in the far southern portion of the watershed, and because the City has not collected this data itself, data on populations of aquatic birds within the drainage were not available.

Other influences on sources of fecal bacteria

The basin did have one landfill, Corliss, but it closed in the mid-1960s and its waste was excavated in 2007. In addition, the County closely monitors nearby ground and surface water for contamination from landfills, and determined that the site is not polluting (King County 2001*b*).

At the time of the MST study, ordinances limited households to no more than three small animals (dogs, cats, goats), one pig, and three fowl per property up to 10,000 ft^2. Additional small animals were allowed on larger properties, and large farm animals were allowed in properties at least 20,000 ft^2 (about half an acre). Backyard chicken farms became very popular in the Seattle area around 2005, and residential areas with large lots such as in the northern portion of the basin are especially likely to maintain chickens (McCrate 2013). Today, there are several thousand backyard chicken farmers in the City, and flocks are usually between 3 and 7 birds (the limit of three birds increased to eight birds in 2010). In the city as a whole, goats and pigs were very rare, and are still uncommon today.

Chapter IV. Conclusions and Recommendations

Several of the metrics influencing bacterial sources are shared between the Amazon Creek basin and each of the three comparison basins. These basins were similar in terms of percent impervious area, proportion of pasture land, type of sewage systems, amount of sewer pipe leakage, and bacterial contribution from landfills and wastewater treatment plants (Table 4.1). Soil permeability and presence of cross-connections was also generally similar, although half of Springbrook basin is better-drained than is the ACB, and Thornton basin may have had more illegal connections. However, for each of the three comparison basins, several metrics did not align with the ACB.

Table 4.1. Outcome of metrics in comparison to the Amazon Creek basin.

			Comparison Basin	
Comparison Metric	**Amazon**	**Mill**	**Springbrook**	**Thornton**
Impervious area (%)	33.0	37.1	48.4	42.8
Soil permeability	Poorly drained	Poorly drained	Moderate to poorly drained	Poorly drained
Proportion of pasture land	0.0	0.0	0.0	0.0
Sewage system	Separate	Separate, limited septic	Separate	Separate
Sewer leaks	None detected	None detected	None detected	None detected
Sewer-Stormwater cross connections	None detected	None detected	None detected	Some detected
Wastewater treatment plant	No	No	No	No
Dog parks (acres)	4.1	0.0	0.0	0.7
Domestic dog density (dogs/mi2)	701	490	761	1,951
Estimate Ducks/ mi2	14.5	30.4	33.8	Unknown
Estimate Geese/ mi2	13.9	5.8	16.3	Unknown
Estimate Gulls/ mi2	0.4	4.3	6.9	Unknown
Landfills	No	No	No	Yes, but non-polluting

Mill Creek
Around the time of the study, Mill Creek basin had no land dedicated for pasture animals; impervious surfaces covered 37.1% of the watershed; the basin was served by a separate sewer system and a few of septic systems; there were no cross-connections or major sewer leaks detected; soils are poorly drained with low permeability; and there were no sewage treatment plants or landfills. All of these metrics are similar to the ACB's metrics.

However, in Mill Creek basin, there were no dog parks, and dog density in the ACB is 143% of dog density in Mill Creek at the time of the study. The density of homeless people was unknown. Backyard farm animals were probably less prevalent in Mill basin than they are in the ACB, because ordinances were more restrictive than Eugene's ordinances, and in a significant portion of the basin no urban fowl or livestock were allowed. Wild ducks were about twice as dense in Mill as in the ACB (30.4 vs. 14.5 per mi^2), and geese were about half as dense (5.8 vs. 13.9 per mi^2). Gulls were much more prevalent in Mill basin than in the ACB (4.3 vs. 0.4 per mi^2), probably a factor of Mill Creek's proximity to the coastline.

Springbrook Creek
Around the time of the study, Springbrook Creek basin had no land dedicated for pasture animals; impervious surfaces covered 48.4% of the watershed; the basin was served by a separate sewer system; there were no cross-connections or major sewer leaks detected; there were no sewage treatment plants or landfills; there was an average of 761 dogs/mi^2 and 16.3 geese/mi^2. All of these metrics are similar to the ACB's metrics.

However, in Springbrook basin, soil permeability is variable, with about half the basin moderately well-drained and the other half poorly drained. At the time of the study, there were no dog parks. The density of homeless people was probably insignificant, because much of the area is industrial and lacks services and amenities typically sought by the homeless. Residents in the area do not commonly keep backyard farm animals. Lastly, wild duck density was 233% of the ACB's density (33.8 vs. 14.5 per mi^2). Gulls were much more prevalent in Springbrook Creek than in the ACB (6.9 vs. 0.4 per mi^2), probably a factor of the Creek's proximity to the coastline.

Thornton Creek
Around the time of the study, Thornton Creek basin had no land dedicated for pasture animals; impervious surfaces covered 42.8% of the watershed; the basin was served by a separate sewer system; no major sewer leaks were detected; there were no sewage treatment plants; soils are poorly drained with low permeability; backyard chickens were popular and prevalent, with an average flock size around five birds; backyard goats and pigs were rare; and the one landfill in the basin closed in the 1960's and was determined to be non-polluting. The impacts on fecal bacteria from all of these metrics are similar to impacts from the ACB's metrics.

However, Thornton basin probably had more illegal connections between stormwater and sewer systems than does the ACB. There was only one, small (0.7 acres) dog park at the time of the study, and the park was removed from the creek. Because Thornton basin has a greater density of people, dog density was much higher (278% that of the ACB's dog density)—1,951 dogs/mi^2 vs 701 dogs/mi^2. The density of homeless people was unknown, but may be denser than the homeless population within the ACB. Wild bird density in this basin is unknown.

Conclusion

Among dog parks, dog densities, homeless counts, aquatic bird densities, and prevalence of farm animals, the only matching metrics were dog and geese concentrations in Springbrook basin, and prevalence of backyard farm animals in Thornton basin (Table 4.2). From these findings, I conclude that the results from MST studies within this region cannot be descriptive of likely proportions of fecal bacteria in the Amazon Creek basin. Based on management patterns that emerged during my interviews with water planners, I outline in the following two sections recommendations for the City of Eugene and best management recommendations for any community with bacteria-impaired waters.

Table 4.2. Summary of similarity in comparison to the Amazon Creek basin:
Y (similar); N (not similar); S (somewhat similar); U (unknown similarity).

	Comparison Basin		
Comparison Metric	**Mill**	**Springbrook**	**Thornton**
Impervious area	Y	Y	Y
Soil permeability	Y	S	Y
Proportion of pasture land	Y	Y	Y
Sewage system	Y	Y	Y
Sewer leaks	Y	Y	Y
Sewer-Stormwater cross connections	Y	Y	N (more)
Wastewater treatment plant	Y	Y	Y
Dog parks	N (less)	N (less)	N (less)
Domestic dog density	N (less)	Y	N (more)
Unsheltered homeless	U	N (less)	N (more)
Estimate Ducks/ mi2	N (more)	N (more)	U
Estimate Geese/ mi2	N (less)	Y	U
Estimate Gulls/ mi2	N (more)	N (more)	U
Landfills	Y	Y	Y
Domestic farm animals	N (less)	N (less)	Y

Recommendations for the City of Eugene

1. **Conduct an MST study**. At this point in time, a library-dependent MST study is the most cost-effective, efficient, and accurate determination of main sources of fecal bacteria in Amazon Creek. Because Eugene has multiple characteristics related to fecal bacteria that are unique relative to MST-studied basins in the region, likely sources of bacteria are still unknown. Although money for an MST study could be spent instead on implementing management practices, it is entirely unknown which management practices would be effective (and therefore "best" management practices), because the main source or sources of bacteria are still unknown. If the City implemented a suite of management practices that targeted each potential source of fecal bacteria, they will introduce multiple experimental variables at once, and if fecal bacteria levels subsequently decrease it will not be clear which practices were most effective. This scenario wastes resources, as opposed to performing an MST study and spending subsequent funds targeting only the one or two main sources.

In addition, implementing a suite of management practices instead of an MST study may include controversial policies that could be avoided altogether if the City first performs a study. Conversely, the City and its residents stand to gain considerable benefits from using the results of an MST study. This study will indicate the most significant sources of fecal bacteria at different sites, which the City can then use to validate future policy actions and focus management on the most problematic species. This reduces long-term costs of bacteria management. In the event that the City attempts to implement potentially controversial solutions, such as reducing domestic chicken ordinances, fining people who feed waterfowl, or prohibiting camping away from public facilities, it is essential to have a study showing that the targeted source is contributing a large portion of the fecal bacteria in the creek.

There are two important caveats to this recommendation. First, laboratory analyses should differentiate between chickens and wild birds. Both types are prevalent in Eugene and subsequent management practices should target the group of birds that is a significant contributor. Second, the City should initiate an MST study only if monies are secured that will quantitatively evaluate the effectiveness of subsequent management practices.

2. **Investigate the fecal bacteria contribution from transients and unsheltered homeless by collecting water quality data upstream and downstream of camps during the summer and winter**. Unlike the Amazon Creek Basin, few basins within my study area have a sizeable population of people who were homeless. The ones that do have a sizeable population (Dungeness Bay, Johnson Creek, Thornton Creek, and Tillamook Bay) did not devise their MST studies to examine a possible correlation between homeless camps and fecal bacteria levels. Therefore, the relative effect of Eugene's unsheltered homeless population on fecal bacteria remains unknown. However, the information I gathered on prevalence and location of transients and unsheltered homeless by contacting agencies who manage open space in the Eugene area (Bureau of Land Management, City of Eugene Parks & Recreation Dept., The Nature Conservancy, and Oregon Dept. of Transportation) suggests that these groups may be a significant source of fecal bacteria (see Appendix B).

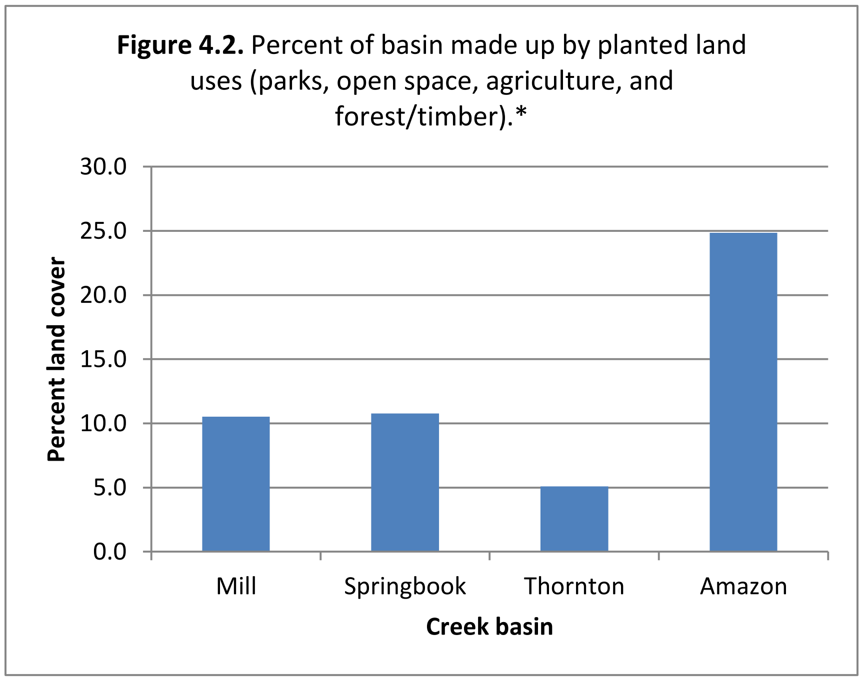
The City will be better able to implement management practices once it knows whether or not illegal camps are affecting local water quality, and if so, during which seasons. The City should also test for leaks in the lateral sewer lines of residences nearby the homeless camps, to distinguish between sewage from leaking pipes and from camp effluent.

3. **In conjunction with continued bacteria sampling, more closely monitor densities of wild birds within all portions the creek and nearby wetlands**, to better determine whether or not aquatic birds are main contributors. In all three comparison basins, birds contributed a significant proportion of the fecal bacteria. However, I did not find evidence that the same is necessarily true for the ACB.

First, birds tend to make up a smaller proportion of the fecal bacteria portfolio in basins with more planted space. This is probably because plants compete with bacteria for nutrients, and because an increase in vegetation increases the take-up of runoff. The ACB has substantially more planted space than do the other three basins (Figure 4.1, Figure 4.2).

Figure 4.1. Some portions of Amazon Creek are heavily vegetated.

Photo by Scarlett Philibosian



*Raw data from City of Eugene (2013) and Washington State Landuse (2010) GIS files.

Second, in my formal count, I observed that the largest populations of ducks and geese usually congregate downstream of the channelized portion of the Creek. Steve Gordon, a community planner and local birdwatcher with 38 years of birdwatching experience in Eugene, and Tom Mickel, a CBC counter in the ACB, corroborated this relative pattern of waterfowl distribution. However, fecal bacteria levels are also high upstream of this location (City of Eugene 2012). In fact, bacteria loads tend to decrease as water moves towards the diversion channel. Further, at the mouth of the sub-basin where ducks and geese are often dense (Baitis 2013), *E. coli* densities in recent years were lower than any of the further upstream monitoring sites (City of Eugene 2012). If the City can corroborate these findings with bacteria loads, they may be able to rule on aquatic birds as a significant bacteria source.

4. **To determine policy efficacy, implement discrete management practices and collect fecal coliform and *E. coli* densities before and after implementation**. For relevant statistics, both a baseline and subsequent bacteria levels must be gathered for at least from several years in order to have averages that will even out the variability between years. In most cases the baseline data exists, because it was used to classify the water as "impaired by bacteria." In addition, metrics of potential sources, such as waterfowl densities and homeless counts should also be collected before and after the City implements a practice. Finally, it is important to gather replicate water samples within the same season or during similar flow rates for each year of study, to decrease variability from bacteria-flushing events. The best comparative data would come from the beginning of seasons with most of the flushing. This strategy would quantitatively determine which management practices are most effective at reducing bacterial loads.

Following are potential best management practices for reducing fecal bacteria:

For all sources:

- Re-vegetate stream banks with native grasses, which generally have longer roots than nonnative grasses and are most capable of trapping pollutants.

For human sources:

- Provide incentives for homeowners to test their lateral sewage lines (such as property tax rebates).
- Charge property owners a yearly fee that can be waived by showing proof of a recent lateral line leak test.
- Adopt leak testing of lateral lines as City responsibility.
- Regularly fine or evict homeless people who camp within a certain distance of public waterbodies.
- Install more latrines near popular camping areas and in exchange for allowing people to camp in that area, require that campers regularly maintain the latrines.
- Partner with local industrial businesses to hire homeless people with RVs or a tent that can patrol the private property at night, in return for a place to sleep and a latrine.

For wildlife sources:

- Re-vegetate stream banks and land abutting stream banks in popular wildlife-feeding areas with dense shrubs and tall grasses. Waterfowl avoid this type of habitat.
- Periodically employ trained dogs to discourage birds from using certain areas within the basin.
- Remove benches from popular wildlife-feeding areas.
- Regularly fine residents who feed wildlife.

For domestic dog sources:

- Regularly fine residents who leave dog feces on the ground.
- Re-locate dog parks to sites that are distant from flowing water.

For backyard farm animal sources:

- Reduce the number of allowed backyard farm animals.
- Provide a collection service for backyard farm animal feces.

5. Whichever strategy the City adopts, adhering to the following four guidelines will aid in the effort to bring the Upper Amazon Creek basin into compliance with Oregon water quality standards:

- Implement practices that target the most significant sources of fecal bacteria.
- Evaluate each management practice discretely (one practice at a time in one area) and quantitatively.
- Discontinue practices targeting groups that are unlikely to be significant sources.
- Discontinue practices that do not significantly lower fecal bacteria loads within the experimental area.

Recommendations for all communities with bacteria-impaired waters

Based on discussions with over 100 community planners, engineers, water quality specialists, and other professionals across the Pacific Northwest, I developed four main recommendations for communities trying to improve the quality of bacteria-polluted waters. Following these recommendations will:

- Help ensure that communities promote and continue practices shown to be effective at reducing fecal bacteria loads.
- Result in fewer resources spent on practices that do not significantly improve water quality.
- Hasten the larger water planning community's ability to effectively lower fecal bacteria levels and decrease the incidence of associated diseases.

1. **Before devising and implementing an MST study, investigate if the MST results in other, hydrologically-similar basins can be used to inform your community about likely significant sources.** The comparison methodology used in this report for the ACB is applicable to any community faced with the challenge of determining likely causes of fecal bacteria pollution. However, certain assumptions need to be made, for example, that meat-packing plants were complying with waste disposal regulations at the time of the comparison studies. In addition, a community is most likely to find a studied watershed similar to its own if the larger region contains many different basins that have been studied with MST and if comprehensive data related to sources of fecal bacteria were also collected. If two or more communities are impaired for fecal bacteria, and comparing metrics shows that the basins are similar, the communities can potentially share the cost of a microbial source tracking study in just one basin, and can also experiment with the efficacy of different BMPs.

2. **If comparison analyses do not elucidate likely sources of fecal bacteria, evaluate availability of resources for both the MST study *and* study of subsequent BMPs.** Communities should perform MST studies only if resources are set aside for monitoring the effectiveness of subsequent management practices. The results of MST studies are likely to change as factors influencing bacterial sources also change. Therefore, MST studies will be most useful when communities are ready to target the main source of fecal bacteria at that time *and* also monitor the efficacy of newly implemented practices. These resources must be available and planners must be committed to following best management practices with monitoring and evaluation. Otherwise, performing an MST study will generate results that are interesting but ultimately separate from the solutions to lower bacteria loads. This latter scenario wastes resources.

3. **Once main sources of bacteria are known, use resources to target the most significant sources of fecal bacteria.** I analyzed 18 basin and sub-basin MST studies that used library dependent methods (i.e., arrived at a fecal bacteria portfolio for the drainage). With the exception of the Willapa River sub-basins (where livestock commonly grazed in close proximity to waterways), wildlife were the source of the majority of the fecal isolates in each study. However, many of the MST-studied communities focus on retrofitting septic systems, converting households on septic to a sewer system, and fencing livestock back from waterways. Practices targeting these sources may not be effective in reducing fecal loads because these sources usually accounted for a small proportion of the total fecal bacteria.

4. **Experiment with new management practices, carefully monitoring any change in fecal bacteria loads.** Several of the MST reports for the basins I analyzed issued management recommendations based on the results of the study, specifically targeting pets or wildlife as sources of bacteria. Usually, communities either did not adopt these recommendations or implemented new practices but did not quantify the effectiveness. Many parks in the MST-studied basins I analyzed currently have signage or brochures about proper pet waste disposal or the problems caused by feeding birds next to waterways, but the efficacy of the programs was rarely studied. Other communities simultaneously implemented a suite of different strategies and subsequently observed higher water quality. However, these communities cannot identify which practice or practices were most powerful. It is imperative that communities try new, potential solutions and monitor and report on the effectiveness of each strategy:

- Establish a baseline of fecal bacteria density (general water quality sampling) or a fecal bacteria portfolio (library-dependent MST study) during base flow and storm flow in wet and dry seasons.
- Monitor the fecal bacteria levels or portfolio after the practice is implemented for at least three years. This includes monitoring other, non-targeted sources of fecal bacteria in the study drainage during the experimental period, such as duck migrations coinciding with active removal of itinerant camps.
- Quantitatively determine whether these practices successfully reduced bacteria loads. One community in the region has an extensive pet waste pickup campaign, aired videos on the city's TV station and local movie theatre, installed pet waste signs in most city parks, and sent an educational brochure about pet waste to all City residents. However,

the community has not documented or quantified how these programs reduce pet waste. This practice was fairly common among my study basins. From these findings, I conclude that one of the best management practices is to ensure that a practice is truly effective.

- Eliminate funding for practices that are ineffective at reducing levels of fecal bacteria. For example, one group of ducks and geese lives at the beginning of the canal in Eugene's Alton Baker Park, adjacent to the Willamette River. Around 2009, the City of Eugene installed signs at this location, showing that feeding waterfowl causes angel wing. Angel wing is an incurable disease that results in twisted wing joints. Several of the flock still had angel wing in August 2013, and a large group of birds clustered around the educational sign, waiting to be fed (Figure 4.3). This illustrates how funds for ineffective practices can be better spent implementing and evaluating new management ideas.

Figure 4.3. Ducks waiting to be fed at an established educational sign that details the ills of this activity.

Photo by Scarlett Philibosian

- Record the specific management practices that are implemented and publicize the results on community websites and at planning conferences. This informs residents about the importance of water quality and actions the community is taking, and also helps other planners implement effective water quality programs in their communities.

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Works Cited

Alderisio, K.A. and N. DeLuca. 1999. Seasonal Enumeration of Fecal Coliform Bacteria from the Feces of Ring-Billed Gulls (*Larus delawarensis*) and Canada Geese (*Branta canadensis*). *Applied Environmental Microbiology* 65(12): 5628-5630.

American Veterinary Medical Association. 2012. *U.S. Pet Ownership & Demographics Sourcebook*. Schaumburg: American Veterinary Medical Assoc.

Arnold, C.L., Jr. and C.J. Gibbons. 1996. Impervious Surface Coverage: the Emergence of a Key Environmental Indicator. *Journal of the American Planning Association* 62(2):243-258.

Bailey, Pamela. 2013. Feral Cat Assistance and Trapping. King County, WA. Pers. comm.

Baitis, Karin. 2013. Soil scientist, Bureau of Land Management. Eugene, OR. Pers. comm.

Balkwill, D.L. and W.C. Ghiorse. 1985. Characterization of Subsurface Bacteria Associated with Two Shallow Aquifers in Oklahoma. *Applied Environmental Microbiology* 50: 580-588.

Bellack, N.R., M.W. Koehoorn, Y.C MacNab, and M.G. Morshed. 2006. A Conceptual Model of Water's Role as a Reservoir in Helicobacter pylori Transmission: a Review of the Evidence. *Epidemeology and Infection* 134(3): 439-449.

Bouchard, Debra. 2012. "Microbial Source Tracking Pilot Projects ~ 2011-12." Kirkland, WA. Powerpoint presentation.

Brastad, Andy. 2013. Director, Clallam County Dept. of Health and Human Services. Forks, WA. Pers. comm.

Burr, Rachel. 2013. Environmental Regulations Coordinator, Parks and Open Space Division, Public Works Dept., City of Eugene, OR. Pers. comm.

Burres, Erick. 2009. "Surface Water Ambient Monitoring Program: Using IDEXX for Fecal Indicator Bacteria Monitoring." California State Water Resources Control Board.

Christensen, Dave. 2013. Wastewater Utility Supervisor, City of Renton, WA. Pers. comm.

City of Eugene. 2002. "Stormwater Basin Master Plan: Amazon Basin Volume II of VII." Prep. by City of Eugene, URS Corporation, and Lane Council of Governments. Eugene, OR.

City of Eugene. 2006. "Amazon Creek Priority Planning Corridor: Waterway Assessments—Amazon Creek Priority Planning Area." Eugene, OR.

City of Eugene. 2012. "Stormwater Annual Report for the City of Eugene, Oregon." Eugene, OR.

City of Eugene. 2013. Bird count data acquired from Tom Mendes, Environmental Data Analyst.

City of Kirkland. 2013. “Juanita Creek Watershed.” <http://www.kirklandwa.gov/depart/Public_Works/Storm___Surface_Water/About_Surface_Water/Juanita_Creek_Watershed.htm>. Accessed 28 Aug 2013. Kirkland, WA.

City of Portland. 2005. “Johnson Creek Watershed Characterization.” Bureau of Environmental Services. Portland, OR.

City of Puyallup, Engineering Dept. 2005. “Clarks Creek Watershed Pollution Reduction Project: Draft Report.” Prep. by URS Group, Inc. and Brown & Caldwell. Puyallup, WA.

City of Renton. 2006. “Monitoring Report: Gene Coulon Park Microbial Source Tracking Study.” Prep. by Herrera Environmental Consultants. Seattle, WA.

City of Renton. 2013. Police Dept., Animal Control Division, City of Renton, WA. Pers. comm.

City of Seattle, Engineering Dept. 1993. “Pipers Creek Bacteriological Source Tracking Investigation.” Prep. by Herrera Environmental Consultants. Seattle, WA.

City of Seattle. 2000. “Thornton Creek Watershed Characterization Report.” Prep. by the Thornton Creek Watershed Management Committee and Seattle Public Utilities. Seattle, WA.

City of Shoreline. 2004. “Thornton Creek and West Lake Washington Basins Characterization Report.” Prep. by Tetra Tech/KCM, Inc. Seattle, WA.

City of Snoqualmie. 2004. “Kimball Creek Water Quality Monitoring and Microbial Source Tracking Study.” Prep. by Herrera Environmental Consultants, Inc. Seattle, WA.

City of Vancouver, Public Works Dept. 1999. “Burnt Bridge Creek Microbial Source Tracking: Identification of Sources of Microbial Pollution in Burnt Bridge Creek Watershed.” Prep. by Mansour Samadpour (University of Washington), Carl Addy (Southwest Washington Health District), and Thomas Newman (Newman Environmental Services, Inc.). Vancouver, WA.

Clean Water Services. 2005. “DNA Fingerprinting of Bacteria Sources in the Tualatin Sub-basin.” Hillsboro, OR.

Corapcioglu, M.Y. and A. Haridas. 1984. Transport and Fate of Microorganisms in Porous Media: a Theoretical Investigation. *Journal of Hydrology* 72: 149-169.

Cosmopolitan Engineering Group and Pacific County Dept. of Community Development. 2005. “Monitoring Report: Upper Willapa River Microbial Source Tracking Study.” Prep. by Herrera Environmental Consultants, Inc. Seattle, WA.

Donovan, E., K. Unice, J.D. Roberts, M. Harris, and B. Finley. 2008. Risk of Gastrointestinal Disease Associated with Exposure to Pathogens in the Water of the Lower Passaic River. *Applied and Environmental Microbiology* 74 (4): 994-1003.

Dougall, Leroy. 2013. Superintendent, Public Works Dept, City of Blaine, WA. Pers. comm.

Duda, A.M., D.R. Lenat, and D.L. Penrose. 1982. Water Quality in Urban Streams: What We Can Expect. *Water Environment Federation* 54: 1139-1147.

Edwards, Sean. 2013. Senior Planner, Dept. of Public Works, Snohomish County. Everett, WA. Pers. comm.

Ellis, J.B. 2004. Bacterial Sources, Pathways and Management Strategies for Urban Runoff. *Journal of Environmental Planning and Management* 47: 942-958.

Espy, W.H., C.W. Morgan, and F.D. Masch. 1966. *A Study of Some Effects of Urbanization on Storm Runoff From a Small Watershed*. Report 23. Texas Water Development Board. Austin, TX.

Eugene Backyard Farmer, The. 2013. Eugene, OR. Pers. comm.

Fairchild, Charles. 2013. Natural Resources Specialist, Bureau of Land Management. Eugene, OR. Pers. comm.

Farthing, Kevin. 2013. Maintenance Division, Public Works Dept., City of Eugene, OR. Pers. comm.

Frodge, Jonathan. 2013. "Investigation of Bacteria Sources in the Thornton Creek Watershed, Seattle, Washington." Seattle, WA.

Gilbertson, Shawn. 2013. Environmental Supervisor, Public Works Dept., Kent, WA. Pers. comm.

Graczyk, T.K., R. Fayer, J.M. Trout, E.J. Lewis, C.A. Farley, I. Sulaiman, and A.A. Lal. 1998. *Giardia* sp. Cysts and Infectious *Cryptosporidium parvum* Oocysts in the Feces of Migratory Canada Geese (*Branta canadensis*). *Applied Environmental Microbiology 64(7): 2736-2738.*

Halela, Sally. 2013. South County Cats Spay/Neuter Assistance Organization. Maple Valley, WA. Pers. comm.

Harvey, R.W., L.H. George, R.L. Smith, and D.R. LeBlanc. 1998. Transport of Microspheres and Indigenous Bacteria Through a Sandy Aquifer: Results of Natural- and Force-Gradient Tracer Experiments. *Environmental Science and Technology* 23: 51-56.

Hendriks, Martin R. 2010. *Introduction to Physical Hydrology*. Oxford University Press, New York.

Henne, L.J.,D.W. Schneider, and L.M. Martinez. 2002. Rapid Assessment of Organic Pollution in a West-central Mexican River Using a Family-level Biotic Index. *Journal of Environmental Planning and Management* 45(5): 613-632.

Hoffman, Charles P., Cindy James, and Greg Zentner. 2008 "Clarks Creek Watershed Fecal Coliform Bacteria, Total Maximum Daily Load: Water Quality Improvement Report." WA Dept. of Ecology. Olympia, WA.

Hudson, C.R., C. Quist, M.D. Lee, K. Keyes, S.V. Dodson, C. Morales, S. Sanchez, D.G. White, and J.J. Maurer. 2000. Genetic Relatedness of *Salmonella* Isolates from Nondomestic Birds in Southeastern United States. *Journal of Clinical Microbiology* 38(5): 1860-1865.

Humphreys, Shawn. 2013. Environmental Health Specialist, Dept. of Community Development, Pacific County. Long Beach, WA. Pers. comm.

James, Cindy. 2009. “Clarks Creek Watershed Fecal Coliform Bacteria Total Maximum Daily Load: Water Quality Implementation Plan.” WA Dept. of Ecology. Olympia, WA.

Jamestown S’Klallam Tribe. 2007. “Protecting and Restoring the Waters of the Dungeness: a Watershed-based Plan Prepared in Compliance with Section 319 of the Clean Water Act.” Sequim, WA.

Johnson Creek Watershed Council. 2013. “Who’s Pooping in Johnson Creek?” Powerpoint presentation for the 2013 Urban Ecology & Conservation Symposium. Portland, OR.

Jones, M.A., L.A. Orr, J.C. Ebbert, and S.S. Sumoika. 1999. “Ground-Water Hydrology of the Tacoma-Puyallup Area, Pierce County, Washington.” USGS Water Resources Investigations Report 99-4013.

King County. 1995. “Little Soos Creek Microbial Source Tracking.” Prep. by Mansour Samadpour and Naomi Chechowitz, University of Washington, Dept. of Environmental Health for King County Dept. of Natural Resources and Parks. Seattle, WA.

King County. 2001*a*. “King County Conveyance System Improvement Project, Thornton Creek MST [Microbial Source Tracking] Study.” Dept. of Natural Resources and Parks. Seattle, WA.

King County. 2001*b*. “Comprehensive Solid Waste Management Plan Chap. 7 – Disposal.” Solid Waste Division, Dept. of Natural Resources and Parks. Seattle, WA.

King County. 2006. “Green-Duwamish Watershed Water Quality Assessment: Microbial Source Tracking Study Report.” Prep. by Herrera Environmental Consultants, Inc. for the Dept. of Natural Resources and Parks. Seattle, WA.

King County. 2009*a*. “Stream Report for Soos Creek.” Stations A320, C320, D320, and G320. Stream and River Water Quality Monitoring, Water and Land Resources Division. <http://green.kingcounty.gov/WLR/Waterres/StreamsData/WaterShedInfo.aspx?Locator=A320>. Accessed 5 Sep 2013.

King County. 2009*b*. “Stream Report for Green River.” Stations 0311, 3106, A319, and B319. Stream and River Water Quality Monitoring, Water and Land Resources Division. <http://green.kingcounty.gov/wlr/waterres/streamsdata/watershedinfo.aspx?locator=0311>. Accessed 5 Sep 2013.

King County. 2009*c*. “Stream Report for Issaquah Creek – 0631.” Stream and River Water Quality Monitoring, Water and Land Resources Division. <http://green.kingcounty.gov/WLR/Waterres/StreamsData/WaterShedInfo.aspx?Locator=0631>. Accessed 27 Aug 2013.

King County. 2009*d*. “Stream Report for Idylwood Creek – A620.” Stream and River Water Quality Monitoring, Water and Land Resources Division. <http://green.kingcounty.gov/WLR/Waterres/StreamsData/WaterShedInfo.aspx?Locator=A620>. Accessed 27 Aug 2013.

King County. 2009*e*. “Stream Report for Mill Creek – A315.” Stream and River Water Quality Monitoring, Water and Land Resources Division. <
<http://green.kingcounty.gov/WLR/Waterres/StreamsData/WaterShedInfo.aspx?Locator=A315>. Accessed 27 Aug 2013.

King County. 2009*f*. “Stream Report for Newaukum Creek – 0322.” Stream and River Water Quality Monitoring, Water and Land Resources Division.
<http://green.kingcounty.gov/WLR/Waterres/StreamsData/WaterShedInfo.aspx?Locator=0322>. Accessed 5 Sep 2013.

King County. 2009*g*. “Stream Report for Springbrook Creek – 0317.” Stream and River Water Quality Monitoring, Water and Land Resources Division.
<http://green.kingcounty.gov/WLR/Waterres/StreamsData/WaterShedInfo.aspx?Locator=0317>. Accessed 30 Aug 2013.

King County. 2013. Wastewater Treatment Division GIS Center. Combined and separated sewer system areas within King County, Washington [Combined_Separated].

Knuckles, Jason. 2013. The Nature Conservancy. Eugene, OR. Pers. comm.

Krause, G., S. Zimmermann, and L. Beutin. 2005. Investigation of Domestic Animals and Pets as a Reservoir for Intimin-(Eae) Gene Positive Escherichia Coli Types. *Veterinary Microbiology* 106(1-2): 87-95.

Lane County Human Services Commission. 2013. “2013 One Night Homeless Count: Highlights.” Eugene, OR.

Leopold, L.B. 1968. Hydrology for Urban Planning, a Guidebook on the Hydrologic Effects of Urban Land Use. U.S. Geological Survey Circular 554. U.S. Department of the Interior. Washington, DC.

Lindqvist, R., and G. Bengtsson. 1991. Dispersal Dynamics of Groundwater Bacteria. *Microbial Ecology* 21 (1): 49-72.

Little, Rick. 2013. Public Information Officer, District 5, Oregon Dept. of Transportation. Springfield, OR. Pers. comm.

Long, Jack. 1992. “City of Eugene Storm Drainage System Maintenance: a Historical Summary.” Eugene, OR.

Long Tom Watershed Council. 2000. “Long Tom Watershed Assessment.” Eugene, OR.

Long Tom Watershed Council. 2007. “Long Tom Watershed Council *E*. *coli* Monitoring Results: September 1999 – December 2006.” Eugene, OR.

Mallin, M.A., K.E. Williams, E.C. Esham, and R.P. Lowe. 2000. Effect of Human Development on Bacteriological Water Quality in Coastal Watersheds. *Ecological Applications* 10(4): 1047-1056.

Marks, S.L., S.C. Rankin, B.A. Byrne, and J.S. Weese. 2011. Enteropathogenic Bacteria in Dogs and Cats: Diagnosis, Epidemiology, Treatment, and Control. *Journal of Veterinary Internal Medicine* 25: 1195-1208.

Mathieu, Nuri and Debby Sargeant. 2008. "Drayton Harbor Watershed Fecal Coliform Total Maximum Daily Load: Phase 1." WA Dept. of Ecology. Olympia, WA.

Morato, E.P., L. Leomil, L. Beutin, G. Krause, R.A. Moura, and A.F. Pestana de Castro. 2009. Domestic Cats Constitute a Natural Reservoir of Human Enteropathogenic *Escherichia coli* Types*. Zoonoses and Public Health* 56: 229-237.

Nooksack Indian Tribe Dept. of Natural Resources. 2010. "Addendum to Drayton Harbor Watershed Fecal Coliform TMDL and Phase 3 Microbial Source Tracking; Semiahmoo Bay." Prep. by Hirsch Consulting Services, Llyn Doremus (Nooksack Indian Tribe), and Geoff Menzie (Puget Sound Restoration Fund). Deming, WA.

Novotny, Vladimir, Jack Ahern, and Paul Brown. 2010. *Water Centric Sustainable Communities*. Hoboken: John Wiley & Sons, Inc.

Oregon Dept. of Environmental Quality. 2006. "Willamette Total Maximum Daily Load." Chap 10: Upper Willamette Subbasin TMDL. Portland, OR.

Osborne, Tim. 2013. Development Engineering Manager, Lakehaven Utility District. Pers. comm. Federal Way, WA.

Paul, M.J. and J.L. Meyer. 2001. Streams in the Urban Landscape. *Annual Review of Ecology and Systematics* 32: 333-365.

Presnell, M.W. and J.J. Miescier. 1971. Coliforms and Fecal Coliforms in an Oyster-growing Area. *Water Pollution Control Federation* 43(3): 407-416.

Puget Sound Restoration Fund. 2008. "California Creek and Drayton Harbor Microbial Source Tracking Pilot Study." Prep. by Hirsch Consulting Services. Bainbridge Island, WA.

Rainier Audubon Society. 2003. Christmas Bird Count data. Retrieved 2013. Auburn, WA.

Rhind, S.M. 2009. Anthropogenic Pollutants: A Threat to Ecosystem Sustainability? *Philosophical Transactions: Biological Sciences* 364 (1534): 3391-3401.

Rogue Valley Council of Governments. 2005. "Bacterial Source Tracking Pilot Study." Central Point, OR.

Scott, T.M., J.B. Rose, T.M. Jenkins, S.R. Farrah, and J. Lukasik. 2002. Microbial Source Tracking: Current Methodology and Future Directions. *Applied and Environmental Microbiology* 68(12): 5796-5803.

Seattle/King County Coalition on Homelessness. 2003. "The 24th Annual One Night Count of People Who are Homeless in King County, Washington." Seattle, WA.

Seattle/King County Coalition on Homelessness. 2007. "2007 Annual One Night Count of People Who are Homeless in King County, WA." Seattle, WA.

Seattle/King County Coalition on Homelessness. 2008. "2008 Annual One Night Count of People Who are Homeless in King County, WA." Seattle, WA.

Seattle Public Utilities. 2007. "Monitoring Report: Thornton Creek and Matthews Beach Microbial Source Tracking Study." Prep. by Herrera Environmental Consultants, Inc. Seattle, WA.

Serenity House of Clallam County. 2011. <http://www.serenityhouseclallam.org/>. Accessed Aug 2013.

Shanks, O.C., C. Nietch, M. Simonich, M. Younger, D. Reynolds, and K.G. Field. 2006. Basin-wide Analysis of the Dynamics of Fecal Contamination and Fecal Source Identification in Tillamook Bay, Oregon. *Applied Environmental Microbiology* 72 (8).

Skaar, Erin. 2013. Executive director, Community Action Resource Enterprises, Inc. Tillamook, OR. Pers. comm.

Snohomish County Dept. of Public Works. 2011. "Stillaguamish Bacteria Microbial Water Quality Assessment (MWQA) Project Work Plan." Prep. by Sean Edwards. Everett, WA.

Sorenson, Deborah. 2013. Alley Cat Project. Seattle, WA. Pers. comm.

Stabach, Greg. 2013. Project manager, Natural Resources Division, Rogue Valley Council of Governments. Central Point, OR. Pers. comm.

Stevens, Gary. 2013. Street and Stormwater Superintendent, Public Works Dept., City of Snoqualmie, WA. Pers. comm.

Taylor, Trevor. 2013. Natural Areas Restoration Supervisor, Public Works Dept., City of Eugene, OR. Pers. comm.

Tillamook Bay National Estuary Project. 1998. "Tillamook Bay Environmental Characterization: a Scientific and Technical Summary." Garibaldi, Oregon.

Timm, Raymond. 2012. "Boise Creek Bacterial Source Tracking Study: 2011 Summary of Findings." Prep. for King County Dept. of Natural Resources and Parks, Water and Land Resources Division. Seattle, WA.

Timm, Raymond. 2013*a*. "Boise Creek Bacterial Source Tracking Study: 2012 Summary of Findings." King County Dept. of Natural Resources and Parks, Water Resources Division. Seattle, WA.

Timm, Raymond. 2013*b*. Senior Aquatic Scientist, King County Dept. of Natural Resources and Parks, Water and Land Resources Division. Seattle, WA. Pers. comm.

Tjemsland, Pete. 2013. Utilities Manager, Public Works Dept., City of Sequim, WA. Pers. comm.

Turner, Ryan. 2013. Public Works Dept., City of Eugene, OR. Pers. comm.

U.S. Dept. of Agriculture, Soil Conservation Service. 1972. "General Soil Map: King County Area, Washington."

U.S. Dept. of Agriculture. 1992. "Agricultural Waste Management Field Handbook. Chapter 3: Agricultural Wastes and Water, Air, and Animal Resources."

U.S. Environmental Protection Agency. 2011. “Using Microbial Source Tracking to Support TMDL Development and Implementation.” Prep. by Tetra Tech, Inc. and Herrera Environmental Consultants. Seattle, WA.

U.S. Environmental Protection Agency. 2013. “Drinking Water Contaminants.” <http://water.epa.gov/drink/contaminants/index.cfm>. Accessed 9 July 2013.

VanDenBergh, Ken. 2013. Soos Creek Water and Sewer District. Renton, WA. Pers. comm.

Washington Dept. of Ecology. 2012. “Water Quality Improvement Projects: Stillaguamish Basin.” <http://www.ecy.wa.gov/programs/wq/tmdl/StillaguamishTMDL.html>. Accessed 30 Aug 2013.

Water Resource Inventory 9 Steering Committee. 2005. “Assessment of Current Water Quantity Conditions in the Green River Basin.” Prep. by Northwest Hydraulics Consultants, Inc. Seattle, WA.

Wharton, Laura. 2013. Manager of Planning, Inspection, Modeling, Monitoring, and Mapping, Wastewater Treatment Division, King County Dept. of Natural Resources and Parks. Seattle, WA. Pers. comm.

Whatcom County Public Works, Dept. of Natural Resources. 2009. “Drayton Harbor Watershed Microbial Source Tracking Pilot Study Phase 2: California Creek, Dakota Creek and Cain Creek Sub-watersheds.” Prep. by Hirsch Consulting Services. Lummi Island, WA.

Whitlock, J.E., D.T. Jones, and V.J. Harwood. 2002. Identification of the Sources of Fecal Coliforms in an Urban Watershed Using Antibiotic Resistance Analysis. *Water Research* 36(17): 4273-4282.

Woodruff D.L., N.K. Sather, V.I. Cullinan, and S.L. Sargeant. 2009. “Microbial Source Tracking in the Dungeness Watershed, Washington.” Prep. for Jamestown S’Klallam Tribe. Richland, WA.

Wright, M.E., H.M. Solo-Gabriele, S. Elmir, and L.E. Fleming. 2009. Microbial Load from Animal Feces at a Recreational Beach. *Marine Pollution Bulletin* 58: 1649-1656.

Young, K.D. and E.L. Thackston. 1999. Housing Density and Bacterial Loading in Urban Streams. *Journal of Environmental Engineering* 125: 1177-1180.

Zhu, X., J.D. Wang, H.M. Solo-Gabriele, and L.E. Fleming. 2011. A Water Quality Modeling Study of Non-Point Sources at Recreational Marine Beaches. *Water Research* 45: 2985-2995.

Appendix A

Description of MST-studied basins and initial similarity comparisons

The following overview is not only applicable to the ACB but is also applicable to any basin in the region with unknown sources of fecal bacteria. Environmental managers who are contemplating the necessity of an MST study in a particular basin can use the following data to determine initial similarity to a basin that has been studied basin and therefore predict likely sources of fecal bacteria pollution.

1. Bear Creek sub-basins, Ashland, OR

The Bear Creek study (2004-2005) was a pilot project. The Rogue Valley Council of Governments tested bacteria sources at eight total sites along six different tributaries of Bear Creek and found only animal, no human contamination (Rogue Valley 2005). However, 38% of the samples could not be identified to a source, probably because the library of geographically relevant bacteria available at that time was not comprehensive (Stabach 2013). Because so many of the bacteria isolates could not be identified to a host, the results of the Bear Creek study were not informative for the Amazon Creek Basin.

2. Big Soos basins, near Kent, WA

Big Soos Creek drains a 65.6 mi^2 outside of Seattle. The headwaters lie in the Cascade-Fairwood neighborhood and the creek flows south, draining portions of East Hill Meridian, Kent, Covington, and Auburn, and nearly 1,400 acres of lakes. The Creek empties into the middle Green River in Auburn. Little Soos Creek is a tributary of Big Soos Creek, draining a 3.6 mi^2 area fed by Lake Youngs reservoir.

A 28-year trend analysis indicated that water quality in the basin decreased since 1979, although the watershed is in better health than neighboring Springbrook Creek basin (King County 2009*a*). Mean bacteria loads have varied greatly, between about 60 (low concern) and 700 (high concern) CFU/100 mL. This depends on how much water is flowing and where in the basin water was sampled. Increased urbanization led to concerns about water quality, especially because Lake Youngs is a domestic water supply. For these reasons, the County hired consulting firms to perform two MST studies in the area.

Study summary

Between 1993 and 1995, King County funded a library-dependent MST study for Little Soos Creek, but 29% of the bacteria strains could not be matched to their original source (King County 1995). This is probably because the library of geographically relevant bacteria available at that time was not comprehensive. Therefore, the results of the Little Soos Creek study would not be informative for the Amazon Creek Basin.

The County funded another library-dependent MST study in 2003, this time sampling from Big Soos Creek. Assuming that bacteria matched to "avian" sources were from wild birds, wildlife were responsible for 73.1% of all the fecal bacteria (31.6% avian, 41.5% other wildlife) (King County 2006). Canine and feline (likely domestic pets because the basin is so developed) hosted 11.4% of the fecal bacteria, and humans accounted for 4.6% of the isolates. Pasture animals hosted 6.9% and the remaining 4.0% were not matched to a source.

Initial comparison

Similarly to the Amazon Creek basin, the Big Soos Creek basin contains no pasture land (King County 2006). However, only 10.2% of the basin's land cover is impervious, compared with 33% of the ACB. This difference will significantly change the ability of a basin to take up pollutants before they reach main waterways. Further, there are almost no septic systems in the Amazon Creek drainage, but almost 20% of the Soos Creek drainage is served by septic systems (King County 2006). Because some of the initial comparison metrics for Soos Creek basin are different from the ACB, the proportionate sources of bacteria in Soos Creek are probably dissimilar to proportions in Amazon Creek.

3. Boise Creek and sub-basins, near Enumclaw, WA

Boise Creek drains 17.7 mi^2 within the larger Puyallup River basin. The creek begins in the Cascade Mountains east of the City of Enumclaw and empties into the White River just south of the city limits. Two areas, draining the upper (0.4 mi^2) and lower (1.0 mi^2) parts of a sub-basin within the City, were also analyzed as potential comparison basins to Amazon Creek. In 1996, Boise Creek was listed as impaired for fecal coliform bacteria, and this waterway currently has the greatest fecal coliform load of all tributaries of the Puyallup River (Timm 2012).

Study summary

The King County Department of Natural Resources and Parks performed MST studies on Boise Creek and its tributaries in 2011, in 2012, and continued testing samples in 2013. Because of the significant presence of farm animals, deer, and elk, the county so far discriminates only between human and ruminant sources of bacteria.

In the upper portion of the Boise Creek sub-basin, the land is fairly evenly divided between residential/commercial development and land that is used by ruminants. Here, the study found bacteria from both human and ruminant sources at both monitoring sites (Timm 2012).

In the larger sub-basin, only human sources of bacteria were confirmed in the more urbanized area. This may be a result of less impact from ruminants in the more urbanized area, and dilution of upstream ruminant bacteria to the point where ruminant bacteria are not commonly found in the downstream portion of the tributary (Timm 2013*b*).

Initial comparison

Unlike the Amazon Creek Basin, most (75.8%) of the whole Boise Creek basin is either forested or used for agriculture. These uses comprise only 11.0% of the ACB. Not surprisingly, only 5.1%

of the whole basin are impervious surfaces. Although Enumclaw is on a separate sewer system, much of the basin lies outside of Enumclaw, where residents are on septic systems.

The two smaller sub-basins are on separate sewer systems (Timm 2013*b*), and have impervious surface percentages that are similar to the ACB. However, pasture land occupies a much greater proportion of these two sub-basins than it does in the ACB—14.0% in the lower sub-basin and 34.8% in the upper sub-basin. Therefore, the relative bacteria sources in the Boise Creek basin and the two sub-basins are probably not similar to proportions in the Amazon Creek.

4. Burnt Bridge Creek, near Vancouver, WA

The Vancouver Public Works department funded an MST study for Burnt Bridge Creek. Between 1996 and 1999, water samples taken from seven sites along the creek were analyzed using library-dependent methods (City of Vancouver 1999). Depending on the site, between 32% and 46% of the E. coli strains could not be matched to a known source, probably because the library of geographically relevant bacteria available at that time was not comprehensive. Because so many of the strains could not be identified to a host, the results of the Burnt Bridge Creek study would not be informative for the Amazon Creek Basin.

5. Clarks Creek, Puyallup, WA

Clarks Creek drains 10.3 mi^2 within the larger Puyallup River basin. Its headwaters lie at Maplewood Springs in the hills of Puyallup, WA. Once descended from the bluffs, the creek flows north through the flat floodplain of the Puyallup River, emptying into the river northwest of the City. In 1996, the state listed Clarks Creek as impaired for fecal coliform and pH, and in 2004, called for a TMDL.

Study summary

Data collected between 1996 and 2001 by the Clarks Creek working group and the Puyallup Tribe of Indians showed high levels of fecal bacteria in Clarks Creek (Hoffman *et al*. 2008). This prompted a study of pollutants and indicators of water quality, contracted through two environmental consulting firms. The microbial source tracking portion of the study was performed between 2002 and 2003, and used library-dependent methods of matching E. coli isolates to isolates of known hosts (City of Puyallup 2005).

Assuming that bacteria matched to "avian" sources were from wild birds, wildlife were responsible for 74.0% of all the fecal bacteria (40.6% avian and 33.4% other wildlife). Canine and feline (likely domestic pets because the basin is well developed) comprised 11.3% of the fecal bacteria sources. Humans accounted for 4.9% of the fecal contamination, livestock 0.6%, and 9.0% of the isolates were not matched to a source.

Initial comparison

The Clarks Creek basin is 30.5% impervious, very similar to the ACB, and has little (1.1%) land devoted to pasture animals. However, at the time of the study, there were over 500 septic systems in the basin (City of Puyallup 2005), an attribute not shared by the ACB.

The portion of Clarks Creek flowing through the city is contained mostly in culverts, ditches, and man-made channels (James 2009). The creek receives stormwater runoff through pipes draining adjacent areas. However, unlike the ACB, the Clarks Creek basin includes eight different "pothole" areas, including two lakes, that trap rainfall and for which there are no outlets for surface water (James 2009, City of Puyallup 2005). Water can sink from the potholes into the groundwater system, but most pollutants would remain in the potholes or, during flood events, be transported by water into adjacent potholes.

Because the hydrology of the basin is different from the ACB's hydrology, and because there were so many septic systems in the basin at the time of the study, the proportionate sources of fecal bacteria in the Clarks Creek basin cannot be descriptive for the ACB.

6. Drayton Harbor, near Blaine, WA

Several creeks carry water to Semiahmoo Bay and its outlet, Drayton Harbor, just south of the Canadian border. Since 1988, the harbor has been listed at the county or state level as bacteria-impaired. Commercial fisherman harvest shellfish in Drayton Harbor, and shellfish that take up pathogenic bacteria and are eaten uncooked cause gastroenteritis. For these reasons, over the last 25 years, parts of the harbor have been closed for fishing or recreation. The major creeks studied for fecal bacteria over the last several years are Cain Creek, California Creek, and Dakota Creek, for a total drainage area of about 55 mi^2. Cain Creek drains 1.2 mi^2, a significant portion of the city of Blaine, starting at the city's airport and empties a few miles to the northwest in Semiahmoo Bay.

Study summary

In 1998, the City of Blaine hired a consulting firm to perform a library-dependent MST study on Cain and Dakota creeks. However, the majority of the isolates could not be matched to isolates of known hosts (Mathieu and Sargeant 2008). The entire harbor was closed to harvest between 1999 and 2004. To address the ongoing problem of bacterial contamination, the Department of Ecology implemented a TMDL plan for the harbor in 2008. Between 2006 and 2009, different partnerships among non-profit organizations, a consulting firm, and local and federal governments coordinated three different studies that analyzed bacteria in the area:

- Water samples were collected from California and Dakota Creeks between 2006 and 2007 and analyzed using both independent and dependent methods (Puget Sound 2008). Ruminant sources of bacteria were detected at all the sites. Other sources found were human, avian, marine mammal, deer, rodent, and raccoons.
- In 2008, the sub-basins of California, Dakota, and Cain creeks were studied, using library-independent methods, by analyzing the presence of certain biomarkers on *Bacteroides* species (Whatcom County 2009). Because much of the basin, especially land around

Dakota and California creeks is used for agriculture, the MST study discriminated only between human and ruminant sources of bacteria. Both human and ruminant sources were identified in Dakota and California creeks, and ruminant sources were found at Cain Creek. Overall, human sources of bacteria were found in 16% of the samples, and ruminant in 8%.

- The most recent MST study was performed in 2009. Samples from Cain Creek were analyzed using library-independent *Bacteroides* markers (Nooksack 2010). Both human and ruminant fecal bacteria were found in water samples, but there is stronger evidence of "chronic" contamination from humans (Nooksack 2010).

Initial comparison

The basin draining California and Dakota creeks (50.1 mi^2) is not similar enough to the Amazon Creek Basin for a more detailed investigation. Unlike the ACB, a large portion (31.2%) of this area is used for hobby and commercial pasture farming. The basin is also only 4.1% impervious, meaning it takes up much more bacteria than does the ACB.

The Cain Creek sub-basin (1.2 mi^2) is similar to the Amazon Creek Basin in some ways. A small proportion (7.1%) of the Cain Creek basin is used as pasture land, which indicates that fecal bacteria from ruminants would probably chiefly come from wildlife sources instead of domestic animals. About 30.3% of the basin was impervious during the study, very similar to the ACB's 33%. Lastly, as in the ACB, sewer lines in the city of Blaine are separate from the stormwater system (Dougall 2013). However, the most likely source of human sewage is from failing septic systems within the city of Blaine and the surrounding area, which drain into Cain Creek. Because Eugene has many more homeless people and almost no septic systems within the basin, the likely sources of contamination in Cain Creek cannot be also be indicated for Amazon Creek.

7. Dungeness River sub-basins, near Sequim, WA

The Dungeness River is 32 miles long, traveling from its headwaters in Olympic National Park at 6,400 ft to its terminus north of the town of Sequim, at Dungeness Bay. The studied portion of the Dungeness River basin drains just less than 200 mi^2, and this area is increasingly developed along the River as it flows north.

Levels of fecal coliform bacteria in the bay and near the mouth of the River have increased since 1997. Since 2000, the State Department of Health periodically closes portions of the Bay to shellfish harvesting. Concerns over shellfish harvest, declining fish habitat, and human health have led to numerous studies and plans for improving water quality in the greater Dungeness watershed. Because the basin has no permitted point sources of bacteria pollution, studies and clean-up efforts have focused on non-point sources (Jamestown S'Klallam Tribe 2007).

Study summary

The Jamestown S'Klallam Tribe, which owns property along the final miles of the Dungeness, hired a research firm to conduct a microbial source tracking study in the lower portions of the watershed. Water samples from the Dungeness River basin and the Dungeness Bay were collected between 2006 and 2009. Two small basins (4.7 mi^2 and 14.2 mi^2) adjacent to the Dungeness River near its terminus were also studied. These drain surface water north of the City of Sequim and on opposite sides of the Dungeness River into the Bay.

The study used library-dependent methods to determine the hosts of the bacteria and found that many of the isolates came from wildlife (Woodruff *et al*. 2009). Assuming that bacteria matched to "avian" sources were from wildlife and not chickens, wildlife was the source of over 61% of the isolates from the Dungeness River, and at least 67% of the isolates from both the west and east basins. Depending on the basin, bird sources accounted for between 32.0% and 43.2% of all isolates. Because isolates were matched only to canine or feline specificity, the impact of pets on fecal bacteria is unclear. These two categories of pets comprised 9.0% of the isolates in the River basin, 8.2% in the west basin, and 13.6% in the east basin. Humans sourced 7.8% of the bacteria in the River basin, 5.1% in the west basin, and 15.2% in the east basin. This last value is the highest percentage of human-sourced fecal bacteria of all the MST studies that I analyzed. Unknown sources accounted for 8.3% of isolates in the River basin, 11.0% in the west basin, and 4.8% in the east basin.

Initial comparison

Similarly to the Amazon Creek Basin, not much of the Dungeness River study area is used by pasture animals—only 3.9%. However, unlike the Amazon Creek basin, half of the Dungeness study area is forested. Further, only 0.9% of the land in the study basin is impervious. This difference will significantly change the ability of a basin to take up pollutants before they reach main waterways. The two small basins adjacent to the Dungeness River near its mouth have greater use by pasture animals—about 10% of the land in each basin, which is more than in the ACB. The basin to the west also has a low impervious value (9.1%) with the basin to the east somewhat higher (17.9%).

Although most of the city of Sequim is on a separate sewer system, there are portions of the city that still use septic systems, and much of the surrounding area within the basins are also served by septic systems (Tjemsland 2013, Woodruff *et al*. 2009). In fact, retrofitting or repairing septic systems in the area is one of the community's primary targets in reducing levels of fecal bacteria (Brastad 2013, Jamestown S'Klallam Tribe 2007). This is not similar to characteristics within in the ACB.

In addition, the study area is unique among the basins I am analyzing in that it has especially heavy use by wildlife, in ways that Amazon Creek basin does not. A wild animal park is located in the west basin, and a large proportion of land abutting the Bay is part of the Dungeness National Wildlife Refuge. Gulls were the source of at least 10% of the fecal bacteria in each of the three studied basins (Woodruff *et al*. 2009), and this group of birds will be significantly less common in the Amazon Creek basin. For these reasons, relative sources of bacterial pollution in this watershed are unlikely to be informative for extrapolating sources of pollution of the ACB.

Notably, the Dungeness Bay watershed is the one of the few basins in this study that has a sizeable homeless population (Serenity House 2011). Unfortunately, the study was not devised in a way that examined the effect of homeless camps on fecal bacteria levels, so I was not able to extrapolate information about this source for the ACB.

8. Green-Duwamish River, King County, WA

The Green-Duwamish River flows for 65 miles and drains 440 mi^2. The river starts just west of the Cascades and flows west to the Howard A. Hanson Reservoir. The upper portion of this basin is closed to public use because it provides much of Tacoma's water supply. The river continues west through private, mostly forested areas, and then turns north in Auburn, draining a large portion of Seattle and several of its suburbs before emptying into Elliott Bay.

A 25-year trend analysis indicated that water quality in the upper part of the basin is relatively high (King County 2009*b*). Mean bacteria loads have varied greatly, between about 40 and 450 CFU/100 mL. This depends on how much water is flowing and where in the basin water was sampled. To establish a baseline for fecal bacteria sources in the Green-Duwaumish watershed, King County hired a consulting firm to perform a microbial source tracking study along the mainstem.

Study summary

The MST study was conducted between 2003 and 2004 using library-dependent methods, in which *E. coli* isolates from water samples were matched to host sources (King County 2006). Two portions of the river drainage were studied: the upper Green River basin, draining 221 mi^2, and a lower Green River basin, which drains 400 mi^{2}of the basin upstream of Auburn.

Proportions of bacteria hosts were similar between the lower and upper sub-basins. Assuming that bacteria matched to “avian,” “canine,” and “feline” sources were from wildlife (because the study area is so undeveloped), wildlife-derived bacteria comprised nearly all of the isolates: 87.0% in the upper sub-basin and 82.8% in the lower (about 30% coming from birds). Humans hosted less than 1% of the bacteria in the upper watershed, and about 6.7% of the isolates in the lower portion. In each sub-basin, about 5% of the isolates came from pasture animals, and about 5% of the isolates could not be matched to a host.

Initial comparison

Similarly to the Amazon Creek basin, there is not much pasture land in the Green-Duwamish basin: about 4% in the lower sub-basin and none in the upper reaches of the river. However, unlike the Amazon Creek basin, much of the Green-Duwaumish basin is forested and there are few impervious surfaces. The lower sub-basin is 67% forested and 4.1% of the land is impervious. The upper sub-basin is 99% forested and 0.6% of the land is impervious. These differences will significantly change the ability of a basin to take up pollutants before they reach main waterways. Further, only 27.6% of the lower sub-basin is sewered—the rest of the basin is served by septic systems (King County 2006). Because several of the initial comparison metrics for the Green-Duwamish sub-basins are different from the ACB, the proportionate sources of bacteria are almost certainly dissimilar to proportions in Amazon Creek.

9. Hamm Creek, near South Park, WA

Hamm Creek drains a 1.9 mi^2 section of urban Seattle near the neighborhoods of South Park and White Center. It is very slow-moving (0.89 cfs) and mean fecal bacteria levels exceeded water quality standards set by the state (King County 2006). Bacteria pollution is a problem year-round and during both base and storm flows, prompting an MST study.

Study summary

Sources of the Creek's fecal bacteria were studied in 2003 using library-dependent methods, in which *E. coli* isolates from water samples were matched to host sources (King County 2006). Assuming that bacteria matched to "avian" sources were from wild birds, wildlife were responsible for 66.6% of all the fecal bacteria (32.9% from birds and 33.7% other wildlife). Canine and feline (likely domestic pets because the basin is so developed) comprised 20.5% of the fecal bacteria. Humans accounted for 2.6% of the isolates and 9.0% were not matched to a source.

Initial comparison

Similarly to the Amazon Creek basin, the Hamm Creek basin contains no pasture land and is 38.4% impervious. However, much of the stormwater runoff is collected by the City's sewer pipes and transported to a wastewater treatment plant (King County 2013). This means that original sources of fecal bacteria are probably not equitably represented in Hamm Creek. Therefore, parallels cannot be drawn between in-depth metrics, such as populations of waterfowl or homeless people and percent of stream bacteria related to these sources. For this reason, the Hamm Creek basin would not help inform planners in Eugene and the basin was not analyzed further.

10. Idylwood Creek, Redmond, WA

Idylwood Creek drains a small area, about 0.6 mi^2, flowing from Bellevue to Redmond, where it empties into Lake Sammamish at Idylwood Park. The mean fecal coliform levels in the stream do not meet the state's water quality standards, and the Creek empties into the Lake at a recreational beach (King County 2009*d*). These concerns prompted an MST study between 2011 and 2012 (Bouchard 2012). Unfortunately, details of the study could not be obtained.

11. Issaquah Creek, Issaquah, WA

Issaquah Creek drains about 61 square miles of King County, flowing through the city of Issaquah and entering Lake Sammamish. The mean fecal coliform levels in the stream do not meet the state's water quality standards, prompting an MST study between 2011 and 2012 (Bouchard 2012, King County 2009*c*). Details of the study could not be obtained. However, over

75% of the basin is forested, and there are many farms in the basin, suggesting that proportionate sources of fecal bacteria and impervious surfaces would not be similar to the ACB.

12. Johns Creek, near Renton, WA

Johns Creek drains 1.9 mi^2 of the City of Renton, a suburb of Seattle. The Creek empties into the southern portion of Lake Washington at a swimming beach in Gene Coulon Park. Water samples at the beach had levels of fecal coliform bacteria above state water quality standards, during periods of both storm and base flow (City of Renton 2006). As a result, the City closed the entire swimming beach in 2004, and closed the majority of the beach in 2005. The City hired a consulting firm to investigate the sources of contamination.

Study summary

Between 2005 and 2006, the firm conducted a library-dependent MST study in the Johns Creek watershed, in which isolates of *E. coli* bacteria were matched to their known hosts. Avian sources alone accounted for 44.7% of the isolates (City of Renton 2006). Assuming that bacteria matched to avian sources were from wild birds, wildlife was responsible for the greatest proportion, 68.3%, of all the bacteria. Canine and feline (likely domestic pets because the basin is so developed) sources comprised 19.7% of the fecal bacteria. Humans accounted for 5.3% of the isolates and 6.6% were not matched to a source.

Initial comparison

In some ways, the Johns Creek basin is similar to the Amazon Creek basin. Neither basin has much land that is used for commercial livestock. Both basins are fully sewered on systems separate from stormwater. However, the Johns Creek basin is much more urbanized than the Amazon Creek basin—84% of the land is developed as residential or commercial space, and impervious surfaces cover 58% of the basin. This was the highest impervious surface value of all the watersheds analyzed in this study. Because surface permeability strongly impacts the fecal bacteria load of a waterway, parallels could not be drawn between the proportionate sources of fecal bacteria in Johns Creek and sources in Amazon Creek.

13. Johnson Creek sub-basins, near Milwaukie, OR

Johnson Creek drains 54 mi^2 of the eastern portion of Portland's metropolitan area. It originates east of Boring and flows about 25 miles though parts of Gresham, Portland, Happy Valley, and Milwaukie, where it empties into the Willamette River. The basin is about 30% developed as residential and commercial space, with more heavy development in the lower portions of the watershed. In 1998, OR DEQ listed Johnson Creek as water quality limited for bacteria, as well as temperature and toxics such as DDT and PCBs. State water quality standards are set at a maximum of 406 *E. coli* organisms per 100 mL, and samples in the creek reached as high as 1,894 organisms/100 mL (City of Portland 2005). Out of concern for the health of human recreators and native fish, a 2005 watershed assessment called for bacteria source tracking on the Creek and its tributaries.

Study summary

In 2012, in cooperation with city and county partners, the Johnson Creek Watershed Council performed library-independent microbial source tracking on the lower and upper portions of the Johnson Creek basin. Fecal bacteria from water samples were analyzed for human and avian sources. Out of 50 water samples, human-hosted bacteria were found in eight of the samples, and avian in five (Johnson Creek Watershed Council 2013).

Initial comparison

The upper Johnson Creek sub-basin (26.6 mi^2) is covered by 15% impervious surface (much less than the ACB), and about 17.0% of the sub-basin is used for pasture animal agriculture (much more than the ACB). Therefore, this sub-basin by itself would not be informative to the Amazon Creek Basin. When the whole basin (54.0 mi^2) is considered, it has similar impervious cover to the ACB (29.6%) and only 9.6% of the land is used for pasture. However, parts of the lower watershed have ponds and sumps that re-route side drainages away from the Creek's mainstem and tributaries (City of Portland 2005). Additionally, the runoff from several neighborhoods flows into Portland's combined sewer system. This system is unlike the Amazon Creek Basin. For these r easons, neither the upper sub-basin nor the whole Johnson Creek basin is similar enough to the ACB for further analysis.

14. Juanita Creek, Kirkland, WA

Juanita Creek drains a small area, about 6.6 mi^2, including the City of Kirkland and others parts of King County. Poor water quality has affected recreation and fish habitat in the Creek and Lake Washington, which is the Creek's terminus (City of Kirkland 2013). Fecal coliform levels in the stream can reach 2,000 CFU/mL, far above the state's water quality standard of 100 CFU/mL. These concerns prompted an MST study between 2011 and 2012, but details of the study could not be obtained.

15. Kimball Creek, near Snoqualmie, WA

Kimball Creek drains 8.7 mi^2 of the center of King County. The City of Snoqualmie contains about 30% of the basin, and the remaining land is unincorporated. The headwaters of the creek lie in mountains south of the City. Several tributaries join Kimball Creek before it empties into Snoqualmie River just north of the City. The creek's water quality has been monitored since 1993. A TMDL written for Snoqualmie River in 1994 classified Kimball Creek as water-quality limited for fecal bacteria. In 2001, Kimball's water quality was "consistently poorer" than similar streams in the region, in terms of dissolved oxygen, turbidity, nutrients, and fecal bacteria (City of Snoqualmie 2004). These parameters often violated state standards. These findings along with concern over increasing development in the region motivated the County to initiate an MST study.

Study summary

Between 2003 and 2004, the City of Snoqualmie hired a consulting firm to perform a microbial source tracking study on Kimball Creek, which flows through the City. The library-dependent study matched *E. coli* isolates to several different host groups. Avian sources comprised the largest proportion of isolates (33.9%); followed by other wildlife (26.2%), canine (13.8%), pasture domestics (11.5%), human (10.6%), and unknown (4.1%) (City of Snoqualmie 2004).

Initial comparison

Like the Amazon Creek basin, the Kimball Creek basin (8.7 mi^2) has very little pasture agriculture (1.1% of land cover) and stormwater runoff is separate from the sewer system. However, septic systems serve one of Snoqualmie's neighborhoods, and there are almost no septic systems in the Amazon Creek basin. Ponds, bioswales, and rain gardens treat a different Snoqualmie neighborhood's stormwater before discharging into main waterways (Stevens 2013). In addition, only 8.8% of the Kimball basin is impervious surface—this is much more pervious than the ACB. For these reasons, the Kimball Creek basin is not similar enough to the ACB for further analysis.

16. Mill Creek, Auburn, WA

Mill Creek, also known as Hill Creek, drains 13.1 mi^2 of suburban Seattle. Lake Doloff and Lake Geneva form the headwaters of the drainage. The upper sub-basin includes portions of Federal Way, Lakeland North, and Lakeland South. From there, the 8.3-mile creek flows through Peasley Canyon into Auburn, then turns north and empties into the Green River in south Kent. In 2004, the state listed the creek as impaired for temperature, dissolved oxygen, and fecal coliform. In 2003, a water quality analysis conducted on the Green River and five of its sub-basins found that the Mill Creek drainage was the most polluted for fecal bacteria. Mean fecal coliform concentrations (CFU/100 mL) were 177 during base flows and 2,200 during storm flows (King County 2006). Mean *E. coli* concentrations (CFU/100 mL) were 127 during base flows and 1,708 during storm flows. Although bacteria loads in Mill Creek have decreased overall since 1979, the drainage is still one of the most polluted for bacteria within the Green-Duwamish River watershed (King County 2009*e*).

Study summary

Out of concern for Mill Creek's water quality, King County hired a consulting firm to perform an MST study. Conducted between 2003 and 2004, the study used library-dependent methods to track *E. coli* isolates to known hosts (King County 2006). Assuming that bacteria matched to "avian" sources were from wild birds, wildlife were responsible for 77.6% of all the fecal bacteria (44.9% avian and 32.7% other wildlife). Canine and feline (likely domestic pets because the basin is so developed) comprised 18.2% of the fecal bacteria sources. Humans were the source for 2.4% of the isolates and pasture animals for 1.8%. This basin is the only one I analyzed that matched all isolates to a source. In this respect, this MST study provides the most comprehensive picture of proportionate sources of fecal bacteria within a drainage.

Initial comparison

Neither the Amazon Creek nor Mill Creek basins have substantial fractions of pasture land. Impervious surfaces comprised about 37.1% of Mill Creek's watershed, a value that is more than but still similar to impervious cover in the ACB. When the study was conducted, sewer lines separate from a stormwater system serviced 82.5% of the basin, and there were a limited number of septic systems in the rest of the basin (King County 2006). Because the two basins match for initial similarity, Mill Creek was analyzed for further similarity to the ACB.

17. Newaukum Creek, near Auburn, WA

Newaukum Creek drains 27.5 mi^2 outside of Seattle. The creek begins in mountains northeast of Enumclaw and flows northwest 14 miles, draining forest, agricultural land, and the northern half of Enumclaw. The creek flows into the Green River just outside of the city of Auburn. Fecal bacteria loads in the basin have decreased substantially over the past few decades, although storm flows in 2003 still carried over 1,000 CFU/100 mL, exceeding state water quality standards (King County 2009*f*, King County 2006). To better address management of fecal bacteria in the watershed, the County hired a consulting firm to perform an MST study on Newaukum Creek.

Study summary

The MST study was conducted between 2003 and 2004 using library-dependent methods, in which *E. coli* isolates from water samples were matched to host sources (King County 2006). Assuming that bacteria matched to "avian" sources were from wild birds, and "canine" and "feline" sources were domestic, wildlife were responsible for 58.2% of all the fecal bacteria (23.0% avian and 35.2% other wildlife). Canines and felines hosted 10.3% of the fecal bacteria, although some of these sources were probably from coyote and bobcat, since land use in the basin is mixed. Pasture animals hosted 23.5% of the isolates, humans 4.0%, and an additional 4.0% were not matched to a source.

Initial comparison

Pasture land makes up nearly half of the Newaukum Creek basin—the highest percentage of pasture land of all the study basins. Because so much of the basin is forested or rural, impervious surfaces cover only 5.0% of the land. Lastly, although parts of Enumclaw are on a sewered system separate from stormwater, nearly all of the basin is served by septic systems (King County 2006, Timm 2013*b*). Because the initial comparison metrics for Newaukum Creek basin are different from the ACB, the proportionate sources of bacteria are probably also dissimilar.

18. Pipers Creek, Seattle, WA

Pipers Creek drains a small (2.9 mi^2) and highly urbanized area of northwest Seattle. It empties into Puget Sound at Carkeek Park Beach. In 1991, the City funded a MST study for Pipers Creek. Similarly to other basins analyzed during this time, 57% of the bacteria strains could not be matched to their original source (City of Seattle 1993). This is probably because the library of geographically relevant bacteria available at that time was not comprehensive. For these reasons, the results of this study would not be informative for the ACB.

19. Springbrook Creek, Kent, WA

Springbrook Creek drains 23.5 mi^2 of suburban Seattle. The creek's main tributaries are Panther Creek, which drains Panther Lake in the East Hill Meridian neighborhood and Mill Creek on the north side of the Kent neighborhood. Springbrook Creek flows through the south portion of the City of Renton before entering the lower Green River. In 2004, the state listed the creek as impaired for fecal bacteria and dissolved oxygen. A 28-year trend analysis indicated that fecal bacteria loads had decreased significantly since 1979, but the mean load was about 500 CFU/100mL, far above water quality standards, and peaked as high as 34,000 CFU/100 mL (King County 2009*g*). In contrast, the neighboring watersheds of Big Soos and Newaukum creeks had better water quality than did Springbrook during the MST study.

Study summary

King County hired a consulting firm to investigate the sources fecal bacteria in Springbrook Creek. The study, conducted between 2003 and 2004, used library-dependent methods to track *E. coli* isolates to known hosts (King County 2006). Assuming that bacteria matched to "avian" sources were from wild birds, wildlife were responsible for 73.8% of all the fecal bacteria (40.4% avian and 33.4% other wildlife). Canine and feline (likely domestic pets because the basin is so developed) comprised 19.1% of the fecal bacteria sources. The final 7.1% of the isolates were not matched to a source. Notably, none of the isolates were matched to humans or pasture animals. The basin is the only one analyzed that did not find evidence of human fecal contamination.

Initial comparison

As in the Amazon Creek basin, the Springbrook Creek basin is fully sewered on a system separate from stormwater (King County 2006). Neither basins have substantial fractions of pasture land. In addition, impervious surfaces comprise 48.4% of Springbrook's watershed, a value that is more than but still similar to impervious cover in the ACB. Therefore, this basin was analyzed for further similarity to the ACB.

20. Stillaguamish River, Snohomish County, WA

The Stillaguamish River begins on the west side of the Cascades in Snohomish County. It flows 67 miles to Puget Sound, draining 702 mi^2. In 2002, Washington's Department of Ecology analyzed water quality in the Stillaguamish River basin and found low levels of dissolved oxygen and high levels of fecal bacteria in several areas, especially along tributaries (WA Dept. of Ecology 2012). The Department has issued several TMDL reports and implementation plans, including an MST study in the watershed (Edwards 2013, Snohomish County 2011). However, the methods and results of the MST study could not be obtained.

21. Thornton Creek, Seattle, WA

The Thornton Creek basin drains 11.6 mi^2 of the cities of Seattle and Shoreline. The basin's chief waterways are the north and south forks of Thornton Creek, along with the mainstem. The headwaters lie near North Seattle Community College and Shoreline's Ronald Bog Pond. The forks and their tributaries flow past several ponds, joining to form the Thornton Creek mainstem near Meadowbrook Pond. From there, Thornton Creek continues to its terminus at Matthews Beach Park, where the creek empties into Lake Washington.

Since 1996, the state has listed Thornton Creek as impaired for fecal bacteria, and in 2004, the creek was listed as impaired for temperature and dissolved oxygen. Historically, the creek supported several native salmonids, but most of the species have severely declined (City of Seattle 2000). Water samples collected during base flows between 1990 and 2001 showed mean values of 827 CFU/100 mL (state standard is fewer than 50 CFU/100 mL) and a maximum concentration of 31,000 CFU/100 mL (Seattle Public Utilities 2007). During times of especially high bacteria concentrations, the city closes Matthews Beach to swimming. Due to concerns about bacteria loads and its impact on the watershed, King County and Seattle funded three MST studies in the basin.

Study summary

The first two MST studies used library-dependent methods to match *E*. *coli* isolates to known hosts. The first study, funded by the county in 2001, was designed to determine if human sewage was a significant source of the fecal bacteria. The study found that only 4% of the isolates were sourced from humans, with wildlife contributing 73%, pets sourcing 11%, and 12% of the samples having unknown hosts (King County 2001*a*). Seattle funded a subsequent MST study of the basin in 2007, which found similar proportions (Seattle Public Utilities 2007). Assuming that bacteria matched to "avian" sources were from wild birds, wildlife were responsible for 83.9% of all the fecal bacteria (44.0% avian and 43.9% other wildlife). Canines (probably domestic dogs) accounted for 10.0% of the bacteria; felines (probably domestic cats) for 0.9%; humans for 2.9%; and 6.3% could not be matched to sources. None of the isolates were matched to pasture animals.

The final study, conducted five years later in 2012, used library-independent methods to determine if humans were a significant source of fecal bacteria in the watershed. Presence of the species *Bacteroides thetaiotaomicron* was interpreted as evidence of a recent human source. Results indicated that human fecal bacteria from multiple sources in the basin are in fact entering the waterways at a cumulatively significant level. This change could be explained by 1) a changing dynamic in human sources over the last five years; 2) Incorrectly identified *E. coli* isolates in the 2007 study; or 3) Incorrectly using *B*. *thetaiotaomicron* as an indicator of human sources.

Initial comparison

As in the Amazon Creek basin, the Thornton Creek basin is fully sewered, on a system separate from stormwater. There are no septic systems in the basin. Neither basin is noticeably used by domestic pasture animals. In addition, impervious surfaces comprise 42.8% of Thornton's watershed, a value that is more than but still similar to impervious cover in the ACB. Therefore, this basin was analyzed for further similarity to the ACB.

22. Tillamook Bay, near Tillamook, OR

The Tillamook basin drains over 560 mi^2 and five rivers: Miami, Kilchis, Wilson, Trask, and Tillamook. Increasing levels of fecal pollution led to reductions of shellfish production and in 1998, the state listed the watershed as impaired for bacteria and temperature (Tillamook Bay 1998). It was unclear if most of the pollution was coming from humans or from ruminants, because the watershed includes 185 concentrated animal feeding operations (CAFOs) (Shanks *et al*. 2006). To better determine the source of fecal pollution, the Tillamook Estuaries Partnership and Oregon State University (OSU) initiated an MST study.

Study summary

The MST study, conducted between 2001 and 2003, used library-independent methods to track fecal bacteria to either human or ruminant sources. Results showed that there was widespread contamination from ruminants, and some contamination from human sources in specific parts of the watershed (Shanks *et al*. 2006).

Initial comparison

Unlike the Amazon Creek basin, nearly all of the Tillamook basin is forested—6% in the ACB vs. 90% of Tillamook (Shanks *et al*. 2006). Only 0.9% of the land is impervious, compared with 33% of the ACB. This difference will significantly change the ability of a basin to take up pollutants before they reach main waterways. The CAFOs, although occupying a small proportion of the Tillamook watershed, are numerous and found on all but one of the main rivers. There are no CAFOs in Eugene. For these reasons, sources of bacterial pollution in this watershed are unlikely to be informative for extrapolating bacterial pollution of the ACB.

Notably, the Tillamook Bay watershed is the one of the few basins in this study that has a sizeable homeless population. Counts of unsheltered homeless in recent years range between 350 and 450, although this is probably somewhat higher than the population size 10 years ago (Skaar 2013). Unfortunately, OSU did not devise their study in a way that would examine the effect of homeless camps on fecal bacteria levels, so information could not be extrapolated about this source for the Amazon Creek basin.

23. Tualatin River sub-basins, near Tualatin, OR

The Tualatin River drains 712 square miles of northwestern Oregon, flowing east from the Coast Ranges into the Willamette River. The river and its tributaries periodically have fecal bacteria levels above state water quality standards, with the tributaries generally more polluted than the mainstem Tualatin. Two such tributaries, Fanno and upper Rock creeks, drain a 58.0 mi^2 portion of the watershed, and were studied using MST. The headwaters of both creeks are in the Tualatin Mountains. Fanno Creek empties directly into the Tualatin River, whereas Rock Creek empties into Beaverton Creek, a main tributary of the Tualatin. The two creeks flow through portions of Portland, Hillsboro, Beaverton, Tigard, and Durham.

Study summary

Concerns over human health and fish habitat in the area motivated Clean Water Services, the utility manager of the Tualatin River basin, to perform an MST study. The study, conducted between 2004 and 2005 used library-dependent methods to match *E. coli* isolates to known hosts. Of the canine isolates that could be matched to species, domestic dog sources outnumbered coyote sources in a 7:1 ratio (Clean Water Services 2005). Assuming this ratio holds for all the canine isolates, and assuming that bacteria matched to avian sources were from wild birds, about 75% of the isolates came from wildlife. Birds were the source of 51% of the isolates, rodents 16%, other wildlife 8%, domestic dogs 11%, felines 1%, humans 4%, and 9% could not be matched to a source.

Initial comparison

At the time of the study, about 28.1% of the drainage area were impervious surfaces—similar to the ACB. Although some of the drainage area is served by a sewer system separate from stormwater, it also includes areas with high concentrations of septic systems (Clean Water Services 2005). In addition, pasture land covered 11.0% of the area, a significant percentage considering that the ACB has virtually none. For these reasons, the exact fecal bacteria breakdown cannot be descriptive for the Amazon Creek basin.

24. White Center neighborhood, Seattle, WA

The White Center neighborhood in urban Seattle encompasses a small sub-basin. This area includes Hicks Lake, which is polluted with fecal coliform (Bouchard 2012). The City of Seattle conducted an MST study of the basin between 2011 and 2012, but results and other details of the study could not be obtained.

25. Willapa River sub-basins, near South Bend, WA

The Willapa River drains about 260 mi^2 of Washington's Pacific County. The River's headwaters lie about 20 miles east of Willapa Bay. Water flows northwest past several rural towns and through the cities of Redmond and South Bend before emptying into the Bay. The river is listed as impaired for fecal coliform bacteria, as well as dissolved oxygen and temperature.

Study summary

To better understand the sources of the bacteria, Pacific County hired a consulting firm to perform microbial source tracking on different sub-basins containing the Willapa River. The study, performed in 2003-2004, used library-dependent, ribotyping methods (Cosmopolitan 2005). Pasture animals hosted the largest proportion of fecal bacteria isolates in both the lower (36.0%) and middle (44.0%) sub-basins. Birds, humans, and wild ruminants (deer and elk) were the other major (>10%) sources of at fecal bacteria in both sub-basins.

Initial comparison

Although agriculture is the primary land use along the uppermost reaches of the river (Cosmopolitan 2005), the sub-basins have a small percentage of land dedicated to pasture grazing (about 5% in both sub-basins). The sub-basins monitored in the MST study are upstream of Raymond and South Bend, and the study area is therefore served by septic systems (Humphreys 2013), unlike the ACB. Also unlike the ACB, both the middle (251.9 mi^2) and upper (46.0 mi^2) Willapa sub-basins are heavily forested, at over 90% of the total land cover. Only 0.5% of the total areas of each basin are impervious surfaces; this was the lowest value of all watersheds that I analyzed. Because several of the initial comparison metrics for these sub-basins are different from the ACB, this basin was not analyzed further.

Appendix B

Unsheltered transients and homeless people within the Amazon Creek basin: a potentially significant source of fecal bacteria.

The January 2013 count of homeless people in Lane County found 1,102 unsheltered homeless people (Lane County 2013), and this number increases during the warmer months (Turner 2013). Based on discussions with homeless shelters and city employees in Eugene and in my study basins, more unsheltered homeless people live in the area during the summer than in the winter. Some homeless people are able to save earnings from their work by living in illegal campsites during the summer. In the winter, when work is more difficult to find and the weather is inhospitable, the numbers of unsheltered homeless people tend to decrease as they find homeless shelters, use their savings to pay for housing, or move to a new area (Skaar 2013).

Because some of the homeless population is also transient, it is difficult to exactly count the number of unsheltered people within Eugene or the Amazon Creek basin at any one time. In recent summers, although many of Eugene's unsheltered homeless live along the banks and canals of the Willamette River, over 130 lived within the ACB, possibly many more. Although homeless people prefer drier areas for camping, most of the places where they can camp in Eugene are next to waterways, and city staff has observed many camps in which the latrine was the waterway itself (Turner 2013). Further, any campsite near a storm drain would introduce fecal bacteria into waterways.

By contacting agencies who manage open space in the Eugene area (Bureau of Land Management, City of Eugene Parks & Recreation Dept., The Nature Conservancy, and Oregon Dept. of Transportation), I gathered the following information about unsheltered homeless and transients living within the ACB in recent years:

- Campsites are usually most concentrated in Amazon Park, Bertelson Nature Park, and open space parcels in West Eugene near Target and Wal-Mart (Taylor 2013, Turner 2013). Amazon Park does have public restrooms, and Bertelson Nature Park had one vault toilet, but those camping nearby do not always use these facilities (Baitis 2013, Turner 2013).
- In August 2013, between 75 and 100 homeless occupied Bertelson Nature Park when the Bureau of Land Management, which owns the property, evicted people from the area (Baitis 2013). The park includes a tributary of Amazon Creek. There was so much waste left behind, including human feces in and around makeshift latrines, that a hazardous material team cleaned the site.
- Between 20 and 40 unsheltered homeless camp in the City's Amazon Park during the summer (Turner 2013). This property is adjacent to Amazon Creek.
- Two former camp areas were located in portions of Meadowlark Prairie and Vinci parcels in West Eugene, with about 14-22 illegal sites during the summer (Fairchild 2013). Multiple people can live at each site, but depending on where people camp on

these parcels and during which times of the year, these two camps may or may not drain into Amazon Creek (Baitis 2013).

- ODOT owns 16 vacant parcels within the ACB, each ranging from a fraction of an acre to about 14 acres, for a total of 37 acres. ODOT does not count homeless people on these lands or ask them to leave, unless someone complains to ODOT about a particular camp. ODOT has had at least 12 complaints in 2013, which is more than in recent years, and at each site, there are usually between 2 and 12 people camping (Little 2013).
- The Nature Conservancy staff in the Willow Creek Natural Area asks homeless people to leave as soon as staff finds campers. In recent years, this was about five to 10 people a year, although in earlier years the number was higher (Knuckles 2013). This property includes the East and West forks of Willow Creek, which drain into the Amazon.
- Human sewage also comes from transients living in smaller numbers at other locations in other vacant land and parks, streets, and alleys.

In addition, camp-out protests, such as the Eugene SLEEPS protest in August 2013, also produce untreated sewage. These particular protestors left feces on park blocks, and later collected their feces and sent it down storm drains, which empty into Amazon Creek (Taylor 2013).

This information suggests that illegal camping in the basin may be a significant source of fecal bacteria in Amazon Creek.