Sewage Treatment Options and the Need for Regulation

Abstract

Large-scale human settlements necessarily create waste streams, including sewage, which in large quantities causes damage to the local and downstream environment. The provision of clean water is a public good, and therefore some sort of external regulation is required in order to ensure a minimum level of environmental quality through sewage treatment. Sewage treatment systems vary greatly in their capacity to filter and cleanse sewage water, and the cost of a system design is affected by several variables: strictness of regulation (level of fines and water quality standards), river discharge rate, and channel flow. Through mathematical modeling in MathCAD, the effect of these variables on the total costs of sewage treatment can be tested. The results of this modeling show that sufficiently high fines will affect the choice of treatment plant design, and that channel flow and river discharge rate also have a large impact on total costs. It is clear from the experiments that regulation is required to maintain water quality. But fines are not the only possible mechanism for achieving this goal, and both flexibility of fine level and flexibility in choice of incentive mechanism are important in optimizing the cost/benefit ratio for both human and non-human systems.

Introduction

The demands of large-scale human settlement, such as agricultural production and the building of urban environments, often come into conflict with the welfare of non-human natural systems. Human society requires a constant stream of resource inputs from the natural environment and also creates a constant stream of waste outputs that must be dumped into one environmental "sink" or another. One of the most problematic of these waste streams is sewage effluent, since it can cause significant damage to the environment into which it is dumped if left untreated, and it is inevitable. Thus, modern industrial societies since the nineteenth century have developed increasingly sophisticated treatment systems in order to at least partially mitigate the environmental damage resulting from sewage.

Of course, the impetus for sewage treatment has largely been government regulation, since the benefits of treatment (cleaner water, healthier natural systems and more robust fish populations) are widely distributed within a watershed and the costs are highly concentrated in the organization responsible for the treatment. These costs are significant, and no private entity on its own has an incentive to guarantee clean water for everyone else. In other words, the benefits of sewage treatment are public goods, and economic theory predicts that public goods will be inadequately supplied unless the government intervenes and requires a particular entity to provide them. Also, there is a question about exactly what minimum level of cleanliness is necessary to maintain a healthy environment, and government must set a common standard throughout a watershed.

The assumption in the case of sewage is that it must be treated in order to ensure the health of the local and downstream environment, and that some form of regulation is required in order to guarantee that a certain minimum amount of sewage treatment takes place. This lab, then, is designed to model the costs and benefits of selecting various sewage treatment options and the variables which affect that selection. By exploring the effect of these variables on the total costs to society from sewage treatment using a mathematical model, one can make better-informed decisions about which sewage treatment options are most cost-effective.

Description of System and Modeling Procedure

The system modeled in the lab is the case of a sewage treatment plant releasing effluent into a river. There are several variables considered in the lab: the design of the treatment plant, the strictness of regulation, the rate of river discharge, and the channel flow. The effects of manipulating each variable, independently of the others, are modeled in MathCAD.

There are four possible treatment plant designs to be modeled: secondary treatment (about 90% of [BOD] removed, with about 50 mg/L left); two different levels of tertiary treatment (which reduce [BOD] to either 30 mg/L or 25 mg/L); and a newer technology that reduces [BOD] to about 15 mg/L. The more that [BOD] is reduced, the more expensive the treatment plant is. All other things being equal, rational choice theory predicts that society would prefer the plant with the lowest total cost.

Regulation in the case of sewage treatment plants is assumed to take the form of a fine for non-compliance with water quality standards. These water quality standards require that the waste load in sewage effluent not cause dissolved oxygen [DO] in the river to drop below a certain threshold at which the ecosystem would be unacceptably damaged. There are two different fine levels, $5,000 per violation and $5,000,000 per violation; and also two different [DO] standards, 6 mg/L and 4 mg/L. The higher standard would be necessary to preserve all fish species in the river, whereas the lower standard would be required to maintain only smallmouth bass and carp.

The last two variables are river discharge rate and channel flow. These both affect the river's flow and therefore the [DO] available in the water. River discharge rate can either be set at twice the normal flow rate in order to model a wet year, or at half the normal flow rate to model a dry year. Channel flow, a measure of the slope of a river and therefore of water speed, can be set at 0.00001 to model the presence of a dam, or 0.0001 to model the removal of the dam.

The lab includes four different experiments, each modeling the effect of a different variable. In each experiment, one variable is tested at two different values, and the performance of each plant design is predicted at each of the two values. Plant performance is measured by the failure rate, i.e. the frequency with which the plant fails to meet the water quality standard. An annualized plant cost is then calculated, as a sum of capital and operating and maintenance costs plus the cost of any fines incurred as a result of failure to meet water quality standards. This total cost is used to rank the desirability of each design in each experimental situation. In Experiment 1, the effect of different fine levels is tested; in Experiment 2, the effect of different [DO] standards is tested; in Experiment 3, the effect of different river discharge rates is tested; and in Experiment 4, the effect of different channel flows are tested.

Graphs

Figure 1

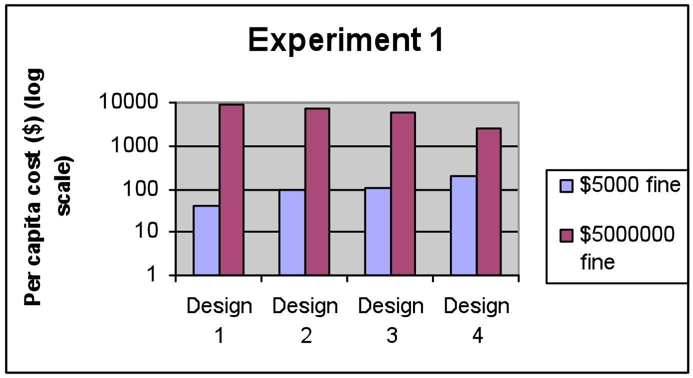


Figure 2

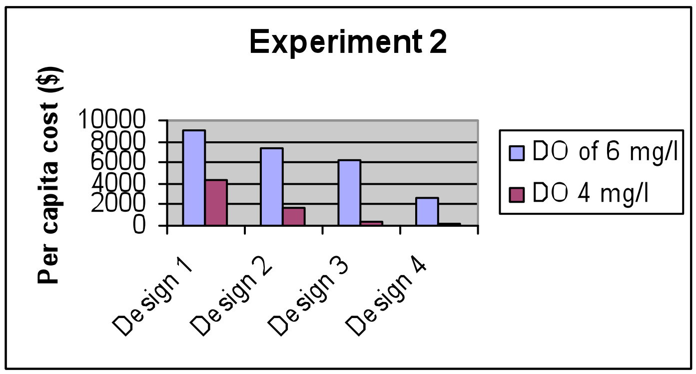


Figure 3

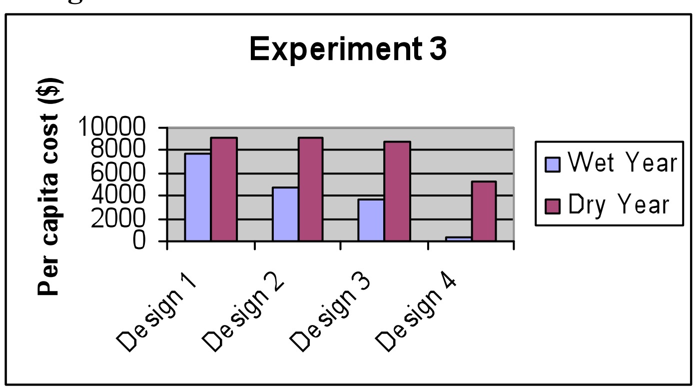
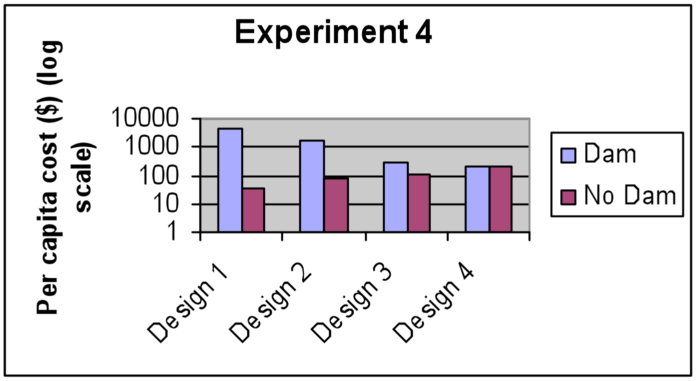


Figure 4



Results and Discussion

Since it would be extremely costly and time-consuming to go out into the field and perform all of these experiments in the real world, mathematical modeling with MathCAD of these different sewage treatment options is perhaps the most direct way to explore the question of sewage treatment. So long as the assumptions, variables, and model equations themselves are sufficiently sophisticated to produce realistic results, this approach is an excellent way to enable students to make conclusions about sewage treatment options using hard data. The only problem encountered during the lab was the minor hindrance of having difficulty with inputting values in MathCAD.

The lab itself yielded a number of important results. From the first experiment, it is clear that the level of the fine imposed on the sewage treatment plant has a large impact on the total cost of treatment. In this case, comparing fines of $5,000 and $5,000,000, the higher fine actually reverses the order of preference for the plant designs. Whereas with the low fine Design 1 yielded lowest total costs, with the much higher fine the lowest total cost is generated by Design 4 (Figure 1). This is because the cost of the fines in this case greatly outweighs the capital and O&M costs. Such a result suggests that, if it is concluded that it is critically important to maintain water quality at a certain level and keep violations below a certain level, a high fine will provide a powerful incentive to install the best technology for [BOD] reduction.

From the second experiment, one sees that even at a lower [DO] standard, the fine level of $5,000,000 still generates total costs such that Design 4 is preferable (Figure 2). One may have predicted that a lower [DO] standard would give results that make a less expensive plant design seem preferable, but that is not the case here. This may not be true at all [DO] standards—for example, at a [DO] standard of 1 mg/L Design 1 will most likely be preferred—but at least for the two values tested it appears that the effect of the fine level outweighs the effect of the desired [DO] value. Because of limited time in the lab, there is not very comprehensive data, so it would be hard to predict in general which parameter, fine level or [DO] standard, would have the greater effect on total costs for each increment of change.

The third and fourth experiments provide a different sort of information than the first two experiments. Rather than modeling the effects of parameters imposed solely by humans, they model the effects of natural parameters (i.e. local conditions) over which humans have little or no control. The third experiment shows that, though the flow rate does not affect the order of preference of the plant designs, it does affect the total costs (Figure 3). Thus, the total cost to society will change based not on difference in human choices but on uncontrollable natural conditions—a drought year will make it more difficult for any plant design to maintain water quality. If there is still a preference for the best technology (Design 4) under this scenario, it may make sense to lower the fine in drier years, because the purpose of incentivizing the optimal technology has been achieved and keeping the fine high will raise costs unnecessarily.

The fourth experiment demonstrates that the channel flow and water speed have a significant impact on the water quality. With a shallow slope and slower water speed, the most expensive plant design is still preferable (Figure 4). A steeper slope and faster speed in this experiment meant that no violations occurred with any of the plant designs—in other words, the choice of plant design would have no impact on water quality and therefore one could choose the lowest-cost design (Design 1) without any negative environmental consequences.

Conclusion

This lab vividly demonstrates the impacts of various variables on the desirability of different sewage treatment plant designs. Before gathering data, one may have drawn widely divergent conclusions based on certain assumptions. For instance, one might have assumed that the more expensive plant design (Design 4) was always best, because cleaner water is always worth the cost. The results of the lab show that this is not always the case. Assuming that the goal of sewage treatment is to optimize cost/benefit ratios for both human and natural systems (i.e. optimize the cost/benefit ratio for the whole human/non-human system), it is not always necessary to choose the most expensive treatment option, because this may impose unnecessary costs on the human system which provide little benefit to non-human systems, creating a sort of “deadweight loss.” In certain cases, one can maintain a high level of water quality even with the cheapest treatment plant. Experiment 4 suggests that one must first examine local conditions in order to determine what water quality standards are necessary to maintain environmental health, because a stream with a steeper slope and faster water speed will require less stringent regulations on water quality.

The thesis that a regulatory system with substantive, punitive fines is essential to the protection of ecological values in our rivers is not always true. Fines are one way to create a disincentive for disposing of untreated human sewage, but another method may be for downstream users to pay the upstream sewage treatment operator to maintain clean river water. Besides financial incentives like fines or ecosystem services payments, the government may choose to set water quality standards and institute a criminal penalty (e.g. prison sentences) for failing to achieve them. Though it may not be very practical, one could also institute a cap-and-trade program for sewage dumping within a particular watershed. Thus, there are other methods besides punitive fines for maintaining the ecological value of rivers.

If one does choose to use fines, Experiment 1 shows that they must be set high enough to overcome other costs. Low fines are not any more effective than no fines at all. Experiment 3 demonstrates that it would be wise to allow for an adjustment of fines based on environmental conditions like flow rate. As mentioned above, in a drought year even the most advanced treatment plant design will have a higher violation rate and this will create unnecessarily high costs for treatment through more frequent fines. The goal is to create an incentive for the most cost-effective way to maintain environmental quality, and so once the fine level has led to the adoption of the best technology, it is no longer cost-effective to allow the cumulative amount of fines to increase further. Flexible fine levels, which would decrease in dry years and increase in wet years, would maintain water quality more cost-effectively.

Through all of these experiments, though, it is clear that water quality will not be maintained unless local sewage treatment operations are subject to some form of external regulation, either through government-imposed penalties or private ecosystem services payments. Regulation, then, in one shape or another *is* essential to the protection of ecological values in our rivers.