JOURNAL OF
EMERGING INVESTIGATORS

Article

Efficacy of natural coagulants in reducing water turbidity under future climate change scenarios

Benjamin D. Cho[1]**, Seoghyun Kim**[2]
[1] Farragut High School, Knoxville, Tennessee
[2] Department of Biological Sciences, Kangwon National University, Chuncheon, South Korea

SUMMARY

There is a growing need for sustainable solutions to mitigate poor water quality with the uncertainty of climate change. Natural coagulants, substances derived from organic materials that help to bind together particulate matter in water, have arisen as potential alternatives to synthetic coagulants, which typically contain harmful chemicals such as aluminum sulfate. The objective of our research was to 1) determine the effects of temperature on the efficacy of natural coagulants and synthetic coagulants in reducing water turbidity, and 2) model how natural coagulation efficacy could vary across various segments of a watershed under future climate change scenarios. We hypothesized that both natural coagulants and their synthetic counterparts would have an inverse relationship between temperature and reduction in turbidity. Utilizing water samples from the Tennessee River Watershed, we conducted experiments that estimated the impact of water temperature on turbidity reduction efficiency of four coagulants. We found that turbidity reduction was higher at lower temperatures for only two of the coagulants. The eggshells, one of the natural coagulants, had a stronger association for increased turbidity reduction at lower temperatures out of those two. We then projected and mapped turbidity reductions under two climate change scenarios and three future time spans for eggshells. There were spatiotemporal variations of turbidity reduction for eggshells and a clear depreciation in natural coagulation efficacy with the progression of climate change. Our results suggest that site-specific and time-varying turbidity reductions utilizing natural coagulants under future climate change conditions can be vital for optimal water treatment plans.

INTRODUCTION

The leading causes of poor water quality are grazing in riparian zones (transitional areas between terrestrial ecosystems and aquatic environments) and the commercialization of agriculture (1). With increased market demand for agricultural goods, farmers utilize riparian zones for agricultural production (1). The increased commercialization of farming creates ripple effects throughout the entire water network (2). For instance, sewage leakage, pesticide, and fertilizer runoff can cause algal blooms that can dismantle entire ecosystems in the Tennessee (TN) River Watershed (3). More recently, blue-green algae infested the Harpeth River, which spans nearly 120 miles and is a tributary to the Cumberland River, due to a rise in eutrophication (4). Eutrophication is the biological process of excess nutrient buildup in water that causes ecologically harmful blue-green algae to grow rampantly (4). Research has shown that algae can be fatal to native aquatic plants and organisms (4). Rising temperatures due to climate change only catalyze the effects of agricultural runoff, triggering more algal blooms which block photosynthetic capabilities of aquatic plants and inevitably harm entire aquatic ecosystems (4).

Water turbidity can be used to measure the concentration of particulate matter, such as the excess nutrients that cause algal blooms, in water (5). More specifically, turbidity is defined as the murkiness of water and is measured in Nephelometric Turbidity Units (NTUs) (5). Particles in water provide points of attachment for bacteria and pollutants, making turbidity a proxy measure for poor water quality (5). The Citarum River (known as the dirtiest river in the world), for instance, has turbidity levels near 320 NTUs, which far exceeds the 50 NTUs that is recommended for aquaculture and recreation (6). Conversely, drinking water theoretically should have a turbidity of 0 NTUs. Tennessee's polluted waterways manifest high turbidity levels, a situation with harmful ecological implications for the present and the future (7). Researchers agree that TN watersheds are rife with pollution and have become even more polluted in recent years—55% of Tennessee freshwater was considered polluted in 2020, compared with 32% in 2010 (8).

One method to mitigate turbidity is coagulation. Coagulation is the process of adding compounds to a water system, which quickly deionize and form clumps of colloids (9). These colloids become dense enough to sink to the bottom of the water system, clearing the water above it (9). Though most extensively investigated in the realm of wastewater treatment, studies show that coagulants are also extremely effective in rivers and streams (10). Researchers found a strong and positive association between the addition of coagulants and the size and density of particulate matter in rivers (11). These colloids are more likely to flow to the bottom of the waterbed, leaving clearer, less turbid water near the surface. Two types of coagulants are of interest: synthetic and natural. Synthetic coagulants are those that have been chemically created in a laboratory or facility and are typically derived from natural gas products via polymerization (12). Natural coagulants are extracted from the natural environment and are derived from plant or animal sources (12). The advantages of natural coagulants include their renewability, biodegradability, non-toxicity, and safety for environmental and human uses compared to their synthetic counterparts (13).

The potential harm synthetic coagulants can exhibit

https://doi.org/10.59720/23-104

is shown in a case study of aluminum sulfate use for the prevention of algae growth in lakes. This study found that smaller bodies of freshwater—streams, shallow lakes, ponds, etc.—were extremely susceptible to ecological harm (14). For example, Lake Morey saw over 90% of its benthic invertebrate population perish (14). Natural coagulants, with their reported benefits of sustainability and safety to the ecosystem, have been tested as successful coagulants in wastewater treatment plans and freshwater (12). Eggshells, corn starch, and bentonite all decreased turbidity of wastewater by significant amounts, with bentonite having a reduction value of 97% (15). Due to their derivation from organic materials, unlike their synthetic counterparts which produce hazardous byproducts, natural coagulants are biodegradable and contain no harmful substances that would deteriorate ecosystems. These three natural coagulants were tested in our study because of their accessibility and pronounced efficacy in reducing turbidity. Aluminum sulfate was tested as a synthetic alternative, given its wide use in current wastewater treatment plans and expansion into recreational use (16, 17).

As for the effect of temperature on coagulation, both natural coagulants and synthetic coagulants decrease sludge dewaterability as temperature increases (18). Sludge dewaterability is the reduction of water content in sludge, which allows for easier disposal of waste (19). Though dewaterability does not directly reduce turbidity, dewaterability reduces the volume of the waste by removing weight and moisture, thereby impacting its turbidity with global warming only worsening, coagulation efficacy may decline. One study suggests that turbidity removal decreases by 5% with a 38 degrees Celsius increase in temperature (20).

Given the increasing water temperatures due to climate change and the need for sustainable solutions to mitigate poor water quality, understanding how natural coagulation efficacy varies over time and space under varying future climate change scenarios is imperative. We hypothesize that both the natural coagulants and their synthetic counterparts follow an inverse relationship between temperature and reduction in turbidity, given the results of previous research (20). From testing our hypothesis and projected mean water temperatures, the natural coagulant with the strongest association between water temperature and turbidity reduction is mapped across various segments of the TN Watershed under two potential climate change scenarios using historical and three future time spans. These maps are useful to showcase how turbidity reduction efficiency by a natural coagulant varies under future climate change conditions.

RESULTS

To investigate our hypothesis, we sought to establish the relationship between water temperature and reduction in turbidity. That way, we could understand whether climate change directly impacts coagulation efficacy. The extent to which turbidity was reduced (turbidity reduction) according to the estimated relationships is referred to as turbidity reduction efficiency. We tested the natural coagulants (i.e., eggshell, corn starch, bentonite) and aluminum sulfate as a synthetic alternative in water collected from Fort Loudoun Lake, which is part of our case study in the TN River Watershed (**Figures 1 and 2**). We determined the inverse relationships

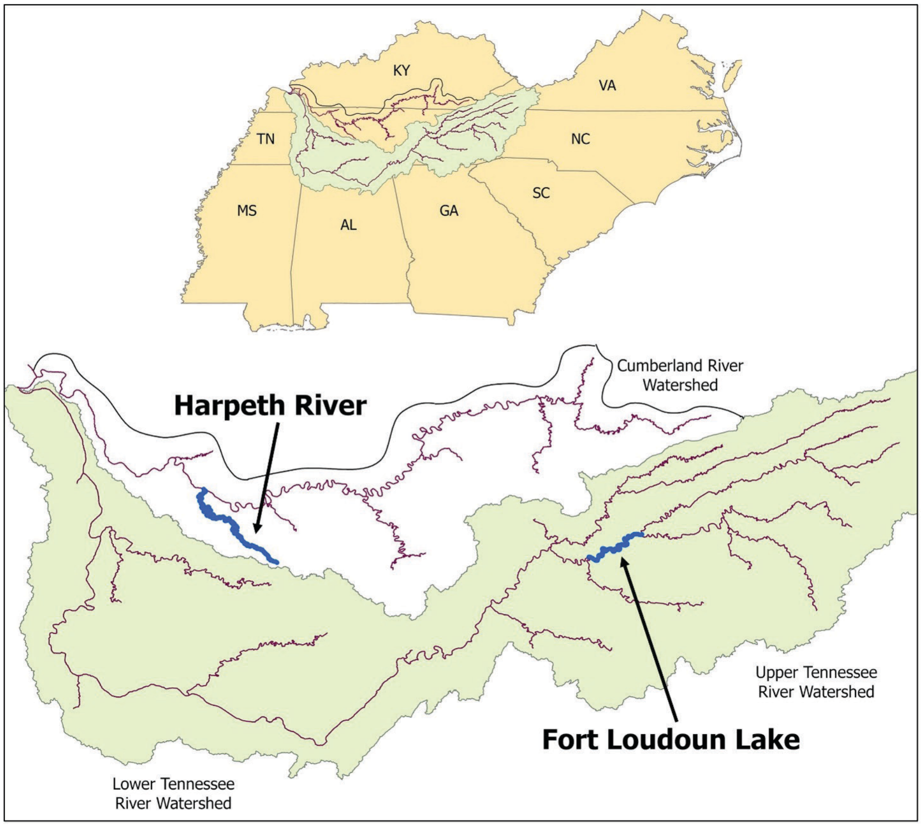

Figure 1: Tennessee River Watershed The upper figure shows the location of the Watershed in the Southeastern United States. The lower figure shows Fort Loudon Lake, the Harpeth River, other large streams and rivers, and the boundary of the Watershed.

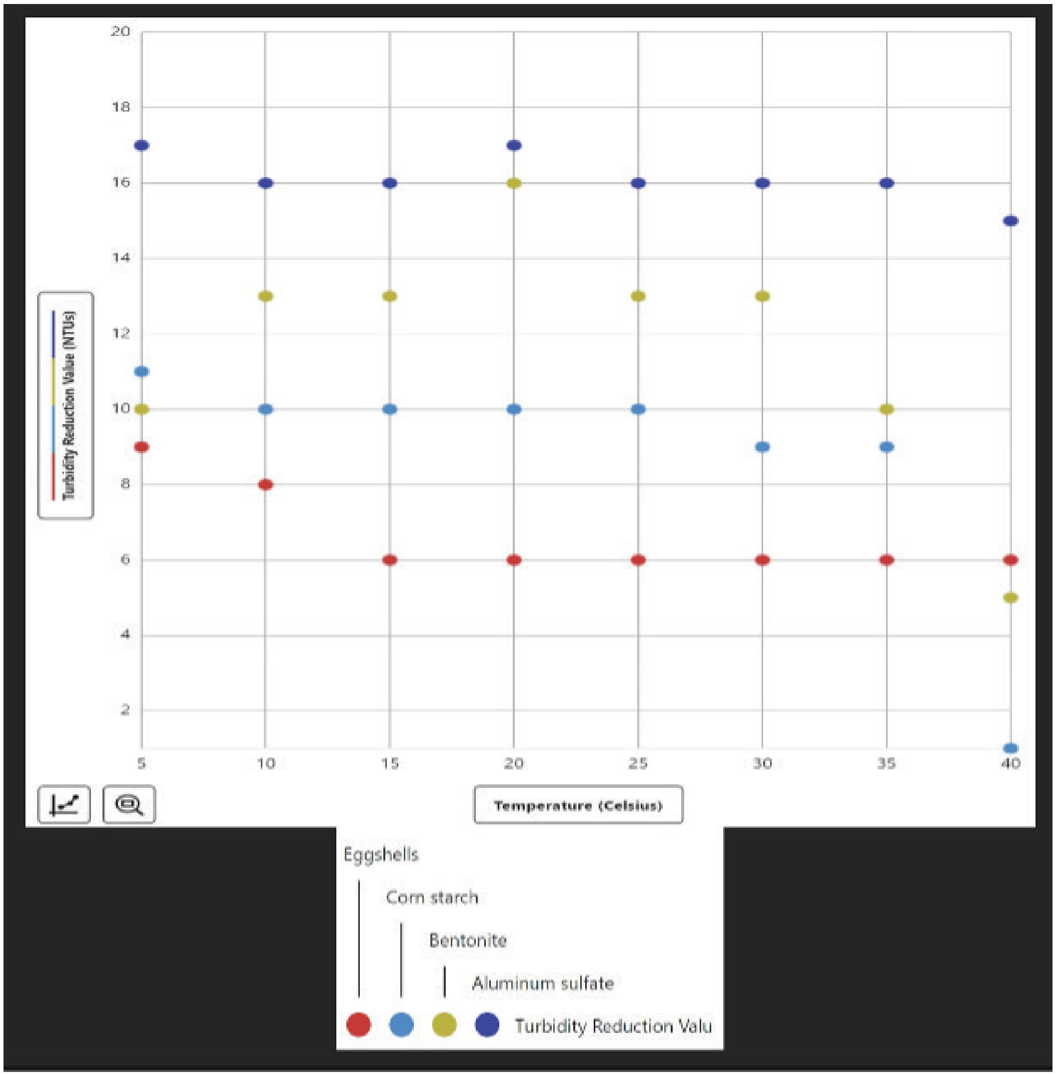

Figure 2: Impact of temperature on the turbidity reduction efficiency of coagulants. Colored points on the graph represent turbidity reduction values compared with the initial 30 NTU lake water in the sample. For instance, the data point indicating a reduction value of "9" for eggshells at 5 degrees Celsius is derived from an initial 30 NTU lake water sample that was remeasured at 21 NTUs after eggshells were incorporated. Note that the eggshells, corn starch, and bentonite are the natural coagulants whereas the aluminum sulfate is the synthetic based coagulant.

between water temperature and turbidity reduction values, compared to the initial 30 NTU lake water in the sample, for each of the four coagulants (**Figure 3**). Aluminum sulfate, corn starch, and eggshells had negative slopes and bentonite had a concave-downward slope (**Figure 3**). Eggshells had the highest adjusted R^2 of 0.91 and a *p*-value of 0.00025, reflecting its goodness of fit, suggesting that this natural coagulant has the strongest association between temperature and turbidity reduction among the four coagulants. Also, the relationship between water temperature and turbidity for aluminum sulfate was not significant ($p=0.062$). These findings suggest an inverse relationship between water temperature and turbidity reduction for eggshells and corn starch. However, this was not the case for aluminum sulfate or bentonite. Both the natural coagulants and their synthetic counterpart follow an inverse relationship between temperature and reduction in turbidity.

To map the turbidity reduction values of a watershed under future climate change conditions, we determined the relationship between mean stream temperature and air temperature. The robust and positive impact of air temperature on stream temperature is shown across various segments of the TN River Watershed (**Figure 4**). This relationship had an adjusted R^2 value of 0.74, suggesting that the increase in stream temperature can largely be explained by the increase in air temperature. The slope of the linear relationship indicates that an increase in air temperature by 1 degree Celsius is associated with an increase in water temperature by 1.22 degrees Celsius.

Using our experimental results, we mapped the natural coagulant with the strongest association between water temperature and turbidity reduction (i.e., eggshells) across various segments of the TN River Watershed under two future climate change scenarios using historical and three future time spans (**Figures 5 and 6**). To procure the turbidity reduction values for eggshells under the climate change scenarios, we used the inverse relationship between water

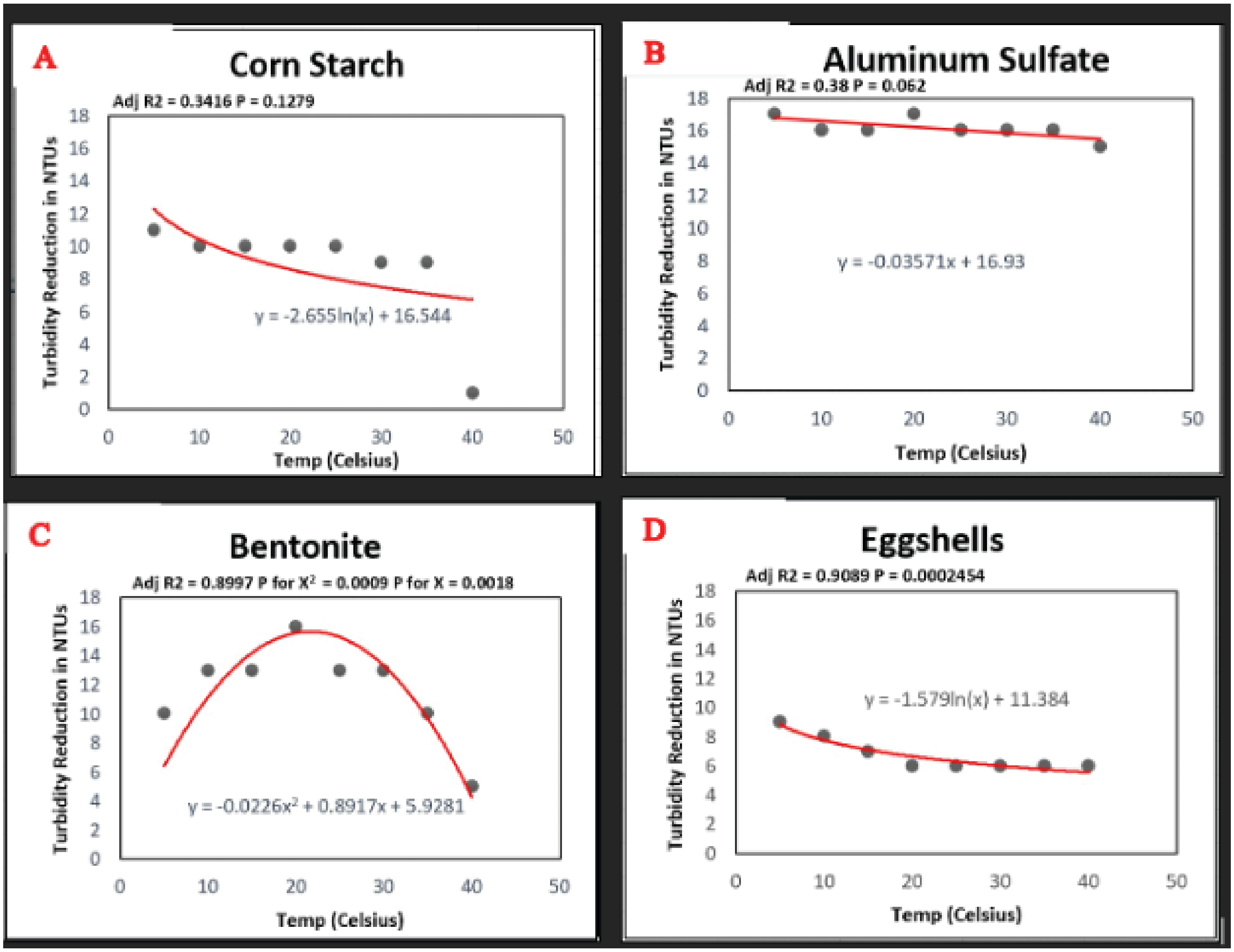

Figure 3: The estimated relationships between turbidity reduction (initial 30 NTU of sample lake water minus the NTUs after adding the coagulants) and water temperature for the four coagulants. A is Corn Starch, B is Aluminum Sulfate, C is Bentonite, and D is Eggshells. The red line represents the fitted relationship using the linear regression model seen in Panel D, and the dots represent the data collected from the experiment. The adjusted R^2 value, or adjusted coefficient of determination, is a statistical measure used to evaluate the goodness of fit of a regression.

temperature and turbidity reduction for eggshells with the projected stream temperature data for the future climate change scenarios (**Figures 3 and 4**). The high-emission scenario predicts a higher air temperature rise, which would raise the stream temperature more than the low-emission scenario. Color mappings of the turbidity reduction values, compared with the initial 30 NTU lake water in the sample, are shown for eggshells across the various segments of the TN River Watershed. It is evident that as time progresses, climate change has a more significant effect on turbidity reduction, hence the maps gradually gaining purple hues. The maps apply the annual mean water temperatures for each of the four periods to the relationship between turbidity reduction and water temperature (**Figures 3, 5, 6**). We present the summary outcome of combining the relationship shown in Figures 3 and 4 with the experimental relationship for eggshells in Figure 2 (**Table 1**), and it shows that there is a -0.27 NTU discrepancy for the low emission climate scenario between the time period 2020 and 2080 and a -0.22 NTU change for the same time period.

DISCUSSION

We tested the effects of water temperature on turbidity reduction of water from Fort Loudoun Lake, which is part of the Upper TN River Watershed, for three natural coagulants (i.e., eggshells, corn starch, bentonite) and aluminum sulfate as their synthetic counterpart. We found a statistically significant relationship between turbidity reduction and temperature for both cornstarch and eggshells. We did not see this relationship for bentonite or aluminum sulfate. The results caused a partial rejection of our hypothesis because both the natural coagulants and their synthetic counterparts follow an inverse relationship between temperature and reduction in turbidity. We found the strongest association between water temperature and turbidity reduction for eggshells. The inverse relationship between water temperature and turbidity reduction for eggshells and corn starch has meaningful implications for future application of natural coagulants. Specifically, with rising temperatures due to global warming, the inverse relationship to project turbidity reduction efficiency of a natural coagulant under climate change conditions is

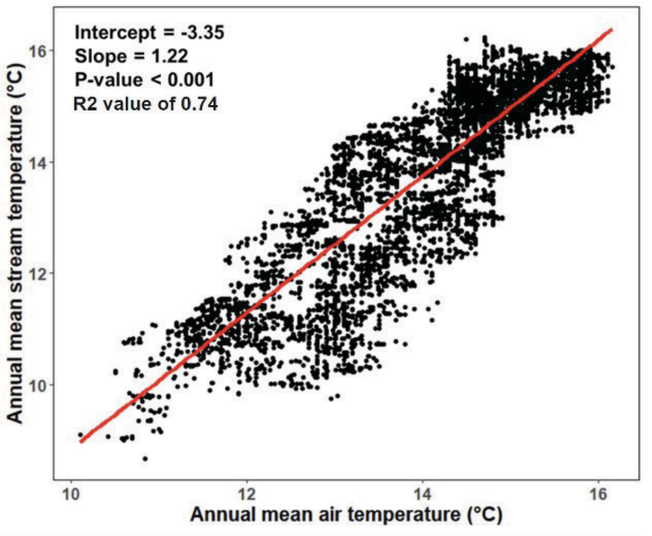

Figure 4: The estimated relationship between annual mean stream temperature across various segments (defined as subsets of stream networks by stream confluences) and annual mean air temperature in the Tennessee River Watershed during 1980-2010. The red line represents the fitted relationship using the linear regression model, and the dots represent the paired air and water temperature data from the EPA and National Weather Service, respectively. The adjusted R^2 value, or adjusted coefficient of determination, is a statistical measure used to evaluate the goodness of fit of a regression. As for the *p*-value less than a 0.001, this signifies strong evidence against the null hypothesis.

critical for sustainable water treatment plans in the future. With this knowledge, treatment can be adequately dispersed and heavily utilized in more climate-change-prone areas and less utilized in areas where climate change does not impact turbidity reduction as much.

While the finding of lower turbidity reduction with higher temperatures for both eggshells and cornstarch confirms previous findings (22), the finding of a statistically significant relationship for a natural coagulant, compared with a nonsignificant relationship between water temperature and turbidity reduction for its synthetic counterpart, is new in the literature. The eco-friendly, biodegradable nature of natural coagulants, however, outweighs the temperature insensitive synthetic coagulants.

Application of this research would be most appropriate for areas of the TN Watershed and nearby waterbodies with high signs of pollution, such as in the Harpeth River. Eggshells' ability to biodegrade in water within a year (23) is an appealing characteristic for use, as the optimal concentrations of eggshells in water is roughly 50 mg/L (16). Several hundreds of pounds of coagulant can treat more than 100 billion liters of water. Using the outcome of our experiment and other necessary data (i.e., historical annual mean stream temperature data, historical and climate change-specific annual mean air temperature data, and stream network data), we projected and mapped the turbidity reduction values. This was compared with the initial 30 NTU lake water in the sample, for eggshells across various segments of the TN River Watershed. Depending on the severity of pollution,

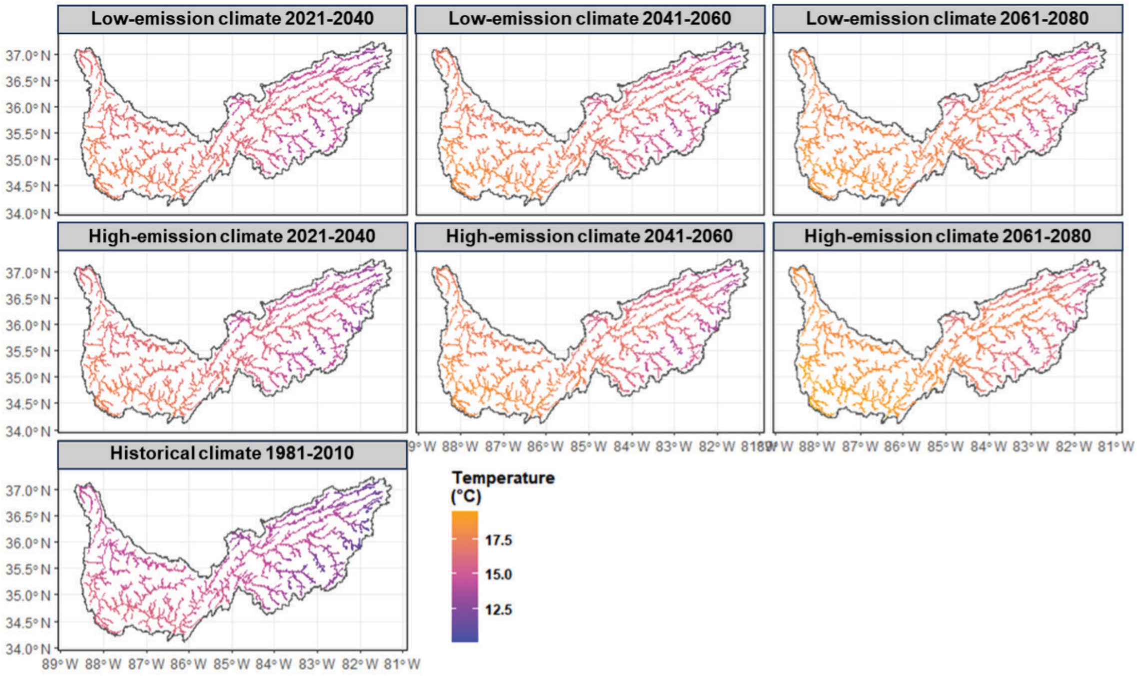

Figure 5: Color maps of the annual mean water temperature of the historical data for 1981-2010 and the projected annual mean water temperatures for 2021-2040, 2041-2060, and 2061-2080 under the low-emission and high-emission scenarios across various segments (defined as subsets of stream networks by stream confluences) of the Tennessee River Watershed. To estimate the annual mean water temperature under the climate scenarios, air temperature data that were collected for the two climate change scenarios based on the shared socio-economic pathways SSP2-4.5 and SSP3-7.0 from a General Circulation Model, were applied to the linear relationship between annual mean stream temperature across various segments and annual mean air temperature (shown in **Figure 3**). Darker colors (blue/purple) correspond with lower temperatures, while lighter colors (orange) correspond with higher temperatures. The vertical and horizontal axes are longitude and latitude coordinates.

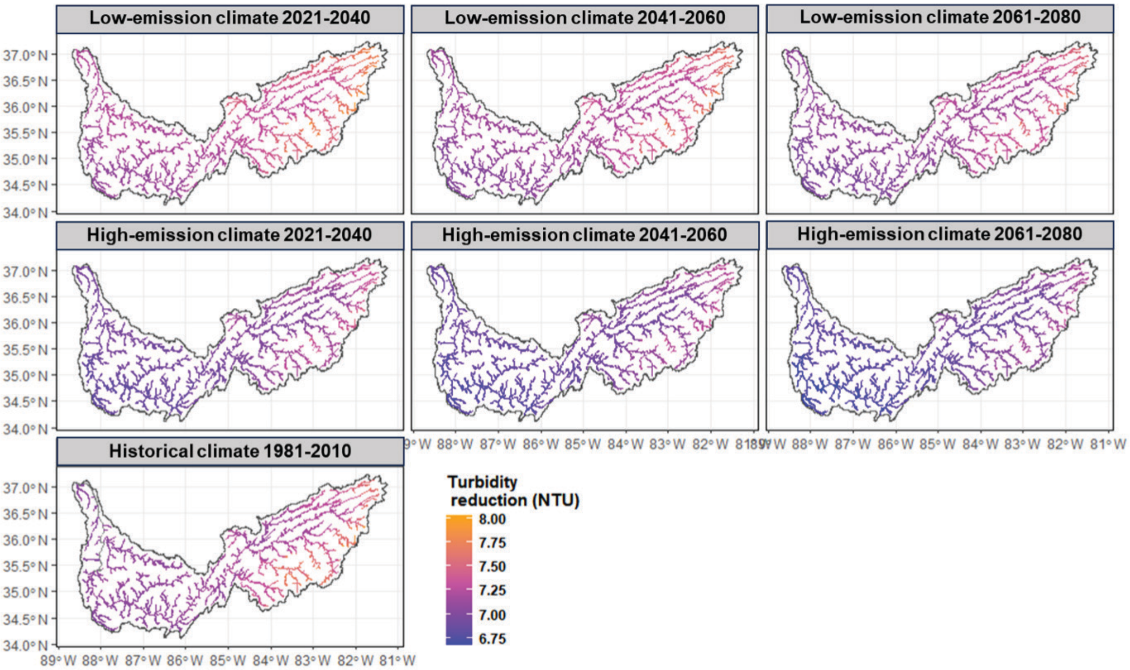

Figure 6: Color maps of turbidity reduction values using eggshells, compared with the initial 30 NTU lake water in the sample for 1981-2010 and for 2021-2040, 2041-2060, and 2061-2080 under the low-emission and high-emission climate scenarios across the various segments (defined as subsets of stream networks by stream confluences) of the Tennessee River Watershed. The vertical and horizontal axes are longitude and latitude coordinates. To estimate the turbidity reduction by eggshells, the annual mean stream temperatures in the four time periods (shown in **Figure 4**) were applied to the relationship for eggshells between turbidity reduction and stream temperature (shown in **Figure 2**).

several hundreds of pounds of eggshell coagulant could be dispersed in a given area annually. Both time and space affect eggshells' turbidity reduction (**Figure 5**). When looking at the variation over time, the coloration of the maps slightly darkens. For instance, the high-emission climate scenario for 2021-2040 shows turbidity reduction in the range of 6.79-7.00 NTU for the Lower Watershed. Yet, looking at the high-emission scenario for 2061-2080, this range decreases to 6.68-6.86 NTU. Though these differences in turbidity may seem marginal, 0.2 NTUs is the difference between clean and dirty drinking water. These data portray a decrease in turbidity reduction over time as temperatures rise; in other words, as climate change progresses, eggshells will become less effective in removing turbidity. Looking at the low-emission climate change scenario in Figure 5, the same can be concluded. For example, the low-emission climate scenario shows a decrease in turbidity reduction within the range of 7.07-7.35 NTU in 2021-2040 to the range of 6.94-7.25 NTU in 2061-2080 for the Lower Watershed.

Maps also illustrate spatial variation in turbidity reduction over time (**Figure 5**). For example, as time passes, turbidity reduction becomes less effective with some spatial variation. For instance, the turbidity reduction of the high-emission scenario in 2021-2040 is around 7.25-7.61 NTU in the Upper Watershed (the right-hand region of the map). As climate change progresses, the efficiency of turbidity reduction becomes noticeably lower, as seen in 2061-2080 (6.68-6.85 NTU). This finding largely agrees with current research in the

	Mean Stream Temperature (°C)			Turbidity Reduction Values (NTU)		
	Mean	Min	Max	Mean	Min	Max
Historical 1981-2010	14.3	10.1	16.2	7.22	6.98	7.97
Low-emission 2021-2040	15.9	11.7	17.7	7.31	7.07	8.04
Low-emission 2041-2060	16.6	12.4	18.4	7.22	7.00	7.89
Low-emission 2061-2080	17.2	13	18.9	7.15	6.94	7.77
High-emission 2021-2040	15.9	11.7	17.8	7.00	6.79	7.61
High-emission 2041-2060	16.8	12.6	18.6	6.92	6.73	7.49
High-emission 2061-2080	17.8	13.6	19.5	6.86	6.68	7.39

Table 1: Summary of the annual mean water temperature and turbidity reduction (NTU) values for historical and projected water temperatures under different emission scenarios in the TN River Watershed. The summary values (i.e., mean, min, max) are based on color mappings of the mean stream temperature (shown in **Figure 4**) and of the turbidity reduction by eggshells (shown in **Figure 5**) for 1981-2010 and for 2021-2040, 2041-2060, and 2061-2080 under the low-emission and high-emission scenarios across the various segments.

field. Though the investigation of natural coagulants' ability to reduce turbidity under temperature control in freshwater systems was unknown prior to this study, Wilkinson et al. found that the water quality after chlorophyll treatment—which is not a coagulant but has similar properties to many natural coagulants—was significantly better in cooler water compared to warmer water (24). Also, evident variation is visible in each segment of the watershed for any given time period. For example, the low-emission scenario in 2061-2080 shows the Lower Watershed has lower turbidity reduction efficiency than the Upper Watershed.

We projected the turbidity reduction maps using the historical annual mean water temperature and the projected annual mean water temperatures for three future time spans. We also projected two climate change scenarios for each of the three time spans. Conclusively, the maps showed: (1) turbidity reduction is projected to be higher in the Upper Watershed than in the Lower Watershed; (2) turbidity reduction is expected to decrease across the entirety of the watershed due to an increase in water temperature from climate change; (3) the decrease of turbidity reduction efficiency from higher temperatures is expected to be more significant in the Lower Watershed than in the Upper Watershed; and (4) the decreasing turbidity reduction efficiency in the Lower Watershed than in the Upper Watershed is more significant in the high-emission scenario than in the low-emission scenario.

Further investigation of the efficacy of synthetic coagulants compared with natural coagulants can determine whether future application of synthetic coagulants in freshwater systems is necessary. Additionally, understanding how turbidity reductions from using natural and synthetic coagulants are influenced by temperature can help determine which compounds should be tested in the future for sustainable water treatment plans. Those contributions would fill the gap in knowledge of how temperature impacts the ability of natural coagulants to reduce turbidity in freshwater systems. Nevertheless, the quantified effects of temperature on turbidity reductions for eggshells presented in our maps provide a steppingstone to showcase how turbidity reduction efficiency by a natural coagulant varies across time and space.

Despite the implications of our findings, it is worth noting three caveats. First, more accurate and better fitting relationships between water temperature and reduction in turbidity by natural coagulants could be estimated with additional observations collected. We could repeat the same experiment that estimated the impacts of water temperature on turbidity reduction efficiency of four coagulants using water collected from the study area at different locations at different times. Additional experimental values for each area would require considerable time to collect water, re-test each coagulant, and re-perform quantitative measures to produce the desired maps. Secondly, our research study did not test *Moringa oleifera*, known as an extremely fast-growing, drought resistant plant found in East and Southeast Asia. The ground up seed powder of this plant has been evaluated as the most effective natural coagulant, more efficient in turbidity reduction than eggshells, cornstarch, or bentonite (25). Its cationic proteins are distributed throughout the liquid and interact with negatively charged particles decreasing turbidity (25). Testing this natural coagulant, along with others, would be imperative under temperature conditions to replicate its performance under future climate change scenarios to understand what concentrations of natural coagulants we need to apply to help improve water quality. Third, our method of determining the NTU of the water was based on visibility. Using more complicated equipment, such as a turbidity probe, could have achieved more accurate measurements of NTU. Turbidity probes are able to measure to the tenth of an NTU and offer more accurate measurements than the turbidity tube utilized for this research project (26).

Our study has future implications to optimize the application of coagulants in water treatment plans. Not only can this research be useful in increasing the efficiency of resource allocation for water treatment, but it contributes to filling the gap in knowledge on how natural coagulants work in water treatment, namely with increasing temperatures due to climate change. The site-specific and time-varying turbidity reductions of different segments across the TN River Watershed under different climate conditions can help determine the application of different quantities of eggshells for water treatment in the wake of climate change. In doing so, we proactively anticipate and adjust future resource needs for sustainable solutions to mitigate poor water quality by counteracting the effects of future plausible climate change trends.

MATERIALS AND METHODS

Coagulant Preparation

Inspired by the methodology conducted by Sibiya *et al.*, the following steps were taken (16). The three natural-based coagulants (eggshells, corn starch, and bentonite) and the synthetic coagulant (aluminum sulfate) were prepared in the laboratory. The eggshells were obtained via household waste. The 100% pure Argo Corn Starch was obtained from a local grocery store, and bentonite clay was purchased from an online retailer. To ensure the homogeneity of the substances, a blender was used for two minutes to grind each coagulant into a fine powder. Each powder was then stored in four separate containers at room temperature. Lake water taken from Fort Loudon Lake with an initial turbidity of 30 NTUs was used as the sample of contaminated water, which was collected in August 2022.

Turbidity Analysis

The coagulation analysis was conducted using a Heidolph Magnetic Stirrer, a turbidity tube, and two 500 mL beakers, each with a small magnetic stirring bar, and also a hand-held stirring rod. The optimum dosage for these natural-based coagulants, along with aluminum sulfate, is 50 mg/L (16). Thus, 0.5 grams of powdered eggshells, corn starch, bentonite, and aluminum sulfate were measured using a balance scale before being added to 100 mL of distilled water. The solution was rapidly mixed by hand using a stirring rod, and the following steps were taken for each coagulant. Each 10 mL (or 0.05 g) of a coagulant was poured into 1 liter of lake water to create a 50 mg/L solution. Then, the solution was mixed by hand and divided between two 500-mL beakers. A magnetic stirring rod was put into both beakers and placed on the Heidolph Magnetic Stirrer apparatus. The first beaker was agitated to rapid mixing speed (500 rpm) for two minutes and then to a slower mixing speed (90 rpm) for 15 minutes. This procedure was repeated for the second beaker of solution. Thermometers were placed into each beaker, which were

https://doi.org/10.59720/23-104

put in the refrigerator (set at 3 degrees Celsius) to cool to 5 degrees Celsius each (first of eight temperatures).

After preparation of the coagulants, the lake water solution was then tested for its turbidity after being introduced to each coagulant. To start, the lake water solution was poured into a transparent turbidity tube. The tube has hatch marks running along the side, indicating the depth of the water. A secchi disk is located at the bottom, which is a small cross that slowly disappears as turbid water is poured into the tube. When the secchi disk is no longer visible by looking down from the top opening of the tube, the depth was recorded. A conversion chart published by Utah State University was utilized to convert the measured depth to the solution's turbidity, which was recorded in **Figure 1** (27). The lake water solution was redistributed evenly between the beakers, and the turbidity of each beaker was re-measured to evaluate potential discrepancies in turbidity. The water in each beaker was warmed and placed on the magnetic stirrer apparatus, which included a built-in hot-plate and temperature probe. The process of measuring the turbidity was repeated for each of the remaining temperatures (10, 15, 20, 25, 30, 35, and 40 degrees Celsius). Different samples of lake water were used for each temperature; however, the turbidity was remeasured to ensure the initial turbidity values of the data points were equivalent. Each trial necessitated two separate beakers to make up for the lack of a 1-L beaker. Steps were taken to ensure that both beakers had equal turbidities and temperatures to prevent inaccuracies. Each data point was measured by combining two 500 mL solutions of each coagulant, mixed separately but confirmed to have equal initial turbidities. The turbidity reduction values, compared with the initial 30 NTU lake water in the sample, are reported in **Figure 2**.

Statistical Testing

After we collected the turbidity reduction values, we utilized the software R to create **Figure 2**. We used the temperature values for the x-axis and the turbidity reduction values for the y-axis. To determine which of the four coagulants tested had the strongest relationship between temperature and turbidity reduction, however, we transferred the experimental data set to an Excel spreadsheet. We tested each data set for the four coagulants in the experiment for their R^2 and *p*-values, which are presented in **Figure 3**. This measured the proportion of the variance in the dependent variable that is predictable from the independent variables. Values range from 0 to 1, with higher values indicating a better fit. Then, we selected models depending on this R^2 value. For instance, aluminum sulfate best fit a linear model while eggshells best fit a natural logarithmic one.

In **Figure 3**, we determined a linear regression model to predict the future temperatures of the Tennessee Watershed in the time span from 2020-2080. We downloaded files for historic stream temperature values and air temperature values from the watershed and segmented the watershed defined by its stream confluences (points where two or more streams or rivers meet and join together). Once again, we determined the R^2 value and the *p*-value (**Figure 3**).

Post-Experiment Projection and Mapping

We selected two climate scenarios from the results of a general circulation model (GCM). One scenario is referred to as the shared socio-economic pathways, SSP2-4.5, with a rise in average global temperatures of 2.7°C by 2100. This is under the assumption that socioeconomic factors follow their historic trends without significant shifts, which causes future increases in CO_2 emissions to follow their historic trend before starting to decrease by the mid-century. Eventually, these emissions reach net-zero by 2100 (21). The second scenario is referred to as SSP3-7.0 with a rise in average global temperatures of 3.6°C by 2100 under the assumption that countries become more competitive with one another, shifting towards national security to protect their own food supplies. This causes a doubling of current CO_2 emissions by 2100 (21). These two scenarios were selected for analysis to allow future water treatment planners to anticipate the levels of a natural coagulant that are appropriate for low (SSP2-4.5) and high (SSP3-7.0) climate scenarios. We designated these two scenarios as low and high scenarios. Other scenarios could have been selected for the analysis. However, to accurately showcase the depreciation of natural coagulation efficacy with climate change, only two scenarios were necessitated. This would allow us to prepare for and assess the future climate change conditions across multiple plausible pathways.

Using the gathered turbidity reduction values in comparison to the initial 30 NTU lake water in the sample and temperature for the four coagulants, we sought to project and map the turbidity reduction. The focus was on the natural coagulant with the strongest association between water temperature and turbidity reduction efficiency, i.e., eggshells. This projection and mapping, which spans the TN River Watershed under different future climate conditions, was accomplished in the following steps.

First, we estimated the relationships for the four coagulants between the reduction in turbidity in NTUs to the initial 30 NTU lake water in the sample (values indicated in Figure 1). The coagulants were noted as the dependent variable and the temperature in degrees Celsius as the independent variable. Second, we estimated the relationship between the historical annual mean stream temperature for the TN River Watershed in degrees Celsius as the dependent variable. On the other hand, the historical annual mean air temperature in degrees Celsius acted as the independent variable using data for the 1981-2010 period.

Third, we projected and mapped the annual mean water temperature for future time spans under different climate change scenarios for the Watershed using the estimated relationship from the second step. Due to the absence of water stream temperature data corresponding to the climate change scenarios, we estimated it by applying the air temperature data projected for the two climate change scenarios to the historical air-water temperature relationship for the watershed from 1981-2010. The historical annual mean stream temperature data for 1981-2010 that was derived from the relationship in step 2 was then used with the projected annual mean air temperatures for 2021-2040, 2041-2060, and 2061-2080 under two climate change scenarios. One of the climate change scenarios was based on SSP2-4.5 reflecting low-emission climate scenario and the other one based on SSP3-7.0 reflecting high-emission climate scenario. This step projects the future stream temperatures in the TN River Watershed for "low-emission" and "high-emission" climate change scenarios. The estimation that a one degree increase in air temperature resulted in a 1.22 degree increase in stream temperature was used to estimate the future stream temperatures in the aforementioned time periods. Fourth, we projected and mapped the turbidity reduction values in comparison to the initial 30 NTU lake water in the sample for eggshells for the TN River Watershed for the three periods using the relationships from step 3 and the experimental data from step 1.

The historical annual mean stream temperature for 1981-2010 was obtained from the EPA StreamCat dataset, and the stream network was obtained from the USGS national hydrography dataset (28, 29). We only considered large streams and rivers within the TN River Watershed with areas greater than 100 km^2, which provided sufficient spatiotemporal variability in the maps. The historical annual mean air temperatures from 1981-2010 were obtained from the National Weather Service (30) and future air temperatures for the two climate change scenarios at the three future time spans were obtained from ClimateNA (31).

ACKNOWLEDGMENTS

We extend our sincere gratitude to Anna Kim for her invaluable guidance on the usage of equipment during the lab experiment. Our appreciation also goes to Lauren George Smith and the six anonymous panelists at the 2023 Southern Appalachian Science and Engineering Fair for their constructive discussions and feedback on the poster version of this research paper.

Received: May 19, 2023
Accepted: September 1, 2023
Published: November 13, 2024

REFERENCES

1. “Agricultural Contaminants | U.S. Geological Survey.” *USGS,* 1 Mar. 2019, www.usgs.gov/mission-areas/water-resources/science/agricultural-contaminants#:~:text=Agricultural%20contaminants%20can%20impair%20the. *Accessed: January 30th, 2023.*
2. Klapproth, J., and J. Johnson. “Understanding the Science behind Riparian Forest Buffers: Effects on Water Quality.” *Virginia Cooperative Extension,* vtechworks.lib.vt.edu/bitstream/handle/10919/48062/420-151_pdf.pdf?sequence=1&isAllowed=y
3. “Understanding Algal Blooms.” *vSt. Johns Water Management District,* www.sjrwmd.com/education/algae/#:~:text=Algal%20blooms%20can%20be%20dramatic
4. “Harpeth River Is at a Tipping Point – Harpeth Conservancy.” *Harpeth Conservancy,* harpethconservancy.org/our-work/clean-water-protection/reducing-pollution/nutrient-pollution/harpeth-river-is-at-a-tipping-point/.
5. “Turbidity and Water | U.S. Geological Survey.” *USGS,* 6 June 2018, www.usgs.gov/special-topics/water-science-school/science/turbidity-and-water.
6. Sholeh, M., *et al.* “Analysis of Citarum River pollution indicator using chemical, physical, and bacteriological methods.” *AIP Conference Proceedings,* December 2018, https://doi.org/10.1063/1.5082473.
7. Hart, H. “Effect of Land Use on Total Suspended Solids and Turbidity in the Little River Watershed, Blount County, Tennessee.” August 2006, race.tennessee.edu/cgi/viewcontent.cgi?article=3019&context=utk_gradthes
8. Mays, M. “More than Half of Tennessee’s Waterways Are “Impaired.”” *WKRN News 2,* 21 Apr. 2022, www.wkrn.com/special-reports/more-than-half-of-tennessees-waterways-are-impaired/.
9. “Coagulation and Rapid Mixing”, www.oregon.gov/oha/PH/HEALTHYENVIRONMENTS/DRINKINGWATER/OPERATIONS/TREATMENT/Documents/Coagulation.pdf
10. Su, Z., *et al.* “Coagulation of Surface Water: Observations on the Significance of Biopolymers.” *Water Research,* vol. 126, 1 December 2017, pp. 144–152, refhub.elsevier.com/S0257-8972(18)30294-9/rf0015, https://doi.org/10.1016/j.watres.2017.09.022.
11. Greenwood, J. *How are coagulants and flocculants used in water and wastewater treatment?* 2 February, 2022, www.wcs-Group.co.uk. www.wcs-group.co.uk/wcs-blog/coagulants-flocculants-wastewater-treatment.
12. Aboushabana , M. “Natural versus Synthetic Polymers for Wastewater Treatment.” *Dober.* 18 April 2023, www.dober.com/water-treatment/resources/natural-versus-synthetic-polymers-for-wastewater-treatment.
13. Nimesha, S., *et al.* “Effectiveness of Natural Coagulants in Water and Wastewater Treatment.” *Global Journal of Environmental Science and Management,* vol. 8, no. 1, 1 Jan. 2022, pp. 101–116, www.gjesm.net/article_244726.html, https://doi.org/10.22034/GJESM.2022.01.08.
14. Cooke, G. Alum Application to Lake Elsinore, California: Responses to Questionnaire. 2001, mywatersheds.com/wp-content/uploads/2018/07/01-Alum-Application-to-Lake-Elsinore-Cooke-8-01.pdf.
15. Sibiya, N., *et al.* “Application of Natural Coagulants as an Alternative to Alum for Wastewater Treatment.” *ResearchGate,* Nov. 2020, www.researchgate.net/publication/346058712_Application_of_Natural_Coagulants_as_an_Alternative_to_Alum_for_Wastewater_Treatment.
16. Ashmeal, A., *et al.* “A Comparative Study of Natural and Synthetic Coagulants in the Treatment of Oily Wastewater.” 1 March 2021, laccei.org/LACCEI2021-VirtualEdition/work_in_progress/WP387.pdf
17. “Why Use Aluminum Sulfate in a Pond? | Aluminum Sulfate for Muddy Pond.” *Outdoor Water Solutions,* 19 May 2020, outdoorwatersolutions.com/news/why-use-aluminum-sulfate-in-a-pond/.
18. Fitria, D., *et al.* “Impact of Temperature and Coagulants on Sludge Dewaterability.” *International Journal of Technology,* 1 July 2022, ijtech.eng.ui.ac.id/article/view/4886. https://doi.org/10.14716/ijtech.v13i3.4886.
19. “What Is Sludge Dewatering & What Is It Used For? - Micronics, Inc.” *Micronics, Inc.,* 23 Apr. 2019, www.micronicsinc.com/filtration-news/what-is-sludge-dewatering/.
20. Dayarathne, H. N. P., Angove, M. J., Jeong, S., Aryal, R., Paudel, S. R., & Mainali, B. (2022). Effect of temperature on turbidity removal by coagulation: Sludge recirculation for rapid settling. *Journal of Water Process Engineering, 46,* 102559. https://doi.org/10.1016/j.jwpe.2022.102559.
21. IPCC. “Sixth Assessment Report.” *www.ipcc.ch,* IPCC, 2021, www.ipcc.ch/report/ar6/wg1/.
22. “Adjusted R Squared.” *IBM,* 3 Jan. 2023, www.ibm.com/docs/en/cognos-analytics/11.1.0?topic=terms-adjusted-

https://doi.org/10.59720/23-104

r-squared.
23. Wilkinson, O. “How to Use Eggshells in Your Garden and Compost.” *The Modern Milkman,* 29 Mar. 2022, blog.themodernmilkman.co.uk/eggshells-in-your-garden/#:~:text=If%20you%20split%20your%20eggshells.
24. Lindstrom, C., “How temperature relates to turbidity and chlorophyll.” *ArcGIS StoryMaps,* December 2020, storymaps.arcgis.com/stories/005be052a680438d98e58f682506dfd5
25. Nhut, H. T., *et al.* “Use of Moringa Oleifera Seeds Powder as Bio-Coagulants for the Surface Water Treatment.” *International Journal of Environmental Science and Technology,* 20 Sept. 2020, https://doi.org/10.1007/s13762-020-02935-2. Accessed 5 Apr. 2021.
26. Hughes, J. “Measuring Turbidity with IoT - Water Quality.” *Manx Technology Group,* 11 Jan. 2023, www.manxtechgroup.com/measuring-turbidity-with-iot-water-quality/#:~:text=The%20entry%2Dlevel%20turbidity%20sensor. Accessed 20 Aug. 2023.
27. Utah State University. “Turbidity Tube Conversion Chart.” *Extension.usu.edu,* 2016, extension.usu.edu/utahwaterwatch/monitoring/field-instructions/turbidity/turbiditytube/turbiditytubeconversionchart.
28. “National Hydrography Dataset”. *USGS.* www.usgs.gov/national-hydrography/national-hydrography-dataset
29. “StreamCat Dataset”. *US EPA,* 20 August 2020, www.epa.gov/national-aquatic-resource-surveys/streamcat-dataset-readme
30. “National Weather Service”. *National Weather Service,* 2018, Weather.gov. www.weather.gov/
31. “Current and projected climate data for North America.” *AdaptWest,* adaptwest.databasin.org/pages/adaptwest-climatena/