# Water Quality Improvement for an Urban World
## Honors Capstone

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## 1.0 Introduction

Water Quality is one of the most important factors in human health. Water quality is only growing in importance as infrastructure ages and areas become more urbanized. Growing population density adds stress to an already aging infrastructure, it is estimated that the average water system age is 45 years (Tabuchi, 2017). A consequence of this is a higher rate of failure as components of the system go past their recommended lifetime. A common failure is sewage overflows. Sewage overflows (SO's) can happen in combined sewers or a sanitary sewer. When the SO happens in a combined sewer system (where stormwater and sewage is mixed) it is considered a combined sewage overflow. Our system targets either situation (SO or CSO). Both SO's and CSO's happen due to a larger volume of water in the system than the wastewater treatment plant can safely treat. When such events happen, the superfluous water is diverted from the plant and released (or stored when possible). Our design is placed at the outflow pipe to partially treat the wastewater. These sewage overflows are an issue as it releases pathogens into the environment, increases turbidity and, increases nutrients loading. Pathogens pose an issue for both downriver communities and aquatic life. The increased turbidity is linked to increased total dissolved solids; this increases the temperature of the system aswell as can reduce the capacity for photosynthesis.

The design itself was started in the University of Michigan Center for Socially Engaged Designs' Innovation in Action competition for 2021. The design takes into account the socially engaged design principals. As such it included conversations with stakeholders such as the wastewater treatment plant manager, rowers, business owners, aquatic biota experts, and downstream communities.

The Quality Water and Contamination Control Unit is our design to reduce the many issues related to sewage overflows. Our design (further explained later) uses screening, granulated activated carbon, and UV. Screening is the first step and removes the large constituents. then it goes into the main body of where it meets three granulated activated carbon filters which reduce turbidity and many other constituents of concern such as chlorine, trihalomethanes, mercury, pesticides, herbicides, iron, lead, and bacteria. UV can reduce the pathogen load by 99.9% without creating harmful disinfectant byproducts.

Statistical Hypothesis Testing via two One Sample t-tests were conducted to investigate whether or not a statistically significant relationship was in our prototype's ability to reduce turbidity by a certain percentage accuracy while altering water flowrates would be present. The idea behind conducting these statistical tests would be so that results from them could be later used to further optimize and refine the physical structure of the protype in future prototyping design stages.

Our design showed that around 40% reduction of turbidity was plausible though the testing was insufficient to make any definite conclusions.

Our next steps include further testing of turbidity and flowrates of the current design, as well as adding coliform testing to ensure the expected reduction of pathogens is happening. Improvements to the design itself includes moving the outlet tube to the bottom of the body, adding the turbine and solar panels to make the system energy independent. Finally, adding a hatch at the top to make it easier to remove the filters for replacement or cleaning. The current system has potential to greatly reduce the issues related to sewage overflows.

## 2.0 Methods

The following section outlines the ideological and physical methodology of this project

### 2.1 Socially Engaged design

The socially engaged design methodology takes into account the impact of a design on active stakeholders. It encourages equity and socially conscious designs that not only work in the short term but long term as well (Center for Socially Engaged Design, 2022). In this section we will cover the global, cultural, systems impact as well as the ergonomic design principles.

#### 2.1.1 Global Cultural/Systems Impact

Designing a prototype that was environmentally sustainable and conscious of the communities it served was a crucial objective throughout the entirety of the designing, developing, and constructing processes.

In regards to ensuring that our prototype was environmentally sustainable, we consistently made strides in ensuring that the majority of the materials we utilized would be both recyclable and reusable in the actual construction of prototype. A notable component of our prototype that embodies this includes that activated carbon in our QWACC solution. This activated carbon is both biodegradable and would have zero negative externalities when needing to be replaced and recycled after its effective duration of approximately 36 months (Paragan Water Systems, 2018).

Communities such as Flint, Ann Arbor, and the greater Metro Detroit area would greatly benefit from our QWACC solution as several of these counties municipal wastewater departments have aging sewage infrastructure and raise potentially community concerns in regard to the safety of their local water supply(s). Due to increased industrialization and storm water runoff, cases of combined sewage outflows (CSO's) have been consistently more prominent in much of southeast Michigan for several years now. This is especially a pertinent concern in Flint and its neighboring communities as many individuals simply do not trust the existing county's efforts in ensuring a clean, safe water supply after the Flint lead water crisis that only ended back in 2019 (Denchak, 2018)—and an increased concern for CSO would only raise more concerns and distrust amongst locals and their cities municipal county. In addition to being cognizant of societal externalities caused by the Flint Water Crisis to Flint and a majority of metro Detroit, we catered our solution to be affordable by a majority of municipal sewage budgets—as our protype net cost was well under $1000 (see table 1); and ensured that it was easy to install—as no significant technical skillset(s) or expensive toolset(s) would be required to gather and/or assemble our QWACC solution.

#### 2.1.2 Societal Ergonomic Design Principles

Throughout the construction and implementation process of our water treatment solution prototype, we ensured that our design would be an appropriate weight and size to prevent ergonomic and musculoskeletal injuries during the assembly process. Sewage maintenance workers are particularly prone to numerous musculoskeletal injuries (e.g. Rotator cuff injuries, soft tissue injuries, osteoarthritis, etc.) due to excessive weight/awkward positioning during the installation/maintenance processes of certain water treatment equipment (Duque, 2018). To combat these potential injuries, we decided to ensure that our solution's components net weight(s) were sub 20 lbs., and that all components could be pre-installed, and one would not need to assemble the solution in the actual sewage in the actual sewage unit itself—preventing several of the awkward potential positionings that could lead to excess fatigue and injuries.

Additionally, we determined that a cylindrical shape would be optimal for our prototype to both effectively remove particulates and be easily handled/installed by workers in a given sewage unit because its potentially counterparts (e.g. a square and/or rectangular shape) would be larger in terms of surface area and weight and thus would be harder to handle and install. Particularly, having more unused surface area in the QWACC solution would mean that there would be an increased probability that excess waste would potentially remain in the chamber and could eventually deteriorate multiple internal components—Hence, it was to the greater benefit to reduce this negative externality and increase the potentially effective longevity of our solution by simply choosing a different shape.

### 2.2 Pre-construction

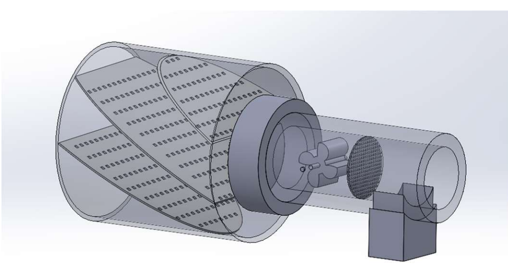

**Figure 1: CAD of initial prototype design**

This design was started in the winter of 2021 in the Center For Socially Engaged Design's "Innovation in Action" competition. At this time the team was composed of Tao Cai, Rosalia Otaduy-Ramirez, and Vanessa Woolley. This competition produced the initial design that is shown in Figure 1.

This design included an initial screening system and catchment, turbine to reduce flow velocity, several activated carbon filters, UV lights (not pictured), and solar panels (not pictured). The goal of this prototype was to reduce the potency of untreated wastewater into the Huron River specifically from the Ann Arbor Wastewater Treatment Plant (though the design has further applicability).

In the process of design, the team consulted with many local stakeholders such as: rowers, downriver communities, business owners, fish biologists, local activists, and management at the wastewater treatment plant. The insights that these stakeholders contributed were invaluable to the initial design and selection of the issue itself.

**2.3 Prototyping**

Prototyping was undertaken over the course of the Winter 2022 semester with support from the Center for Socially Engaged Design. Materials were provided as well as lab space in the Center for Socially Engaged Design lab.

The initial prototype we constructed was a simplified version of the full design introduced in the previous section. Our design was simplified in order to accommodate supply chain issues, budget, and timing. The simplified design omitted the power components of the design including the solar panels and turbine.

The methodology of construction was to create a rough proxy in order to test the turbidity reduction aswell as UV, and screening feasibility as both a proof of concept and a jump point for future iterations. The construction started with sourcing the required materials which is summarized in the following list:

**Table 1: Material price and quantity**

| Material | Quantity | Cost (USD) |
|---|---|---|
| 8 inch clear PVC pipe (2 feet in length) | 1 | $ 149.95 |
| 4 inch clear acrylic display case (8 inches in length) | 2 | $ 25.06 |
| 4 oz Oatey PVC cement | 1 | $ 12.05 |
| 1 foot x 2 foot acrylic sheet | 1 | $ 12.86 |
| Landscape fabric | 1 | $ 19.99 |
| 20 lbs IPW industries Coconut shell granulated activated carbon | 1 | $ 79.87 |
| ¼ inch 23 gauge chicken wire | 1 | $ 32.99 |

| | | |
|---|---|---|
| 4 Aquarium UV lights (10.24 in in length) | 4 | $ 83.08 |
| Total | - | $ 427.90 |

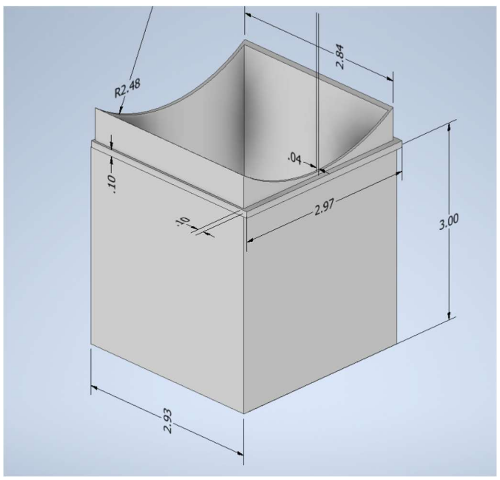


**Figure 2: Catchment design with dimensions in inches**

The first step in construction was prepping all components of the body. This started with cutting the large PV to a 1-foot length, then the bottoms we sawed off the display cases for the inlet and outlet, finally two concentric circles were cut out of the acrylic to connect the large pipes to the smaller. Then the inlet screen and the catchment were designed. The catchment went through iterations to properly fit into our inlet. The final CAD is in the figure to the right. The catchment was printed using a Ender 3 Pro with a model made in Autodesk Inventor Professional 2022. The initial screen was chicken wire cemented to the inlet pipe. The filters were then made with two layers of landscape fabric sewn together and filled with Granulated Activated Carbon before the filter was encased in the chicken wire for stability and ease of installation. Finally, all components were put together along with the UV evenly spaced in the top and bottom.

### 2.4 Testing

The following section outlines the physical and hypothetical testing conducted on the prototype.

#### 2.4.1 Physical Testing Parameters and Setup

The physical testing of our prototype was conducted on April 2$^{nd}$, 2022 in the University of Michigan- Ann Arbor flume lab. Testing focused on turbidity reduction and flowrate. This consisted of setting up the prototype with a 90-degree joint and a standing tube where water is put into the prototype.

**Figure 3: Testing Setup**

**Figure 4: Water Flowing through prototype**

Each trial consisted of flushing the body with water to ensure a consistent starting condition for subsequent trials. Then a set amount of water was mixed with soil to create turbid water. The initial turbidity was measured with the secchi disk. A secci disk is a circular disk with quarters of alternating black and white that is used to measure turbidity in a water source. After this the water was poured into the model at a set rate. The time to get the same volume of water out was measured aswell as a final measurement of turbidity.

Secchi disk measurements are taken by lowering the secchi disk into the water until not visible, taking a measurement of depth, then slowly bringing up until just visible again and taking a measurement. The two depths are then averaged and can be converted to values of NTU with the following equation from the Penn State College of Agriculture:

$$\text{Turbidity} = 24.2d^{-1.52} \quad (1)$$

Where:

Turbidity is in units of NTU

*d* is depth in units of feet

This relation was found from plotting the relation of turbidity and depth and fitting a curve to the data. This plot is shown in the figure below (Penn State College of Agriculture, 2017).

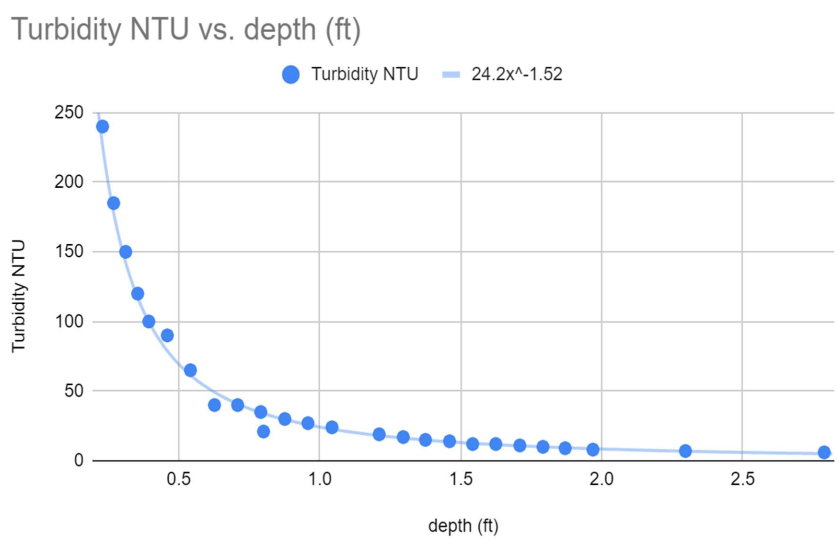


**Figure 5: Relation between turbidity and depth (data from Penn State College of Agriculture- plot generated by Vanessa Woolley)**

We took our initial and final turbidity on each run and got the percent removal of turbidity. On each trial we also calculated the flowrate based on the volume and time with the following formula.

$$Q = \frac{V}{t} \tag{2}$$

Where:

Q is the flowrate in gallons per minute (gpm)

V is the volume in gallons

t is the time elapsed in minutes

### 2.4.2 Model of Statistical hypothesis testing:

To further investigate and optimize our protype's strengths and weaknesses, we decided to conduct statistical hypothesis testing. The primary question we wanted to investigate in this round of hypothesis testing included whether or not there was a *significant* turbidity percentage reduction accuracy at a given water flow rate after water passed through our water treatment solution. In order to do so, we decided to design an experiment which would involve varying flow rates and measuring the given turbidity reduction percentage.

The design of our preliminary experiment involved sampling 15 different trials at 3 different flow rates (slow, medium, and fast)—and each flow rate would have 5 trials. However, as we began the actual testing phase of the protype by running water through it—wear and tear began to impact the structural stability of the prototype in the practice trials. So, in order to preserve the structural integrity of the protype, we decided to reduce the measured flow rates to two (medium and high), and have only 3 trials per flow rate instead of 5.

The Final experimental design could be summarized as follows:

***Research Question:*** We want to identify whether or not there is a significant turbidity percentage reduction accuracy at a given water flow rate after water passes through our water treatment solution.

***Target Condition:*** Turbidity reduction should be 40%

***Independent Variable:*** Flow rates will be altered (while passing through filter)

***Dependent Variable:*** Turbidity reduction percentage of water

**Table 2: Data Collection Structure (tabular):**

At Flow rate (GPM): [Medium Flow Rate]

| Trial # | Turbidity Reduction Percentage (%) |
|---|---|
| 1 | |
| 2 | |
| 3 | |

At Flow rate (GPM): [High Flow Rate]

| Trial # | Turbidity Reduction Percentage (%) |
|---|---|
| 1 | |
| 2 | |
| 3 | |

In regards to modeling the statistical analysis of the collected data, it was determined that conducting a One Sample t-test for both flow rates would be an optimal analysis metric to test significance—as both samples were independent of each other and tested under normal circumstances.

The Model for our One Sample t-tests for our statistical analysis was as follows:

- One Sample t-test conducted at a significance level of $\boldsymbol{\alpha} = 0.05$. Assume Normal conditions (observations).
- $\mathbf{t_{critical}}$ determined from t distribution table (see Figure 1 attached appendix).

One Sample t-test:

$$\text{Null Hypothesis: } H_0: \mu = \mu_0$$
$$\text{Alternative Hypothesis: } H_1: \mu \neq \mu_0$$

$n = \text{number of trials}$

$\mu_0 = \mu = \text{hypothesized ideal mean percentage reduction}$

$X_k = \text{Turbidity Data Point}$

$\overline{X} = \text{Mean value of Turbidity Data Set}$

$$\text{Sample Variance} = S^2 = \frac{1}{n-1}\sum_{k=1}^{n}(X_k - \overline{X})^2 \qquad (3)$$

$$\text{Standard Deviation} = \sigma = \sqrt{S^2} = S \qquad (4)$$

$$\text{Test Statistic} = T = \frac{\overline{X} - \mu_0}{\frac{S}{\sqrt{n}}} = \frac{\overline{X} - \mu_0}{\frac{\sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(X_k - \overline{X})^2}}{\sqrt{n}}} \qquad (5)$$

$$\text{t critical value} = t_{critical} = t_{n-1} \qquad (6)$$

where $n - 1$ is the number of degrees of freedom

if $t_{critical} > T$, then we fail to reject $H_0$

### 3.0 Results

The following sections outline the results of the initial prototype.

### 3.1 Final Construction

Though construction had many setbacks such as the need for landscape fabric, cracking of the acrylic, and some difficulty with adhesives, the final product was usable and was able to test turbidity reduction. The following figure is an image of the final prototype.

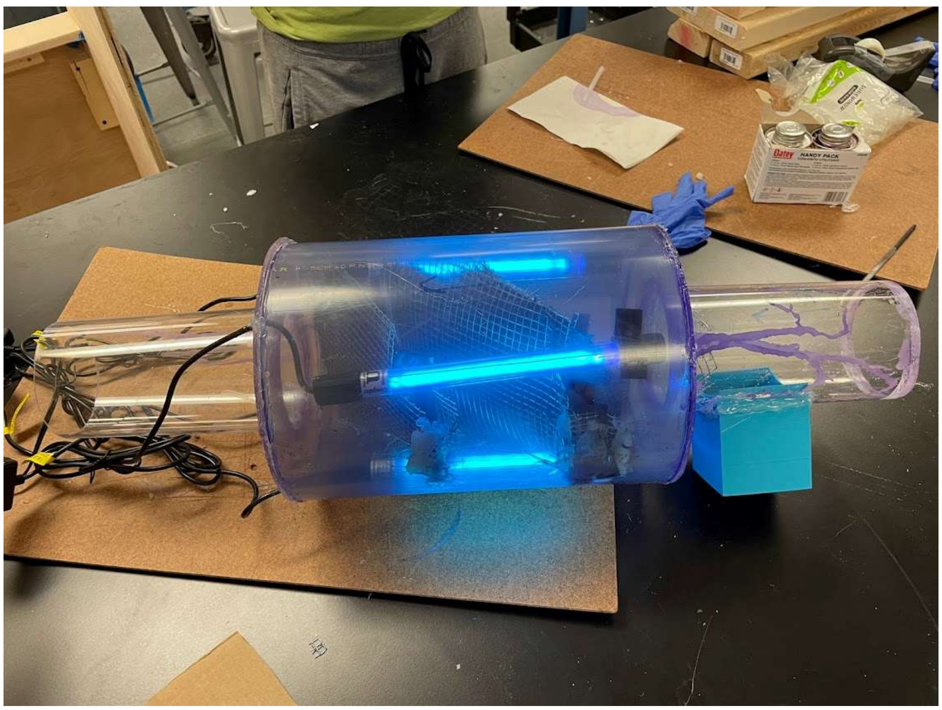

**Figure 6: Final constructed prototype**

### 3.2 Turbidity

Turbidity was our main testing parameter as it is a common proxy for total suspended solids (TSS) (Rugner, Schwientek, Beckingham, Kuch, & Grathwohl, 2013). TSS is an important constituent to remove from wastewater as increased TSS can cause increased temprature in water, reduced clarity, hinder photosynthesis, and allow bacteria growth (Campbell, 2021). Therefore, removal was an important parameter. We aimed for a reduction of 40% as a baseline for our quick treat system.

The result of our testing is shown below. On average, most of the trials reached our goal of 40% reduction. Though, further testing is required to verify as the first trial had significant standard deviation.

**Table 3: Turbidity reduction at a flow rate 1.69 of GPM**

| Trial # | Turbidity Reduction Percentage (%) |
|---|---|
| 1 | 79.46 |
| 2 | 41.53 |
| 3 | 32.38 |

**Table 4: Turbidity reduction at a flow rate 3.69 of GPM**

| Trial # | Turbidity Reduction Percentage (%) |
|---|---|
| 1 | 43.02 |
| 2 | 46.00 |
| 3 | 40.60 |

### 3.3 UV disinfection

The choice of UV disinfection was made due to its ability to reduce pathogens in the water without chemical handling or residuals. In cases where UV is used for sterilization the optimal wavelength is 253.7 nm (Alfaa UV, 2020). UV can destroy 99.9% pathogens in 10 seconds within 6 inches of the light (Alfaa UV, 2020). There are no toxic biproducts and the environmental impact is low as it doesn't use much energy. We did not have access to a culturing test, but future testing could include testing to ensure the full contact time is reached in our design.

Implementing an additional 185 nm wavelength UV can reduce up to 2 ppm of total organic carbon (TOC) from water (Dallan, 2002). Though this was not in our current design- that could increase the effectiveness of our design.

One consideration in addition to full contact time is possible shielding due to turbidity (Cantwell, Hoffmann, Rand, Devine, & VanderMarck, 2010). We expect this not to be a huge issue as there is sufficient exposure time (above the recommended 10 seconds and 6 inches required) aswell as the turbidity is reduced (reducing the number of particles contributing to shielding).

**Commented [VW1]:** Could calc the contact time

### 3.2 Flow Rate

Two Flow rates were tested during this experimental process: A medium flow rate of 1.69 Gallons per minute and a high flow rate of 3.69 Gallons per minute—each having their own respective One Sample t-test.

Results for the two one sample t-tests are provided below:

*One Sample t-test at medium flow rate 1.69 GPM*

Null Hypothesis: $H_0: \mu = 40$
Alternative Hypothesis: $H_1: \mu \neq 40$
$n = 3$
$X_1 = 79.46, \ X_2 = 41.53, \ X_3 = 32.38$
$\bar{X} = 51.12$
$$S^2 = \frac{1}{3-1}\sum_{k=1}^{n=3}(79.46 - 51.12)^2 + (41.53 - 51.12)^2 + (32.38 - 51.12)^2 = 623.16$$
$$S = \sqrt{S^2} = \sqrt{623.16} = 24.96$$
$$T = \frac{51.12 - 40}{\frac{24.96}{\sqrt{3}}} = 0.77$$
$t_{0.05,2} = 4.303$

Thus, because $t_{critical} > T$ we fail to reject $H_0$ and can conclude that at flowrate 1.69 GPM, there is not significant accuracy of turbidity reduction percentage.

*One Sample t-test at High flow rate 3.69 GPM*

Null Hypothesis: $H_0: \mu = 40$
Alternative Hypothesis: $H_1: \mu \neq 40$
$n = 3$
$X_1 = 43.02, \ X_2 = 46.00, \ X_3 = 40.60$
$\bar{X} = 43.20$
$$S^2 = \frac{1}{3-1}\sum_{k=1}^{n=3}(43.02 - 43.20)^2 + (46 - 43.20)^2 + (40.60 - 43.20)^2 = 7.32$$
$$S = \sqrt{S^2} = \sqrt{7.32} = 2.71$$
$$T = \frac{43.20 - 40}{\frac{2.71}{\sqrt{3}}} = 2.05$$
$t_{0.05,2} = 4.303$

Thus, because $t_{critical} > T$ we fail reject $H_0$ and can conclude that at flowrate 3.69 GPM, there is not a significant accuracy of turbidity reduction percentage.

**4.0 Discussions and Conclusions**

Through our prototype construction and testing, we were able to demonstrate that our water treatment solution did in fact have the capabilities reduce turbidity by approximately 40% at varying flow rates. However, our statistical hypothesis testing demonstrated that there was no significant accuracy in turbidity reduction percentage at both medium and high flow rates—in other words, the data was inconclusive in determining an optimal reduction accuracy of 40% consistently. Future steps on this project would include verification of the sterilization, improvements in design, and further testing of turbidity reduction.

We can verify the UV has sufficient contact time to allow the expected pathogen reduction by performing additional contact time and intensity calculations in relation to flowrate to verify the results further.

The improvements of design that we have slated is the movement of the outlet from the centerline of the body to the lower end to reduce stagnation within the body. We would also add the solar panels, battery, and turbine that we had in our original design. We would also add rubberized seals to the catchment to make it easier to remove. Finally, we would add an access hatch on the top of the body to allow the removal and replacement of the filters when that time comes.

Although the two individual one sample t-tests provided non-significant results, this was valuable to our prototypes future development as it provided further insights of the given water flow rate bound(s) of what threshold(s) may produce statistically significant percentage reduction accuracies. Hence, we would strive to test more flow rates to alter our “medium” and “high” rates accordingly to determine at what rates would produce statistically significant results. Additionally, by increasing the number of trials conducted at each tested flow rate, we would more than likely decrease the variance levels amongst each sample size—further optimizing our protype design by better establishing thresholds of significant water flow ranges and potentially making physical design changes based on those new thresholds (e.g. readjustments of activated carbon, thicker interior materials, etc.).

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## 6.0 Appendix

### Figure 7: Critical Values of the t Distribution

**Table T** Critical Values of the *t* Distribution

| *df* | One-Tail = .4<br>Two-Tail = .8 | .25<br>.5 | .1<br>.2 | .05<br>.1 | .025<br>.05 | .01<br>.02 | .005<br>.01 | .0025<br>.005 | .001<br>.002 | .0005<br>.001 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.325 | 1.000 | 3.078 | 6.314 | 12.706 | 31.821 | 63.657 | 127.32 | 318.31 | 636.62 |
| 2 | 0.289 | 0.816 | 1.886 | 2.920 | 4.303 | 6.965 | 9.925 | 14.089 | 22.327 | 31.598 |
| 3 | 0.277 | 0.765 | 1.638 | 2.353 | 3.182 | 4.541 | 5.841 | 7.453 | 10.214 | 12.924 |
| 4 | 0.271 | 0.741 | 1.533 | 2.132 | 2.776 | 3.747 | 4.604 | 5.598 | 7.173 | 8.610 |
| 5 | 0.267 | 0.727 | 1.476 | 2.015 | 2.571 | 3.365 | 4.032 | 4.773 | 5.893 | 6.869 |
| 6 | 0.265 | 0.718 | 1.440 | 1.943 | 2.447 | 3.143 | 3.707 | 4.317 | 5.208 | 5.959 |
| 7 | 0.263 | 0.711 | 1.415 | 1.895 | 2.365 | 2.998 | 3.499 | 4.029 | 4.785 | 5.408 |
| 8 | 0.262 | 0.706 | 1.397 | 1.860 | 2.306 | 2.896 | 3.355 | 3.833 | 4.501 | 5.041 |
| 9 | 0.261 | 0.703 | 1.383 | 1.833 | 2.262 | 2.821 | 3.250 | 3.690 | 4.297 | 4.781 |
| 10 | 0.260 | 0.700 | 1.372 | 1.812 | 2.228 | 2.764 | 3.169 | 3.581 | 4.144 | 4.587 |
| 11 | 0.260 | 0.697 | 1.363 | 1.796 | 2.201 | 2.718 | 3.106 | 3.497 | 4.025 | 4.437 |
| 12 | 0.259 | 0.695 | 1.356 | 1.782 | 2.179 | 2.681 | 3.055 | 3.428 | 3.930 | 4.318 |
| 13 | 0.259 | 0.694 | 1.350 | 1.771 | 2.160 | 2.650 | 3.012 | 3.372 | 3.852 | 4.221 |
| 14 | 0.258 | 0.692 | 1.345 | 1.761 | 2.145 | 2.624 | 2.977 | 3.326 | 3.787 | 4.140 |
| 15 | 0.258 | 0.691 | 1.341 | 1.753 | 2.131 | 2.602 | 2.947 | 3.286 | 3.733 | 4.073 |
| 16 | 0.258 | 0.690 | 1.337 | 1.746 | 2.120 | 2.583 | 2.921 | 3.252 | 3.686 | 4.015 |
| 17 | 0.257 | 0.689 | 1.333 | 1.740 | 2.110 | 2.567 | 2.898 | 3.222 | 3.646 | 3.965 |
| 18 | 0.257 | 0.688 | 1.330 | 1.734 | 2.101 | 2.552 | 2.878 | 3.197 | 3.610 | 3.922 |
| 19 | 0.257 | 0.688 | 1.328 | 1.729 | 2.093 | 2.539 | 2.861 | 3.174 | 3.579 | 3.883 |
| 20 | 0.257 | 0.687 | 1.325 | 1.725 | 2.086 | 2.528 | 2.845 | 3.153 | 3.552 | 3.850 |
| 21 | 0.257 | 0.686 | 1.323 | 1.721 | 2.080 | 2.518 | 2.831 | 3.135 | 3.527 | 3.819 |
| 22 | 0.256 | 0.686 | 1.321 | 1.717 | 2.074 | 2.508 | 2.819 | 3.119 | 3.505 | 3.792 |
| 23 | 0.256 | 0.685 | 1.319 | 1.714 | 2.069 | 2.500 | 2.807 | 3.104 | 3.485 | 3.767 |
| 24 | 0.256 | 0.685 | 1.318 | 1.711 | 2.064 | 2.492 | 2.797 | 3.091 | 3.467 | 3.745 |
| 25 | 0.256 | 0.684 | 1.316 | 1.708 | 2.060 | 2.485 | 2.787 | 3.078 | 3.450 | 3.725 |
| 26 | 0.256 | 0.684 | 1.315 | 1.706 | 2.056 | 2.479 | 2.779 | 3.067 | 3.435 | 3.707 |
| 27 | 0.256 | 0.684 | 1.314 | 1.703 | 2.052 | 2.473 | 2.771 | 3.057 | 3.421 | 3.690 |
| 28 | 0.256 | 0.683 | 1.313 | 1.701 | 2.048 | 2.467 | 2.763 | 3.047 | 3.408 | 3.674 |
| 29 | 0.256 | 0.683 | 1.311 | 1.699 | 2.045 | 2.462 | 2.756 | 3.038 | 3.396 | 3.659 |
| 30 | 0.256 | 0.683 | 1.310 | 1.697 | 2.042 | 2.457 | 2.750 | 3.030 | 3.385 | 3.646 |
| 40 | 0.255 | 0.681 | 1.303 | 1.684 | 2.021 | 2.423 | 2.704 | 2.971 | 3.307 | 3.551 |
| 60 | 0.254 | 0.679 | 1.296 | 1.671 | 2.000 | 2.390 | 2.660 | 2.915 | 3.232 | 3.460 |
| 120 | 0.254 | 0.677 | 1.289 | 1.658 | 1.980 | 2.358 | 2.617 | 2.860 | 3.160 | 3.373 |
| ∞ | 0.253 | 0.674 | 1.282 | 1.645 | 1.960 | 2.326 | 2.576 | 2.807 | 3.090 | 3.291 |

*Source:* From *Biometrika Tables for Statisticians*, Vol. 1, Third Edition, edited by E. S. Pearson and H. O. Hartley, 1966, p. 146. Reprinted by permission of the Biometrika Trustees.

### Table 5: Experimental Data: Flowrate

| | flowrate data and calcs | | | |
|---|---|---|---|---|
| Trial | volume (L) | volume (gal) | time (min) | flowrate (GPM) |
| M1 | 7.5 | 1.981505945 | 1.216666667 | 1.628635023 |
| M2 | 7.5 | 1.981505945 | 1.016666667 | 1.949022241 |
| M3 | 7.5 | 1.981505945 | 1.333333333 | 1.486129458 |
| avg M | | | | 1.687928907 |
| H1 | 7 | 1.849405548 | 0.4166666667 | 4.438573316 |
| H2 | 7 | 1.849405548 | 0.5666666667 | 3.26365685 |
| H3 | 7 | 1.849405548 | 0.55 | 3.362555542 |
| avg H | | | | 3.688261903 |

**Table 6: Experimental Data: Turbidity**

| | initial | | | | | final | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Trial** | **Secchi 1 (in)** | **Secchi 2 (in)** | **avg sechhi (in)** | **avg secchi (ft)** | **turbidity (NTU)** | **Secchi 1 (in)** | **Secchi 2 (in)** | **avg sechhi (in)** | **avg secchi (ft)** | **turbidity (NTU)** | **change in turbidity** |
| **M1** | 2.5 | 2.4 | 2.45 | 0.2041666667 | 270.7936099 | 2.7 | 3 | 2.85 | 0.2375 | 215.1823632 | 55.61124667 |
| **M2** | 1.3 | 1 | 1.15 | 0.09583333333 | 854.8898143 | 2.2 | 1.9 | 2.05 | 0.1708333333 | 355.0626509 | 499.8271634 |
| **M3** | 0.8 | 1.2 | 1 | 0.08333333333 | 1057.233364 | 2 | 2.2 | 2.1 | 0.175 | 342.2926171 | 714.9407466 |
| **H1** | 1.6 | 1.5 | 1.55 | 0.1291666667 | 543.0835882 | 2.7 | 2.7 | 2.7 | 0.225 | 233.6135013 | 309.4700869 |
| **H2** | 1.4 | 1 | 1.2 | 0.1 | 801.337314 | 2 | 2 | 2 | 0.1666666667 | 368.6423845 | 432.6949295 |
| **H3** | 1.1 | 1 | 1.05 | 0.0875 | 981.6645893 | 2.1 | 1.7 | 1.9 | 0.1583333333 | 398.5340077 | 583.1305817 |

**Table 7: Penn State turbidity and depth relation**

| depth (cm) | depth (in) | depth (ft) | Turbidity NTU |
|---|---|---|---|
| 7 | 2.755905512 | 0.2296587927 | 240 |
| 8.2 | 3.228346457 | 0.2690288714 | 185 |
| 9.5 | 3.74015748 | 0.31167979 | 150 |
| 10.8 | 4.251968504 | 0.3543307087 | 120 |
| 12 | 4.724409449 | 0.3937007874 | 100 |
| 14 | 5.511811024 | 0.4593175853 | 90 |
| 16.5 | 6.496062992 | 0.5413385827 | 65 |
| 19.1 | 7.519685039 | 0.6266404199 | 40 |
| 21.6 | 8.503937008 | 0.7086614173 | 40 |
| 24.1 | 9.488188976 | 0.7906824147 | 35 |
| 26.7 | 10.51181102 | 0.875984252 | 30 |
| 29.2 | 11.49606299 | 0.9580052493 | 27 |
| 31.8 | 12.51968504 | 1.043307087 | 24 |
| 24.4 | 9.606299213 | 0.8005249344 | 21 |
| 36.9 | 14.52755906 | 1.210629921 | 19 |
| 39.5 | 15.5511811 | 1.295931759 | 17 |

| | | | |
|---|---|---|---|
| 41.9 | 16.49606299 | 1.374671916 | 15 |
| 44.5 | 17.51968504 | 1.459973753 | 14 |
| 47 | 18.50393701 | 1.541994751 | 12 |
| 49.5 | 19.48818898 | 1.624015748 | 12 |
| 52.1 | 20.51181102 | 1.709317585 | 11 |
| 54.6 | 21.49606299 | 1.791338583 | 10 |
| 57 | 22.44094488 | 1.87007874 | 9 |
| 60 | 23.62204724 | 1.968503937 | 8 |
| 70 | 27.55905512 | 2.296587927 | 7 |
| 85 | 33.46456693 | 2.788713911 | 6 |