Engineering a Surface Flow Constructed Wetland to Evaluate Efficiency for Combating Water Scarcity

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Engineering a Constructed Wetland

a. Abstract

A shortage of drinking water has always been a problem, especially in developing countries that cannot afford to treat polluted water bodies, but what if there is a way to fix this? This project looks at the efficiency of constructed wetlands for treating polluted water bodies, mainly those pertaining to agricultural runoff, one of the most prevalent forms of freshwater pollution. Using a basic surface flow wetland as a base, a new constructed wetland design was created with features such as tube settlers. Theprototype was tested using manually polluted water that was run through the system and measured for atotal of seven parameters (pH, temperature, nitrates, nitrites, carbonate hardness, general hardness, and phosphates) before and after treatment to calculate the water filtration efficiency. The most prominent pollutants from agricultural runoff (phosphates, nitrates, and nitrites) showed individual improvements of 36.7%, 51.85%, and 58.89% respectively, showing high potential for this model. The information collected from this study can be used to support the instillation of constructed wetlands in areas most effected by agricultural pollution such as Africa, China, and Europe.

b. Table of Contents

c. Key Words

Engineering a Constructed Wetland

Constructed wetlands, agricultural pollution treatment, lamella settlers, tube settlers

d. Abbreviations and Acronyms

WQI – Water quality index; a measure used to approximate overall water
healthTSS – Total suspended solids

e. Acknowledgements

Graduate student and teaching assistant, Geneva Schlepp, helped me design the testing procedure andedited this research paper and gave general support and guidance throughout the course of the project. High school teacher, Ms. Allender, provided resources for background research and gave feedback on improving this paper.

f. Biography

Monisha Krothapalli is a current junior at Tesla STEM High School in Redmond, Washington. She first became interested in environmental science when she competed in her school's Science Olympiad team in related events. In her freshmen year, she first started conducting research through her state's science fair and has been interested in this field ever since.

She has many other interests including computer science, which she plans to pursue in college alongside environmental science. She is the current founder and President of her school's Girls Who Code club and has been volunteering for several years at her local middle school to teach coding. She isalso interested in art and has been competing since freshmen year, winning several awards so far.

Introduction

This project seeks to pose a solution to the problem of water scarcity by investigating the efficiency of low-cost constructed wetlands for filtering polluted water from agricultural runoff. Worldwide, approximately 1.1 billion people don't have reliable access to clean water and 2.7 billion find water to be scarce at least one month of the year (World Wildlife Fund). The largest sources of freshwater (i.e., rivers, lakes, and aquifers) are becoming increasingly polluted and unsuitable for consumption and usage. Climate change has only worsened this ever-growing problem of water scarcity with the increase of extreme precipitation events such as floods and droughts. One of the main causes of this worldwide crisis is water degradation, of which agricultural activities are a primary contributor (UNESCO). Agricultural runoff carries pollutants such as fertilizers, pesticides, and animal feces which are abundant in pathogens and excess nutrients. This mixture of constituents pollutes water, making it unusable and reducing the resource's availability. The modern water treatment technologies in place, such as municipal wastewater treatment plants, are expensive and energy intensive. This makes them very difficult to implement in poorer areas that cannot afford to manage or maintain the financial burden. An alternative to large-scale wastewater treatment would be the implementation of constructed wetlands, a technology that artificially mimics the processes of real wetlands and purifies water at a much lower cost. For example, the Tres Rios pilot project in Arizona cost $3.5 million to construct; conversely, repairing the 91st Avenue treatment plant would have cost $625 million (University of Arizona), showing how much more cost-effective constructive wetlands are in comparison. However, constructed wetlands are not without their drawbacks.

This project addresses issues and limitations previous models could not. One study, which sought to investigate more efficient techniques of wetland construction, exposed the large land usage that constructed wetlands typically require [1], which is much greater in comparison to conventional treatment plants. Additionally, another concern of constructed wetlands are their low pollutant extraction rates. A study completed in 2016 showed that the median removal rate of total nitrogen and total phosphorus in constructed wetlands was only 37% and 46% respectively [2], which pales in comparison to municipal treatment. To help address these issues, this project contains a clarifier which integrates the usage of tube settlers and limestone filters. The unique design features of this project improve the efficiency of constructed wetlands for purifying water polluted by agricultural runoff. Efficiency will be determined by calculating the percent increase in the water quality index (WQI) from water prior to treatment compared to post treatment. If proven successful, this research can be used to further support the implementation of this technology in underdeveloped areas to combat water scarcity.

Model Improvements and Description

A typical constructed wetland consists of a wetland cell, which is a manmade cell implemented within a water body containing a bush of emergent plants (ex. cattails, bulrushes, and sedges) through which water flows. As water flows through this system, the plants slow down the water flow and take up the nutrients through the plant roots, removing them from the water. Between the two main types of wetland cells - subsurface and surface flow cells – a surface flow cell was used. While surface flow cells have fewer issues with clogging and maintenance, they do unfortunately require more space to implement than subsurface flow cells. However, this problem can be addressed with the addition of the clarifier. This prototype also contains two types of emergent vegetation - common three-square bulrush and soft stem bulrush - which were planted within the main cell.

This new design builds upon the basic design of a constructed wetland with the novel implementation of a clarifier. The clarifier contains tube settlers and a limestone filter, which can be observed in Figure 1. As water enters the clarifier and moves upwards through the tube settlers, it forms a counter current flow, as the sediments within it become heavy and fall towards the sloped edges of the settlers. They then accumulate to form a sludge which will eventually slide down the device toward the sludge deposit. These devices greatly help increase settling efficiency which can in turn decrease the amount of land that is required. As proven by engineer Allen Hazen, settling efficiency is proportional to the difference in sedimentation velocity and the surface loading rate, which is equal to the water flow divided by tank area. The shape and orientation of the tube settlers greatly increase the total surface area of the tank, thereby increasing tank area and allowing the settling efficiency to increase. By increasing settling efficiency in the clarifier, we are able to decrease the amount of settling area that would be needed in the wetland cell and cut down on the issue of land usage.

The limestone filter within the clarifier is also of great use. Limestone, when mixed with water at an acidic level, dissociates to form calcium and carbonate ions, and raises the pH of the water in the process.

Phosphates, which are one of the most common pollutants in agricultural wastewater, bind to the free calcium ions when the water is at a high enough pH and form an insoluble compound. This compound is then easily settled out, increasing overall nutrient extraction and subduing the issue of low nutrient removal rates.

Materials and Methodology

I. Prototype Construction

The prototype involves the assembly of two elevated plastic bins to form a gravity-based flow. One basin acts as a clarifier and the second as a nutrient extraction wetland cell. The clarifier is constructed with a feeder that pushes water directly to the tube settlers. Attached to the mouth of the feeder is a filter with a limestone coating. Twenty-eight small ¼” PVC pipes were then organized in an alternating pattern to create the shape for the tube settler (Fig. 2). The settlers were angled at a 60-degree angle in the center of the first basin to optimize space usage (Fig. 1). Plastic walls were then placed on all sides of the feeder-settler system to ensure that the water would flow in the desired direction.

For the second basin, the bottom was lined with about two inches of soil to ensure enough room for plant roots. Ten common three-square bulrush and ten soft-stem bulrush plants were planted in the soil. The basin was then filled with freshwater four inches above its current level to form a surface flow wetland. Against the outlet of the second basin, a gravel filter was made using pebbles pressed against the basin wall.

The first basin was then placed on an elevated surface (e.g., a ladder) and the second basin was placed slightly lower on a different elevated surface. Using PVC pipes, the basins were connected with one leading from the first basin to the second basin, another from the second basin to the collection basin (Fig. 1).

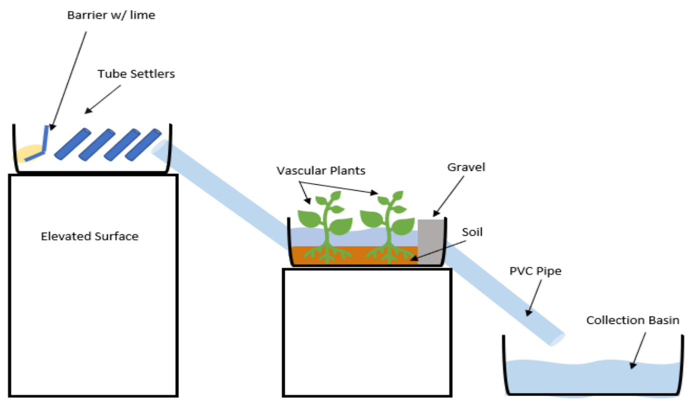


Figure 1. Diagram labels the design of the basins in which the plants and tube settlers were added.

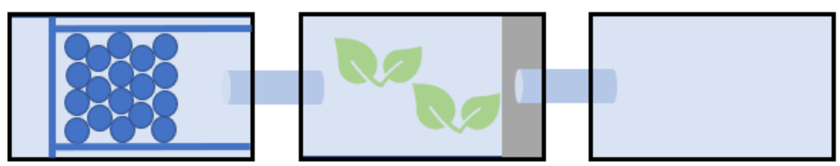


Figure 2. Top view of constructed wetland. Tube settlers angled at 60^0 to settle out suspended solids and decrease the amount of settling area needed.

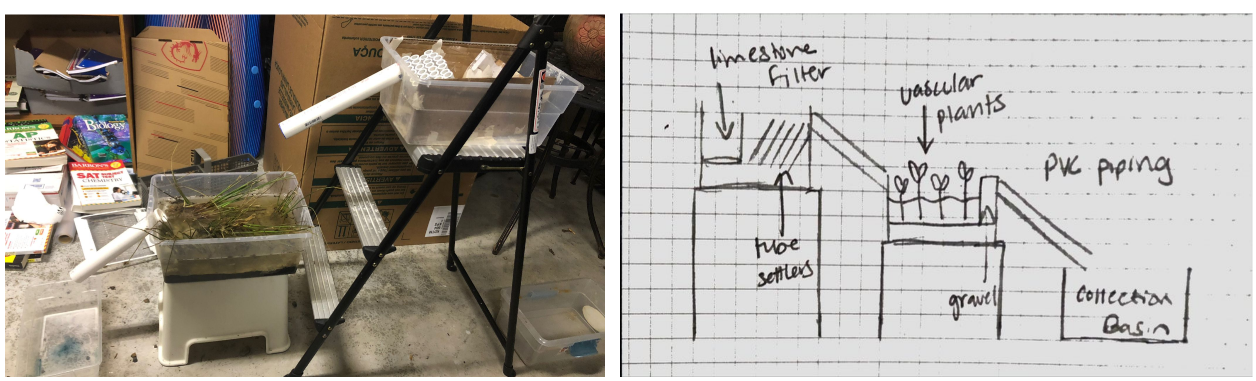


Figure 3. To the left is the constructed prototype and to the right is the sketched diagram.

II. Prototype Testing

To assess the prototype, polluted water was run through the system simulating how the constructed wetland would work in a real body of water. The water was manually polluted with a mixture of fertilizers, pesticides, and debris, components that most often are found in agricultural pollution. Prior to treatment, the water sample was tested for seven markers: pH, nitrates, nitrites, phosphates, general hardness, carbonate hardness, and temperature (Table 2). The pH was measured using Litmus strips and temperature with a thermometer. The rest of the markers were measured using commercially available API kits. After the initial water quality testing, the water was poured through the limestone filter at the top of the prototype and the filtered water was collected from the collection basin and the same tests run prior to the treatment were run on the treated water. This procedure was repeated for a total of nine trials.

III. Data Analysis

After the parameters were collected for the pretreatment and post treatment water, a water quality analysis was performed to calculate the water quality index (WQI), using the Canadian WQI equation. The overall WQI relies on three calculated factors:

$$WQI = \left(100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$$

F_1 is the scope of the index or the percentage of met parameters.

$$F_1 = \left(\frac{\#failed\ paramters}{Total\ \#\ of\ parameters}\right) * 100$$

F_2 is the frequency or the number of individual tests within each parameter that failed to meet the standard.

$$F_2 = \left(\frac{\#failed\ tests}{Total\ \#\ of\ tests}\right) * 100$$

F_3 is amplitude or the extent to which the failed tests exceed guidelines, which are taken from standard EPA values for freshwater bodies, and this is calculated in several steps as labeled below.

$$nse = \left(\frac{\sum excursion}{total\ \#\ of\ tests} \right) \quad excursion = \left(\frac{failed\ test\ value}{guideline\ value} \right) - 1$$

$$F_3 = \left(\frac{nse}{0.01nse + 0.01} \right)$$

The overall rating is determined by which category the final WQI falls in (Table. 1).

Designation	**Index Value**	**Description**
Excellent	95 - 100	All measurements are within objectives virtually all of the time.
Good	80 – 94	Conditions rarely depart from natural or desirable levels.
Fair	65 – 79	Conditions sometimes depart from natural or desirable levels.
Marginal	45 – 64	Conditions often depart from natural or desirable levels.
Poor	0 – 44	Conditions usually depart from natural or desirable levels.

Table 1. Table outlines the index standards for each water quality level

Results

Raw data for the seven different parameters was collected using a variety of commercially available kits and are outlined in the table below (Table 2). While temperature was collected, it was not used as a measure to determine water health.

	Water Quality Parameters vs. Point of Sampling

Trial #		**pH**	**Nitrites (mg/L)**	**Nitrates (mg/L)**	**Phosphates (mg/L)**	**General Hardness (ppm)**	**Temperature (°C)**	**Carbonate Hardness (ppm)**
1	Initial	6.5	40	1	10	120	18.3	80
	Final	7	20	0.5	8	60	14	80
2	Initial	6.5	40	1	10	120	18.3	80
	Final	7	20	0.5	7	30	13.9	60
3	Initial	6.5	40	1	10	120	18.3	80
	Final	6.5	10	0	5	120	14.2	60
4	Initial	6	30	1	8	60	15.9	100
	Final	6.5	10	0.3	7	40	12.8	60
5	Initial	6	30	1	8	60	15.9	100
	Final	6.5	15	0.2	6	50	13	50
6	Initial	6	30	1	8	60	15.9	100
	Final	7	15	0.2	5	60	12.9	80
7	Initial	6	20	0.5	9	140	14.2	40
	Final	6.5	15	0.1	4	120	12.7	60
8	Initial	6	20	0.5	9	140	14.2	40
	Final	6.5	10	0.2	5	80	12.9	30
9	Initial	6	20	0.5	9	140	14.2	40
	Final	6.5	10	0.3	4	80	12.8	30

Table 2. Outlines the raw data parameters that were collected.

The raw data of the seven parameters was then processed through the equation described within the data analysis section of the methodology and the values below were produced for the nine trials. The mean was also calculated from these values.

Trial	**WQI**
1	48.07

2	50.27
3	48.74
4	48.86
5	51.77
6	51.22
7	53.09
8	48.34
9	49.63
Average	49.99

Table 3. Calculated water quality index post treatment of all water samples.

Of the seven parameters, phosphates, nitrates, and nitrites were deemed the most essential for monitoring as they're the most prevalent pollutants within agricultural wastewater. The individual parameter removal efficiency can be clearly viewed in the graph below.

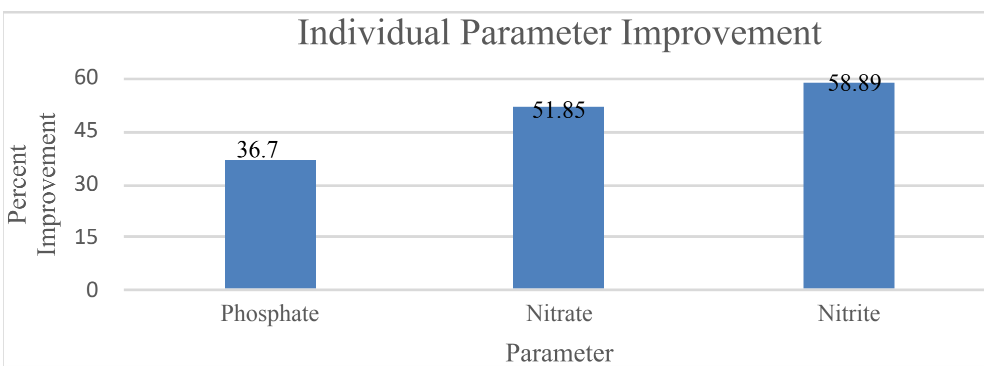
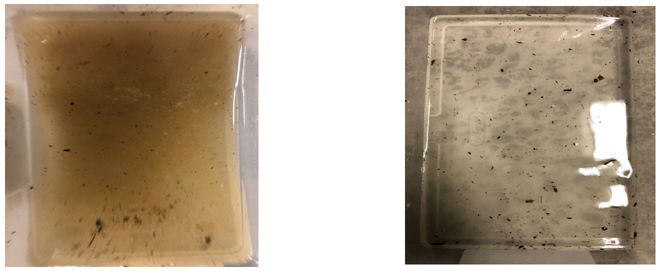


Figure 4. Improvement of most prominent individual parameters.

Additionally, qualitative data from trial four was taken as a representative to show the improvement in turbidity and reduction in suspended solids, for which numerical data was not taken.



Prior to Treatment Post Treatment

Qualitative Data

Figure 5. Qualitative data showing difference in turbidity and TSS post and prior to treatment.

Discussion

With the average WQI being 46.87 prior to treatment and 49.99 post, the average improvement in quality was 6.66% overall. While this number is not as high as expected, the individual parameter improvements showed much higher potential. Both nitrate and nitrite removal levels were high enough that they surpassed the average levels of nitrogen removal for current constructed wetlands outlined in the introduction (Figure 3). The standard deviation of the WQI was 1.722 across all nine trials, a value low enough that we can say with confidence that the nitrogen removal will continue to perform consistently at percentage. Additionally, the qualitative data shows the high levels of turbidity reduction and total suspended solid removal through the treatment, demonstrating how well the prototype is able to handle high levels of dirt and sediments, another common pollutant in agricultural pollution which can have harmful effects on water bodies and offset the ecosystems within them.

These results show the potential that this model has to effectively treat agricultural pollution. Being able to effectively treat polluted water allows us to keep water from being unusable for human activities and alleviates the stress of water scarcity. The cost-effectiveness of this solution allows this prototype to be implemented in countries that are commonly plagued by these issues but cannot afford the tools to manage it. Even within our own country, this technology can be implemented within more rural areas where individual farmers operate. Being able to maintain a clean water supply that can be consumed and reused provides the government with an incentive to implement this prototype in such rural areas where larger treatment plants wouldn’t be feasible.

Conclusions

1. The prototype was able to achieve nitrate removal levels of 51.85%, nitrite removal levels of 58.89%, and phosphate removal levels of 36.7%. Nitrogen removal levels exceeded the average total nitrogen removal levels of current constructed wetlands.
2. Prototype has high levels of turbidity reduction and suspended solid removal and can handle large amounts of sediments and particles.
3. General trends in sediment removal demonstrate the effectiveness of tube settlers and increase of settling area for filtration.

There are some limitations to the prototype and research conducted. The high flow rate of the device decreased the amount of contact time the water had within each basin and limited nutrient uptake, especially in the wetland cell. The scaled model also limited settling area and decreased the overall nutrient removal that the limestone filter aided in.

This project can be improved further through the improvement of the limestone filter, which was the main combatant for phosphates. By experimenting more with different types of lime, such as hydrated lime, and also adjusting the ratio of lime to water, the effects of the design can be improved. Additionally, by reducing the gradient between the compartments and using gated channels between each section, both the flow rate and retention time will be drastically improved, increasing pollutant removal.

Through some further research and improvement, full scale versions of this model can be produced to be utilized in areas such as Africa, China, and Europe whose water supplies suffer greatly due to agricultural activities. Additionally, because of the pollutants this model targets, it can also be used to prevent algal blooms and dead zones within freshwater bodies, and can also be used to treat water contaminated by sewage

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