# Assessing bacterial contamination in the Rivanna River from varying levels of degradation in a sewer main break.

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**Abstract:**

Raw sewage has long plagued human health and still does to this day in many parts of the world at different scales. In the United States, sanitation generally is not thought of as a problem, but due to aging infrastructure and other factors, 187,872 miles of rivers and streams are impaired for their high concentration of *E. coli* (ASCE, 2017)(EPA, 2019). Monitoring for bacterial impairment can be a headache due to the time-lag between sample collection and results and often leads to false positives and false negatives for the water conditions at the time the results are in (Griffith et al., 2009). To make the process more efficient to prevent these false positives and false negatives, modeling bacterial concentrations could be utilized. If a sewer main were to break along the Rivanna river what would the downstream affects be? This scenario was modeled with the motivation of preserving public health, supporting local economies and streamlining decision making processes for local public officials, the EPA and VADEQ. Using WASP8, concentrations of downstream bacterial loads were calculated and compared to EPA Recreational Water Quality Standards to see if the water was safe to swim in or not. It was found that in the worst-case scenario, a 0.1% leak would infect the entire downstream tributaries to more than 100 times the EPA recommendation.

## 1. Introduction

In the long history of mankind, it has generally been the case that humans and excrement have been kept separate. In the last 120 years human waste has been kept separate because of the knowledge of germ theory, but before germ-theory people kept their waste separated from them because feces had and still have an unpleasant odor. These odors and other foul smells were commonly referred to as miasmas. The common belief in those days was that miasmas would cause diseases such as dysentery, cholera, etc. One such event that occurred in 1858, The Great Stink of London, caused so much grief that the City of London allowed Joseph Bazalgette to reroute the existing sewer system. During the Great Stink, sewers would drain directly into the Thames River, which was also the main source of drinking water for the city. Human waste would line the shores of the Thames and after baked in the summer heat would create an awful stench that would sit on the City. Following the rerouting of the sewer system, London was spared from further cholera outbreaks. Some thought the sewers eradicated the miasmas, but others such as John Snow had been preaching since long before the Great Stink that cholera was water-borne. Regardless of public opinions on what caused the multiple outbreaks of cholera in London, there was a successful outcome.

While Europe was wrestling with Germ Theory, the United States remained relatively in the dark on this topic (Richmond, 1954). Public fear of miasmas was so strong that the same effect occurred in the United States as did in London; people put sanitary sewers in their homes (Whittington et al., 2008). Citizens even welcomed paying more in property taxes because they valued the abolition of miasmas so much (Whittington et al., 2008). With so much value being placed on sanitary sewers, the United States was able to provide sewage lines to 80% of the urban population by 1900 (Whittington et al., 2008). Much of these lines were not sent to treatment facilities (Whittington et al., 2008).

In 2017, the American Society of Civil Engineers (ASCE) gave the United States a D+ grade for wastewater infrastructure. They cited aging infrastructure, combined sewers and a

severe lack of funding as some of the reasons for their grading (ASCE, 2017). Due to large up-front costs, once drinking water and sanitary infrastructure is implemented it does not get replaced until absolutely necessary regardless of inefficiencies (Whittington et al., 2008). This leaves many leaky pipes in use nationwide that can pollute waterways and create public health hazards. There is also a small population of people in the Unites States that have "straight-piped" sanitation that sends their waste directly into waterways (Gasteyer and Vaswani, 2004).

As of December 14, 2019 there were 187,872 miles of rivers and streams that were impaired by pathogens in the United States (EPA, 2019). Waterbodies are listed as impaired when efforts to mitigate contamination are not strict enough given the water quality standards for that waterbody (US EPA, 2012). Bodies of water that people use are recreational waterbodies, which are defined as those waterbodies where people swim, surf, waterski, etc. (US EPA, 2012). The water quality standards for these bodies of water recommend that activity be shut down when the geometric mean of *Escherichia coli* (*E. coli*) reaches 126 CFU/100 mL and the statistical threshold value reaches 410 CFU/100 mL (US EPA, 2012). Given this framework and other reasons, there are many difficulties that go into placing a waterbody on the impaired list or closing recreational areas that are important to local economies.

One important reason why monitoring *E. coli* in waterways is difficult is because the source of *E. coli* is generally unknown. Waterbodies have multiple sources of *E. coli* including waterfowl, grazing animals and pets, but what risk do these other contamination sources cause humans? Microbial source tracking assumes that unless the *E. coli* is from a human, there is very little health risk (Ishii and Sadowsky, 2008). Another reason why monitoring *E. coli* is difficult to do is because there is evidence that *E. coli* can persist in the environment, which nixes the idea that *E. coli* has the same lifetime in water as other pathogens (Ishii and Sadowsky, 2008).

Therefore, making *E. coli* a less effective indicator of human health risks.

Most importantly, the greatest downfall when monitoring *E. coli*, and inspiration for this model, comes from the time lag between sampling and action. Sampling *E. coli* requires the growth of cells on plates or in liquid media over 18 - 96 hours to get a count of colonies (Griffith et al., 2009). Given the count of a sample taken on the previous day, officials can then decide about the current day. This decision-making process is inaccurate; allowing for false positives by closing the beach for the current day as well as false negatives for not closing the beach on the day the sample was collected (Griffith et al., 2009).

Due to the inaccuracies that monitoring *E. coli* inherently contains and the large implications that arise from those results, it would be in the best interest of municipalities to model *E. coli* concentrations from point sources in recreational waterbodies to streamline decision making. Given this proposition, a Water Quality Analysis Simulation Program (WASP8) model was used to estimate the downstream effects from a sewer main break of varying severity on the Rivanna River. WASP8 was chosen because bacteria are the center of the study and WASP8 has the power to model bacteria in waterways.

## 2. Materials and Methods

### 2.1. Study area

The Rivanna river is located in Central Virginia with the area of interest upstream of USGS monitoring Site 02034000 in Palmyra, Virginia. With an area of 1,721 km$^2$, the Rivanna watershed covers a wide variety of land uses and travels through the densely developed City of Charlottesville. Using the software BASINS, the river was mapped to show third order and above stream segments as seen in Figure 1. Third order and above streams were selected because the Rivanna river goes through the City of Charlottesville as a fourth order stream, which is where there is the highest likelihood of a sewer
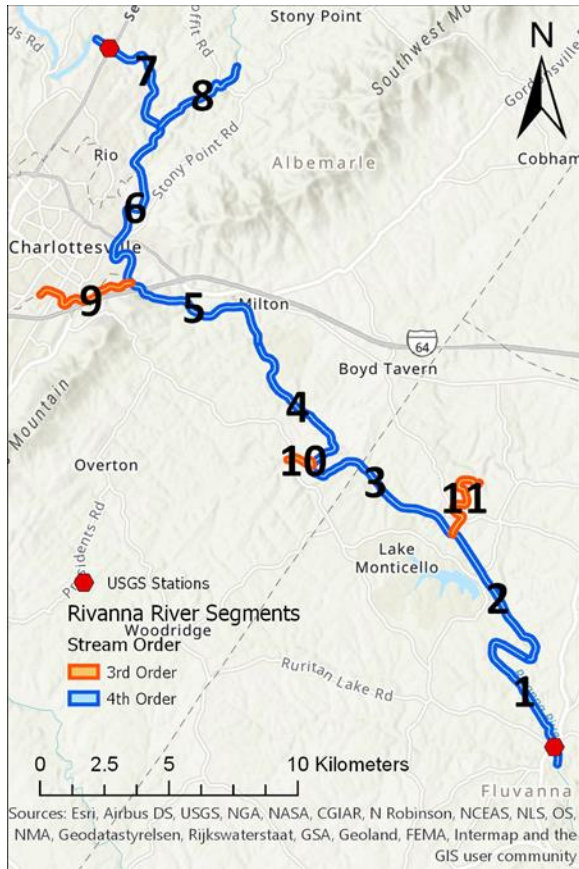
*Figure 1: The refined network that BASINS produced, exported into ArcGIS Pro.*

main break to occur. Another reason for the selection of third order streams was to account for water inputs into the main channel from local creeks including the Moores Creek, Buck Island Creek and Mechunk Creek.

## 2.2. WASP8 Model

To model *E. coli*, WASP8 model was used. After the channel network was configured in BASINS, it was imported into WASP8 and routing was configured to assure that correct sections of the river were flowing in the correct direction, as depicted in Figure 2. WASP8 offers a multitude of options regarding stream transport options; flow routing, stream routing, kinematic wave, weir overflow, hydrodynamic linkage and dynamic flow. Kinematic flow was chosen for this model because it is a straightforward and realistic option for modeling advective transport in river systems. When importing the network from BASINS, important

information including length, width, depth, slope, manning roughness, velocity and travel time was also brought in. The only information that was needed after importing from BASINS was the depth exponent and velocity exponent. Both inputs were decided after consulting the WASP8 Stream Transport guide. The guide had average inputs based on 158 other U.S. gaging stations stating that the average velocity exponent was 0.43 and that the average depth exponent was 0.45 (Ambrose and Wool, 2017).
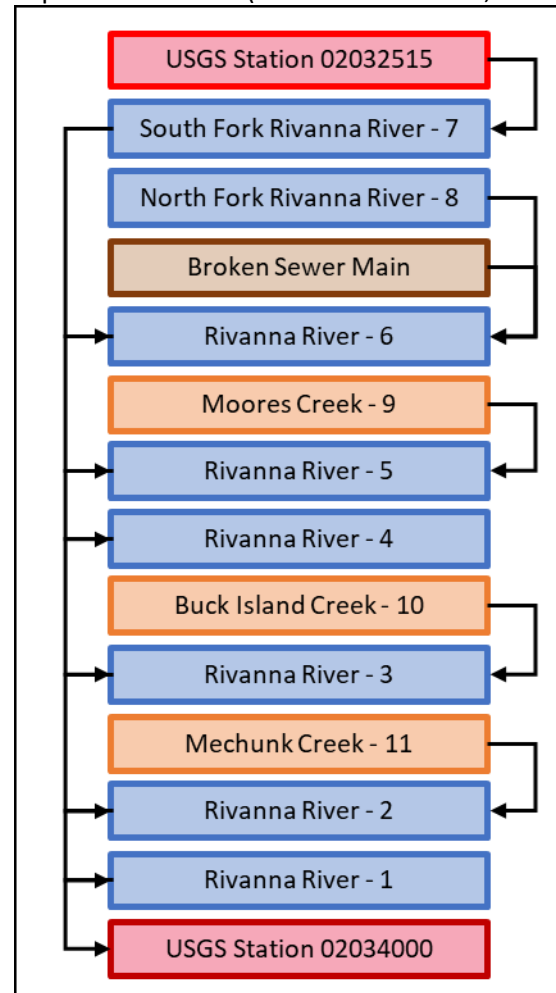


*Figure 2: Flow chart of river flow for input to WASP8 model.*

Next, flows had to be set for the system. In the watershed, there are two USGS stations; 02034000 in Palmyra and 02032515 near Charlottesville. Because bacteria counts are based on concentration it was decided to perform the model in a steady state. Using the

USGS stations, discharge rates were determined by looking at the median flow for everyday over the history of the gage. From viewing the median flow versus time graphs, it was determined that flow into the South Fork of the Rivanna river would be 80 cubic feet per second (CFS) and that discharge in Palmyra would be equal to 200 CFS. This leaves the North Fork of the Rivanna River, Moores Creek, Buck Island Creek and the Mechunk Creek unaccounted for with monitored discharge. To estimate discharge from these sources, the independent watersheds were delineated, and the areas were found. The sum of the watersheds was found and used in the denominator to calculate the percentage of land that each watershed covers among the four. Once a percentage was found, it was multiplied by 120, the difference between flows observed from USGS stations in Charlottesville and Palmyra, to get the roughly estimated flow of the independent watershed. The estimation method found that the North Fork of the Rivanna River contributes 69 CFS, the Mechunk Creek contributes 24 CFS and both Moores Creek and Buck Island Creek contribute 14 CFS. All flow values were then converted into metric values and put into the model. In WASP8, the type of model being run had to be set under the Data Set tab. Advanced Toxicant was chosen to be run over a 5 day period on hourly intervals to give the model time to reach steady state in all portions of the river.

Following the import of the channel information and flows, the sewer leak had to be put into the model as a flow as well. It was decided that the sewer leak could be placed into the model as an ephemeral stream where discharge is varied based on the degradation of the pipe. To do this, the City of Charlottesville Standards and Design Manual was consulted. The manual stated that sewer mains have to be between 8 and 30 inches in diameter, velocity must always be in the range of 2 to 15 feet per second (FPS), and that the manning roughness is 0.014 (City of Charlottesville, 2019). Based on the city standards, a stream of waste was created that had the same cross-sectional area

as a 30-inch pipe, but in the shape of a square. Making the flow cross section in a perfect square made assigning both velocity and depth exponents easier because rectangular channels have these inputs defined in the user's manual as 0.4 and 0.6 respectively (Ambrose and Wool, 2017). 15 FPS and a 30-inch diameter pipe were chosen because there needs to be a margin of safety when predicting potential human health hazards. Using the worst-case scenario allows for a large margin of safety, which is necessary when discussing human wellbeing.

Succeeding the defining of flows in the system, loads of *E. coli* had to be defined as well. While stretches of the Rivanna River are already impaired for pathogen contamination, it was assumed in the model that the river was pristine (VA DEQ et al., 2018). The assumption was made because this study aims to see the magnitude of impact from a sewage leak, not how the river has behaved from other factors. This same reasoning was used when selecting constant air and water temperatures of 20 centigrade. A study on pathogen loading in wastewater found that that geometric mean concentration of *E. coli* in screened wastewater was just over 4 million CFU/100 mL and the maximum concentration of *E. coli* found in screened wastewater was 9.6 million CFU/100 mL (Campos et al., 2013). Using the same worst-case scenario mentality, the maximum concentration was selected for setting the load in the sewer.

Lastly, a bacterial decay rate had to be set. After consulting literature, it was found that bacterial load tends to increase the first day and then between the first and fifth day there was 97% removal. Because WASP8 only allows for a linear decay rate, it was assumed that the 97% removal rate observed from day one to five would suffice for day 0 to five. The parameter used would be 1.86 million cell deaths per day. It was calculated by multiplying 9.6 million CFU/100 mL with 97% and dividing by 5-time steps. When selecting bacteria as the pollutant of interest, Mass Balance was selected as the method to calculate concentrations. To also account for the increase of bacteria that occurs

on the first day, the model will also be run with no decay rate to see how water quality is affected on the first day.

**3. Results**

Using the results from the WRDB output that WASP8 creates, Table 1 was created to summarize the results with the parameters stated in the materials and methods section. Unfortunately, the results reported back from the most severe break in the pipe is not all that interesting because the water is supposedly safe to swim in. To see the change in decay rate, view Table 2.

Table 1: 100% pipe discharge results. Peak bacteria concentrations over five days.

| River Section | Bacteria Conc. (CFU/100 mL) | Swimmable |
|---|---|---|
| 6 | 35 | Yes |
| 5 | 0 | Yes |
| 4 | 0 | Yes |
| 3 | 0 | Yes |
| 2 | 0 | Yes |
| 1 | 0 | Yes |

Table 2: E. coli concentrations when decay rate is zero and 24 hours have passed.

| River Section | Bacteria Conc. (CFU/100 mL) | Swimmable |
|---|---|---|
| 6 | 3.1 Million | No |
| 5 | 2.9 Million | No |
| 4 | 2.9 Million | No |
| 3 | 2.7 Million | No |
| 2 | 2.3 Million | No |
| 1 | 2.1 Million | No |

Table 2 shows that when bacterial decay is zero, all reaches of the river are extremely unsuitable to swim in from 100% discharge from the sewer into the river, which is expected. Table 3 depicts maximum *E. coli* concentrations downstream from 10% flow coming out of the sewer into the Rivanna river after 24 hours of

Table 3: E. coli concentrations when decay rate is zero and flow is 10%.

| River Section | Bacteria Conc. (CFU/100 mL) | Swimmable |
|---|---|---|
| 6 | 360 Thousand | No |
| 5 | 422 Thousand | No |
| 4 | 417 Thousand | No |
| 3 | 368 Thousand | No |
| 2 | 298 Thousand | No |
| 1 | 258 Thousand | No |

Table 4: Maximum E. coli concentrations when decay rate is zero and flow is 5%.

| River Section | Bacteria Conc. (CFU/100 mL) | Swimmable |
|---|---|---|
| 6 | 248 Thousand | No |
| 5 | 227 Thousand | No |
| 4 | 224 Thousand | No |
| 3 | 197 Thousand | No |
| 2 | 163 Thousand | No |
| 1 | 136 Thousand | No |

Table 5: E. coli concentrations when decay rate is zero and flow is 0.1%

| River Section | Bacteria Conc. (CFU/100 mL) | Swimmable |
|---|---|---|
| 6 | 31 Thousand | No |
| 5 | 28 Thousand | No |
| 4 | 28 Thousand | No |
| 3 | 25 Thousand | No |
| 2 | 20 Thousand | No |
| 1 | 17 Thousand | No |

flow. Table 4 shows maximum bacteria concentration within the first 24 hours of 5% flow. Yet again, the entire system is unsuitable for swimming and other recreational activities. For the final simulation, the model was run with 0.1 percent of the flow escaping the sewer and breaching the river. Table 5 shows the peak bacteria concentration after 24 hours of flow.

## 4. Discussion

Based on the results it is inferred that if there were a sewer main break along the Rivanna River, people should be highly discouraged from recreating along the river between Charlottesville and Palmyra, and probably beyond. With this being said, the margin of safety used for the model was incredibly high and if a real leak were to happen that gained the attention of the public works, more information could be used to model the immediate risks. There are many other factors that factor into *E. coli* decay than just a decay rate itself. Ultraviolet disinfection as well as temperature and nutrient availability are important factors that should be considered when assessing the lifecycle of microbes (Griffith et al., 2009). The model can account for these factors, but the study consulted for decay rates was conducted in a watershed setting where microbes were exposed to similar conditions. Due to the same article studying the lifecycle of free-floating *E. coli* and when *E. coli* is sorbed to sediment, sediment modeling was not necessary although the model has the power to do so.

While working with the modeling software there was much to like that was left unused. There was the ability for variable flows, temperatures, radiation and many other parameters that would come in handy for an experimental watershed where everything is monitored. Unfortunately for this study, the watershed was not monitored very well and will certainly cause the model to be misleading. Another reason the model is misleading is because there is variability in flow of sewage. Most people use water and their bathrooms in the morning and in the evening.

One thing that WASP8 could improve on would be the Microbial Decay constant. Table 1 is a testament to that statement. For some reason, when the decay rate was set to 1.86 million bacteria a day, the concentrations in every stream branch would be inaccurate. When trouble shooting this problem, the concentration of the bacterial load in the sewer was checked and it was less than half of 9.6 million CFU/100 mL it should have been. This could have been user error, or something gone wrong in the program, but not having a user manual specified for microbial modeling proved to be a challenge for this particular constant and throughout the whole modeling process.

Ultimately, this model could be used in the future with more monitors in place on sewage lines and throughout the watershed. If a family knew that their sewer was leaking because a tree's root system grew into the pipe, cutting the tree sown, monitoring and remediating the immediate subsurface area could potentially be more cost effective than replacing the whole pipe. This would allow for agencies like Virginia DEQ to keep tabs on a traditionally non-point source of pollution with better hopes of modeling human health risks.

## 4. Conclusion

The effects that raw sewage have on human health have been well documented over the years, but in today's world there are many factors that are leading to the rise of fecal matter in our environment mainly due to the failure of infrastructure and large fixed costs associated with fixing infrastructure (Whittington et al., 2008)(ASCE, 2017). A sewer main break along the Rivanna river could potentially be detrimental to downstream water quality for recreational users. This was modeled with the motivation of preserving public health, supporting local economies and streamlining decision making processes for local public officials, the EPA and VADEQ. Using WASP8, it was found that within 24 hours of a leak coming out of a sewer main into the Rivanna River near Charlottesville, the entire river would be severely impaired with a bacterial load over 100 times the limit. Due to many faults in the modeling done, there is hope that in the future a monitoring network can be used to further improve the model. The model could also stand for some improvements that could allow for greater confidence from the publishing of a user

manual that describes the modeling of bacteria in watershed systems.

**References:**

Ambrose, R.B., Wool, T.A., 2017. WASP8 Stream Transport-Model Theory and User's Guide Supplement to Water Quality Analysis Simulation Program (WASP) User Documentation.

ASCE, 2017. 2017 INFRASTRUCTURE REPORT CARD: A COMPREHENSIVE ASSESSMENT OF AMERICA'S INFRASTRUCTURE.

Campos, C.J.A., Avant, J., Lowther, J., Till, D., Lees, D., 2013. Levels of Norovirus and E. coli in Untreated, Biologically Treated and UV-Disinfected Sewage Effluent Discharged to a Shellfish Water. J. Water Resour. Prot. 978–982. https://doi.org/10.4236/jwarp.2013.510101

City of Charlottesville, 2019. Charlottesville Standards & Design Manual.

EPA, 2019. National Summary of State Information | Water Quality Assessment and TMDL Information | US EPA [WWW Document]. URL https://ofmpub.epa.gov/waters10/attains_nation_cy.control#causes (accessed 5.3.19).

Gasteyer, S., Vaswani, R., 2004. Still Living Without the Basics in the 21st Century: Analyzing the Availability of Water and Sanitation Services in the United States.

Griffith, J.F., Cao, Y., McGee, C.D., Weisberg, S.B., 2009. Evaluation of rapid methods and novel indicators for assessing microbiological beach water quality. Water Res. 43, 4900–4907. https://doi.org/10.1016/j.watres.2009.09.017

Ishii, S., Sadowsky, M.J., 2008. Minireview Escherichia coli in the Environment: Implications for Water Quality and Human Health. Microbes Env. 23, 101–108. https://doi.org/10.1264/jsme2.23.101

Richmond, P.A., 1954. American attitudes toward the germ theory of disease (1860-1880). J. Hist. Med. Allied Sci. 9, 428–454. https://doi.org/10.1093/jhmas/IX.4.428

US EPA, 2012. Recreational Water Quality Criteria.

VA DEQ, VDH, DCR, 2018. 305(b)/303(d) Water Quality Assessment Integrated Report.

Whittington, D., Hanemann, M.W., Sadoff, C., Jeuland, M., 2008. The Challenge of Water and Sanitation.