Comparing sustainable nutrient reduction strategies for small coastal communities

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Abstract

The nutrient loading to the Chesapeake Bay from a rural community in Virginia was evaluated. Students evaluated options for removing nitrogen and phosphorus from stormwater and sewerage. Students evaluated the sources of nitrogen and phosphorus and were able to determine that septic systems posed a particular threat to nutrients in the Bay watershed. Students investigated wastewater treatment option to remove nitrogen and carbon from simulated wastewater. This collaborative, experiential and service based project provided undergraduate engineering students at James Madison University with the opportunity to explore and evaluate the impacts of nitrogen and phosphorus from a rural community. The work has provided assistance to the community by identifying treatment options and providing some initial data for generating a future cost benefit analysis. Further identification of methods to reduce nitrogen and phosphorus concentration is needed to compare cost between treatment methods, and to determine the various impacts, intended and unintended, of various treatment methods.

Keywords

Nitrogen, Phosphorus, Septic, Water treatment, Stormwater

Introduction

The project aims to propose a wastewater treatment system, which focuses on tertiary treatment, nutrient reduction, for the area of Bluff Point in Northumberland County, Virginia. The nutrients, specifically nitrogen and phosphorus, reduce the dissolved oxygen concentration in the Chesapeake Bay waters, harming the living conditions for animals in and around the Bay. The overall goal of the system is to reduce the concentrations of nitrates and phosphates from effluent wastewater, which will decrease the overall nutrient loading and increase the water quality of the Chesapeake Bay. The Chesapeake Bay is a large source of income for the regional economies. Improving Bay water quality is an important step in building and maintaining these economies

The Chesapeake Bay is the largest estuary in the United States and is home to over 200 different species of animals, as well as 17 million people.[2] Water quality in the Chesapeake Bay is an integral part of the survival of the many lives it supports. Aquatic organisms are not the only lives that are dependent on the health of the water. About 75% of the people residing within the watershed rely on the Chesapeake Bay to filter their water. The local economies in the

Chesapeake Bay area have been largely supported by fisheries for generations. Without healthy fish to harvest, the fisheries would decline and the local economies would suffer.[3]

Dissolved Oxygen (DO) is an important factor in maintaining a healthy water quality and fish populations. DO concentrations greater than 5 mg/L are required for propagation of aquatic life within the Bay. DO levels in the Chesapeake Bay are currently below the desired levels due in large part to the excess nitrogen and phosphorus entering the Chesapeake Bay. Decreasing the nitrogen and phosphorus content of water entering the Chesapeake Bay will allow DO levels to recover.

Urbanization in the areas surrounding the Chesapeake Bay has caused nutrients, such as nitrogen and phosphorus, to enter the Chesapeake Bay, which decreases the oyster population by reducing their habitat.[4] The loss of habitat is due to the production of algae blooms that obtain their nutrients from the nitrogen and phosphorus entering the Chesapeake Bay. The overproduction of algae blooms blocks sunlight from entering the water and reduces the DO content of the water creating ‘dead zones’ in the Chesapeake Bay. These dead zones have resulted in loss of habitat for oysters in the Chesapeake Bay. Oyster harvesting in the Chesapeake Bay has dropped from 122 million pounds of oysters harvested in 1880 to only about one million pounds of oysters in 2008.[4] In 1981, oysters provided a business impact of $180 million, while in 2008 oysters only provided a business impact of $13 million. This has been estimated to be a total cumulative loss of $4 billion for the economies of Virginia and Maryland.[5] The effects of the reduction of oyster population has a very large zone of influence, as jobs were needed to harvest the oysters, then to shuck the oysters, then to prep the oysters for sale. Now that the population has decreased, the jobs have also decreased.[4] Oyster habitat may never be back to the original habitat in 1880, but with the reduction of nitrogen and phosphorus entering the Chesapeake Bay, the oyster population should increase. An increase in oyster population would give rise to an economic increase for the area in the form of increase in jobs and economic growth of current oyster harvesting companies.

In 2013, 8.75 million pounds of nitrogen entered the Chesapeake Bay from septic tanks.[2] The large amount of nitrogen is due to the effluent of septic tanks, which is rich in nitrogen. Typical loading concentrations of Nitrogen and phosphorus emitted from septic systems are 70.4 mg/L and 17.3 mg/L respectively.[1] The effluent of the septic tank flows into a drainage basin where the effluent then travels through the soil and enters the groundwater, ultimately entering the Chesapeake Bay. Septic tank effluent accounts for an estimated four percent of the nitrogen and phosphorus loading in the Chesapeake Bay. The Chesapeake Watershed Agreement sets out ten goals to promote the restoration and protection of the Chesapeake Bay.[2] These measures include protecting the habitat of the Chesapeake Bay to maintain wildlife diversity, and making sure the Chesapeake Bay and its rivers are free of harmful contaminants, such as nitrogen and phosphorus that negatively affect natural resources due to the harm on marine health and population.[2] Nitrogen loading to the Chesapeake Bay is to be decreased to 240 millions pounds per year by 2017 and further decreased to approximately 200 million pounds per year by 2025.[6]

The focus of the wastewater system is Northumberland County, Virginia, which is part of the Lower Chesapeake Bay watershed. The area of focus is small compared to entire Chesapeake Bay, however nutrient reduction is required even for small sources throughout the Bay in order to improve water quality.

Pollutant loading from septic systems

A septic system functions by taking the flow of wastewater out of a house or building, into the septic tank where the waste settles. The water then flows out of the tank and into a drain field where the surrounding soil filters it further until it re-enters the groundwater table.[7] A drain field is the outlet of a septic tank that allows for the waste to be slowly filtered through the ground. For a drain field to function properly, the soil must be semi permeable and the groundwater should be at least 3 meters below the surface.[7] Drain Fields can become clogged and must be maintained along with the septic tank. Inadequate design, improper installation, improper operation, or old malfunctioning systems are the main causes for septic system failure.[8] Solutions include, chemical additives, reducing or ceasing the use of garbage disposals, and getting the septic systems regularly maintained. It is also important to practice water conservation; this helps the drainfield stay in tact.[9] Most septic systems are effective at removing phosphorus, but not nitrogen. Without proper care, septic tank effluents can cause dangerous pollutants to enter surrounding groundwater. The water demand from households in the area was estimated from typical household appurtenances and use based on summary data shown in Table 1.[10]

Table 1. Estimated wastewater flow from the study area.[10]

	Flow Rate (gal/capita-day)		
Use	Without water conservation	With water conservation	Average
Bathing	1.3	1.3	1.3
Showers	13.2	11.1	12.2
Dishwashing	1.0	1.0	1.0
Clothes Washing	16.8	11.8	14.3
Faucets	11.4	11.1	11.3
Toilets	19.3	9.3	14.3
Leaks	9.4	4.7	7.1
Other Domestic Use	1.6	1.6	1.6
Total	**74.0**	**51.9**	**63.0**
service area = 432 persons			
Service area use gpd	**31968**	**22420.8**	**27194.4**
use gpd (450 persons)	**33300**	**23355**	**28327.5**

Septic systems are not designed to remove nitrogen or phosphorus. The effluent water leaving a septic system has a typical value of 70.4 milligrams per liter (mg/L) of total nitrogen and 17.3 mg/L of total phosphorus.[1] These values are the same with or without the use of an effluent filter, a filter that prevents larger solids from entering the drainfield. The estimated effluent nitrogen and phosphorus mass from septic systems is shown in Table 2. The study area is immediately adjacent to the bay, so it is assumed that nitrogen and phosphorus exiting the drain fields would be discharged to the Bay.

Table 2: Nitrogen and Phosphorus mass loading from septic systems in the study area

Phosphorous and Nitrogen Loading From Septic Systems for the 432 people in the study area			
	Low Estimate	High Estimate	Typical
Total N (mg/L)	50	90	70.4
Total P (mg/L)	12	20	17.3
(1kg=1,000,000mg), (1lb=0.4536kg), (3.785L=1gallon)			
TN (lbs/gallon)	0.000417	0.000751	0.000587
TP (lbs/gallon)	0.000100	0.000167	0.000144
Mass N (lbs/year)	3414	8763	5831
Mass P (lbs/year)	819	1947	1433

Estimated Nitrogen and Phosphorus Loading from Storm Water Runoff

Although septic tanks are a serious contribution to nitrogen and phosphorus loading in the Chesapeake Bay, there are several other causes, a main one being stormwater runoff .[11] Storm water runoff is the "fastest growing source of pollution to the Chesapeake Bay." This runoff occurs after a precipitation event and carries anything that is on the ground into the water table. Things that are common to find outside of a home or on the street, such as pet waste, lawn fertilizer or pesticides, soap from washing cars or even car oil can be washed out of a residential area and carried into a watershed.[12] These items are chemical contaminants and are high in nitrogen and phosphorus, which is detrimental to the aquatic ecosystem.

The dangerous contaminants within stormwater are not the only issues associated with it. An excess of storm water runoff can erode waterways, such as streams, destroying many miles of aquatic habitats. This erosion can cause excess sediment to settle in places that are not normal to the ecosystem, causing further blockages. These events can cause flooding to local areas, which only further contributes to stormwater runoff.[11] Runoff in suburban areas is significantly higher in contaminants and other particles because of the large area of impervious surfaces and high population of people and their waste. It is shown that runoff from suburban areas is 1.5 to 4 times greater than that of rural areas.[11]

The nitrogen and phosphorus loading from stormwater using nutrient loading rates from the nearby Rappahannock River basin and land use maps was calculated as shown in Table 1. Nitrogen and phosphorus concentrations for the Rappahanock River basin were used due to the proximity of the site to a water source. The study site is 615 acres and pervious/impervious surface area was estimated to be less than five percent impervious surfaces form aerial maps. Nitrogen loading to the Chesapeake Bay was estimated to be less than 60 percent of septic system contributions. Phosphorus loading from septic systems would be over four times the mass loading of phosphorus from stormwater. Therefore, although the service areas is relatively small, the contribution of nutrients from septic emissions exceeds the likely contributions from stormwater, so future analysis was focused on the potential to remove nutrients through municipal wastewater treatment.

Table 1. Estimated mass inputs of nitrogen and phosphorus from runoff in the study area.

Rappahannock Basin Loading		lb/acre/yr	acres	% pervious/ imp	acres per/imp	lb/yr	**total lb/yr**
urban impervious	Nitrogen	9.38	615	5	30.75	288	**3408**
urban pervious		5.34	615	95	584.25	3120	
urban impervious	Phosphorous	1.14	615	5	30.75	35	**327**
urban pervious		0.5	615	95	584.25	292	

Carbon and nitrogen removal in municipal wastewater

The team researched different methods for nitrogen removal. The site for this proposed system is in a rural county with a lot of land used for agriculture, which creates excess stormwater runoff. The team studied recent data and compared the overall nutrient levels of treated stormwater to treated municipal wastewater to determine which would have a greater impact on the Chesapeake Bay. It was concluded that a greater effect would be seen if the system treats municipal wastewater.

Microorganisms in water use carbon-based substrates and oxygen in metabolism to form biomass, carbon dioxide, and water, and ammonia.[13] The biochemical oxygen demand (BOD) is the amount of oxygen required by microorganisms to oxidize organic matter to carbon dioxide and water.[13] The BOD test is used to determine the approximate quantity of oxygen that will be required to biologically stabilize the organic matter present, determine the size of wastewater treatment facilities, and measure the efficiency of some treatment. Initial BOD concentrations for wastewater are expected to be 110-350 mg/L and final BOD concentrations are expected to be 5-20 mg/L.[10] A synthetic wastewater with an estimated nominal 200 mg/L BOD was prepared using glucose as the major carbon source, with additional nitrogen, phosphorus and other micronutrients prepared from basic slat mixtures.

Chemical Oxygen Demand (COD) measures organic strength of domestic and industrial wastes and measures the total quantity of oxygen required for oxidation to carbon dioxide and water [chemistry for environmental engineering]. Initial COD concentrations for domestic wastewater are expected to be 250-800 mg/L.[10]

Nitrification occurs in natural waters. When organic waste breaks down, it consumes oxygen and produces carbon dioxide, water, and ammonia.[14] In untreated domestic wastewater there is typically 20-70 mg/L of total nitrogen, with 12-45 mg/L being ammonia.[10] If left untreated, this ammonia will be present in the wastewater effluent and will continue to decrease the DO in the Chesapeake Bay through nitrification.

Several methods for removing nitrogen and phosphorus exist, including biological nitrification and biological denitrification. These processes incorporate the use of different autotrophic and heterotrophic bacteria for removal. Biological nitrification is the multi-step process of oxidation of ammonia to nitrite and then the oxidation of nitrite to nitrate through the use of autotrophic bacteria in aeration tanks and clarifiers. There are two options for completion of this including attached growth, and suspended growth, which also has two methods: single sludge and two-sludge.[15] This process slows down the nitrogen cycle, therefore decreasing the concentration of nitrogen in the water at any given time, which ultimately limits the DO in the water.

Biological denitrification is the process of reducing nitrate to nitric oxide, nitrous oxide, and nitrogen gas using heterotrophic bacteria. There are two ways to complete the denitrification process. During one process and electron donor is provided for reduction reactions. The other involves first using nitrification, and the denitrification process then depends on energy to start the reduction reaction.[16]

Nitrification of ammonia consumes oxygen and produces nitrite in water. The nitrite is subsequently converted to nitrates in the presence of oxygen. The net overall conversion of ammonia nitrogen to nitrate is illustrated by equation 1:[10]

$$NH_4^+ + 2O_2 + bacteria \rightarrow NO_3^- + 2H^+ + H_2O \qquad \text{(Eq. 1)}$$

If the oxygen is depleted the nitrate may be reduced to nitrogen gas if a carbon source is present. In wastewater the denitrification process may be approximated by the conversion equation shown in equation 2:[10]

$$C_{10}H_{10}O_3N + 10NO_3^- \rightarrow 5N_2 + 10CO_2 + 3H_2O + NH_3 + 10OH^- \qquad \text{(Eq.2)}$$

Combined nitrogen and phosphorus removal processes

Iron is added to sewers in order to control sulfur present in the water. The addition of iron has another consequence, however, which is the removal of phosphorus from the wastewater. The removal of phosphorus is a necessary step in reducing eutrophication from wastewater. This study tested different amount of Fe^{2+} and Fe^{3+} added to wastewater and measured the effects on phosphorus removal, sulfide removal, and pH. The Fe^{2+} and Fe^{3+} serve a dual purpose of converting sulfide to sulfate, and removing phosphorus from wastewater.[17] The setup used in the experiment was multiple aerobic batch reactors with stirrers. The methods and procedures used in this experiment are very well suited to the needs of the Chesapeake Bay, because the current wastewater is still high in Phosphorus. Nitrogen is easier to remove, but both nitrogen and phosphorus must be removed to combat eutrophication of the Chesapeake Bay.

Phosphorus is a very difficult nutrient to remove from wastewater, but is necessary in the reduction of eutrophication. One way to remove phosphorus is through various artificial wetlands filter media. The key issue with artificial wetlands filtration is the media that is used in the removal of phosphorus. There are three different types of materials that can be used in phosphorus removal, natural materials, industrial by-products, and man-made products. One of the biggest concerns for filter materials is the retention rate of the different filtration materials. The retention capacity of the materials ranged from 0.001 to 420g P/kg. Calcium is a very common in the removal of phosphorus in the different filtration methods, as calcium acts like iron (Fe) and Aluminum (Al) in the chemical removal of phosphorus from wastewater. The highest capacity for phosphorus retention in natural wetland materials, industrial by-products, and man-made products respectively is: heated opoka, blast furnace slag, and light weight clay aggregates (LWA).[18]

The majority of the biological treatment processes remove either nitrogen or phosphorus. Anoxic to Aerobic biolofgical reactors (A2O) and sequencing batch reactors (SBR) are two processes that remove nitrogen and phosphorus, but there are pros and cons of each process.

An advantage of the A2O process is that the process provides alkalinity (the ability of an aqueous solution to neutralize an acid) in the water and also provides good settling sludge. The major limitation that the A2O process has is that the nitrogen and phosphorus removal are limited by the internal recycle ratio, which decreases to capability to remove the nutrients. A2O uses different stages of anaerobic, anoxic, and aerobic chambers to not only remove phosphorus from the water, but also causes denitrification in the water. [19]

SBR is a flexible operation but is much more complex than A2O. The process to remove nitrogen and phosphorus is complex which requires skilled maintenance to work appropriately. Though SBR can remove nitrogen and phosphorus, the design is complicated and is more appropriate for low flow rates. The SBR process combines aerobic and anoxic chambers to stimulate the removal of nitrogen and phosphorus. The purpose of the SBR process was originally to remove only nitrogen, but with slight modification SBR can also be used to remove phosphorus.[20]

A2O and SBR remove the necessary nutrients in effluent, other processes that remove only nitrogen such as Step Feed can be combined with one that removes only phosphorus such as Phoredox (A/O). The major limitations of the SBR and A2O are the time the processes take to remove nitrogen and phosphorus. The A2O process can take up to one hour, while the SBR process can take longer due to more chambers.

Algae may also be used in many wastewater systems to remove excess nitrogen and phosphorus. Algae could be used to remove nitrogen and phosphorus because algae uses nitrogen and phosphorus as nutrients to fuel further growth.[21] Algae removes these nutrients through photosynthesis, provided by energy from the sun, and produces oxygen as an output. This oxygen is extremely useful in waters with low DO content, such as the Chesapeake Bay.

The primary technology regarding algae treatment is the algae turf scrubber (ATS). The ATS uses a layer of algae on a porous sheet to allow water to pass through. When the water passes through the ATS, the algae remove excess nitrogen and phosphorus as well as produce DO in the water.[21] ATS can be used as a tertiary treatment of sewage as well as water in oceans and lakes. ATS is a relatively new technology, with the first treatment of sewage being in 1996.[21] One possible downside of ATS is that they can be extremely large. ATS are not recommended for urban areas where land is costly, but are generally recommended for large rural areas where land price is not as much of a factor.[21]

Demonstration of carbon and nitrogen removal in simulated municipal wastewater

Experiments were conducted using 1-liter batch reactors to demonstrate nitrogen removal potential in a wastewater treatment process. A synthetic wastewater was created from stock chemicals. The nitrate mass was measured in an aerated batch reactor and BOD and COD concentrations were also measured over time. In a lab setting, 80% of ammonia was removed using batch reactors. The total phosphorus concentration in the simple lab-scale reactor did not decrease significantly over time in the aerated reactor. These observations are in agreement with the literature which reports combined nitrogen and phosphorus removal requires a combination or aerobic and anoxic conditions or biological nitrogen removal followed by chemical precipitation of phosphorus through the use of metal salts.

Figure 1: Change in BOD Concentration with time

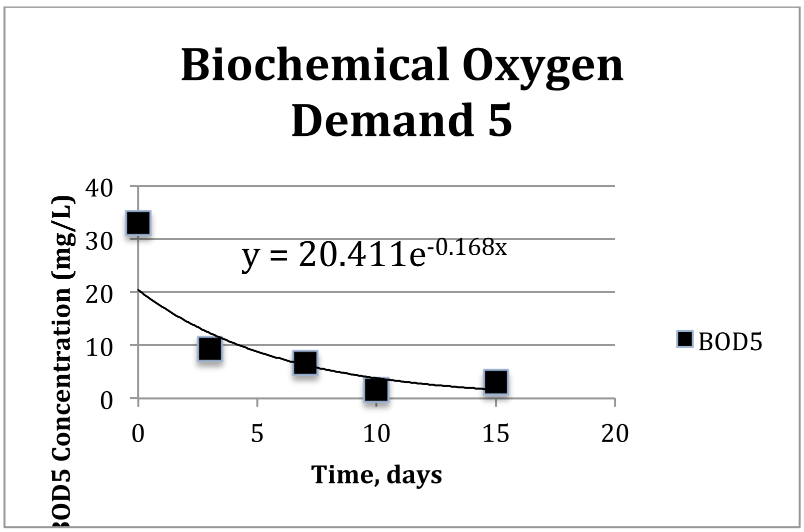


Figure 2: Change in COD concentration with time

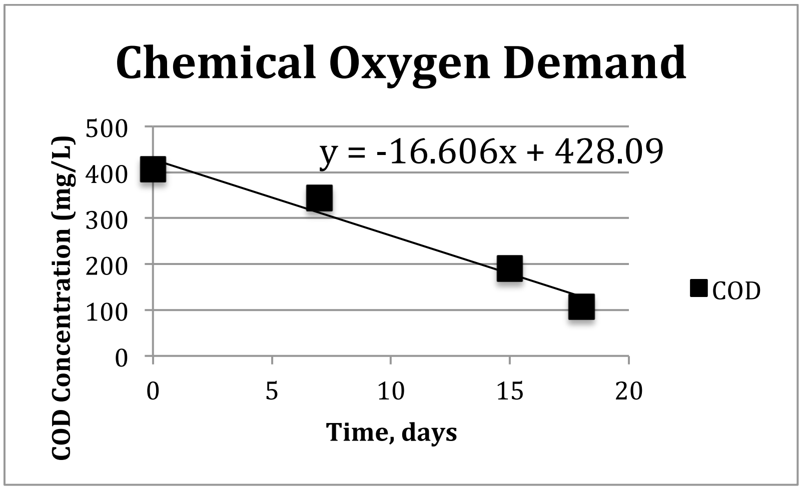
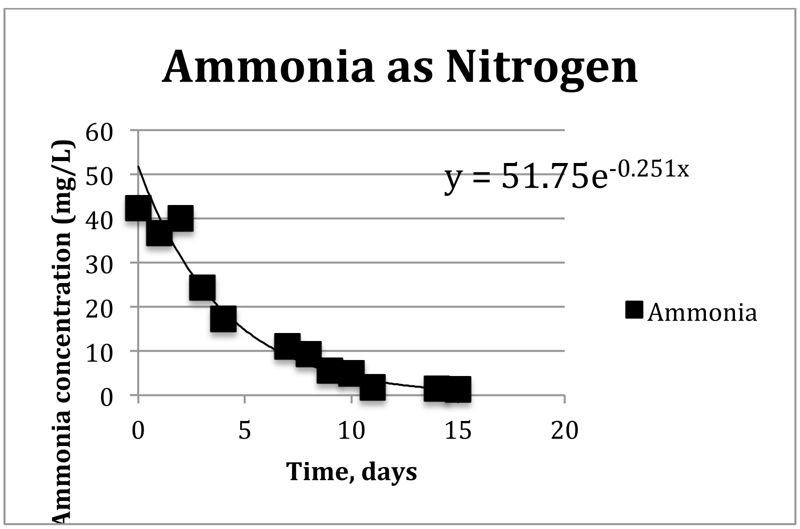


Figure 3: Nitrogen removal in a 1liter laboratory batch aerated reactor to demonstrate nitrogen removal potential in wastewater treatment.



In this study, students evaluated options for removing nitrogen and phosphorus from various sources in Northumberland County, VA. Students evaluated the sources of nitrogen and phosphorus and were able to determine that septic systems posed a particular threat to nutrient contributions from this area. Students then investigated wastewater treatment option to remove nitrogen and carbon from simulated wastewater. Students were able to replicate carbon and nitrogen removal in simulated bench-scale sequential batch reactors. Additional work is underway to demonstrate the principles involved in phosphorus treatment. Additionally, the removal rate models generated in figures 1-3 may be used to provide preliminary sizing estimates and budgetary cost estimates for the Northumberland County government.

Conclusions and Recommendations

Advanced wastewater treatment methods to reduce the nitrogen and phosphorus concentrations is necessary to limit eutrophication in the Chesapeake Bay, which may provide economic, social, and environmental stability to the Chesapeake Bay Watershed itself, and to commercial areas surrounding of the Chesapeake Bay.

Reducing nitrogen and phosphorus from septic tanks through a wastewater treatment system could be used as a model to be implemented throughout the Chesapeake Bay Watershed. The area of focus for this wastewater treatment system is Northumberland County, Virginia, part of the Lower Chesapeake Bay watershed.

This collaborative, experiential and service based project provided undergraduate engineering students at James Madison University with the opportunity to explore and evaluate the impacts of nitrogen and phosphorus from a rural community. The work has provided assistance to the community by identifying treatment options and providing some initial data for generating a future cost benefit analysis.

Further identification of methods to reduce nitrogen and phosphorus concentration is needed to compare cost between treatment methods, and to determine the various impacts, intended and unintended, of various treatment methods. Some treatment methods may not be applicable to areas surrounding the Chesapeake Bay due to addition of chemicals that may harm water quality in the Chesapeake Bay.

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