Using Rapid Prototyping as a Way to Visualize Subsurface Hydrology

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Abstract

All across the United States, individuals are becoming ill from drinking polluted water, and local economies are being harmed because of sewer overflows. Due to the aging infrastructure and growing population, the sewage collection pipes and the treatment plants are not able to handle the overload of sewage that occurs during heavy rainfall or snowmelt. In Wisconsin, the city of Milwaukee also faces this problem. As a means to reduce the overflow that pollutes Lake Michigan, the Deep Tunnel was constructed in Milwaukee to store excess sewage until the treatment plants can clean it. This multi-billion dollar project has prevented more than seventy billion gallons of wastewater from polluting Lake Michigan. There are diagrams and texts that describe the workings of the Deep Tunnel, but many times this information is difficult to understand. A dynamic method of illustration for the Deep Tunnel is useful to inform the public of its advantages and limitations. This research investigated whether rapid prototyping is a feasible method in creating a visual aid that replicates the workings of the Deep Tunnel. The stereolithography (SLA) process was utilized in this research so that the model is translucent enough for the viewer to see the flow of the fluids and WaterShed® resin was used because it is water resistant. This project explored using two immiscible fluids of different densities to produce fluid motion from the top reservoir to the bottom. Once fluid dynamics along with rapid prototyping is understood, visual aids for any aspect of subsurface hydrology can be built for classrooms, museums, or a government building.
Keywords: Rapid prototyping, Stereolithography, Deep tunnel, Sewage overflow, Fluid dynamics

1. Introduction

Freshwater is defined as water having low concentrations of dissolved salts. Although roughly 78% of the world is covered in water, freshwater makes up only 2.8% of the world's water supply[1]. Some freshwater regions are lakes and ponds, streams and rivers, and wetlands. In Wisconsin, the city of Milwaukee was built on three rivers merging together - the Menomonee, the Kinnickinnic, and the Milwaukee. These rivers eventually lead to Lake Michigan which is the largest freshwater lake entirely within the United States and the fifth largest lake in the world. It is very important to protect this scarce resource because it provides the majority of our nation's drinking water,[2] and unless man stops abusing this natural resource, water will become the limiting factor for human beings[3].

Sewage overflows are discharges of either wastewater, stormwater, or both from the sewer system. This usually occurs during wet weather when the volume of stormwater entering the sewers temporarily exceeds capacity of reclamation facilities. Wet weather conditions present the greatest challenge of finding solutions to the issues facing most sewer districts today[4]. To reduce overflows in Milwaukee, the Deep Tunnel was constructed and to this day has prevented more than seventy billion gallons of wastewater from polluting Lake Michigan[5]. Many other cities have also created underground storage tunnels such as the Big Walnut Augmentation/Rickenbacker Interceptor in Columbus, Ohio and the Tunnel and Reservoir Plan in Chicago, Illinois in order to prevent sewage overflows.

The Deep Tunnel does its job in reducing overflow by storing excess sewage until the reclamation facilities can clean it and deliver it into the lake. The Deep Tunnel was built to store only a certain amount of sewage so when the volume of excess sewage coming into it exceeds its capacity, overflow is inevitable. A three-dimensional model allows the public to learn about the workings of the Deep Tunnel and how their tax dollars are being spent to improve the environment. Another purpose of the model is to demonstrate how overflow occurs even with the existence of the Deep Tunnel. This model may encourage the public to take action and help to reduce overflows by conserving water especially during wet weather and installing rain barrels to capture rainwater from rooftops.

This research investigates whether the workings of the Deep Tunnel can be accurately scaled down and built using a process known as rapid prototyping (RP). To accomplish this, an understanding of how the Milwaukee sewage system works and the role of the Deep Tunnel in overflow reduction was attained and then used to produce a compact model that is visually helpful and easily understood. Fluid dynamics was studied as two immiscible fluids of different densities were used to show fluid motion of sewage. Once fluid dynamics along with rapid prototyping is understood, visual aids for any aspect of subsurface hydrology can be built for classrooms, museums, or a government building.

2. Background

There is general information online available to the public concerning the Deep Tunnel that is presented in a format that is easy to understand, but an in-depth description of how and when the Deep Tunnel is used is not accessible and difficult to understand. Information on the Deep Tunnel is best found on the Milwaukee Metropolitan Sewerage District (MMSD) website because the Deep Tunnel was constructed by the MMSD. Other sources available to the public include government agency websites like USAsearch.gov and epa.gov, newspaper articles, and online resources. General information such as the dimensions, construction time and date, capacity, and location can be found using these resources. A model of the Deep Tunnel is available at Discovery World in Pier Wisconsin, but the model is not portable due to its large size and components, and therefore is only available for those visiting the facility.

2.1. sewage overflow

There are two types of sewer systems - combined and separated. Separated sewer systems are made of two pipes which lead to different endpoints. One of the pipes carries the sanitary sewage from homes and businesses to treatment plants while the other one carries stormwater to the nearest lake or river. Combined sewer systems, on the other hand, have only one pipe that handles both the stormwater and sanitary sewage and sends this to the treatment plants [6] as shown in Figure 1. Combined sewer systems are demonstrated in the model.

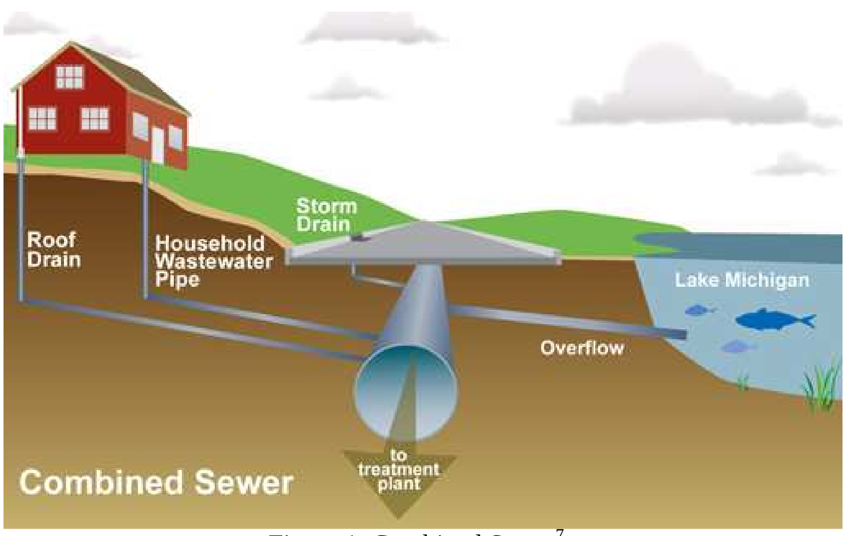

Figure 1. Combined Sewer[7].

Most of the sewer systems are separated in order to prevent overflow during heavy rainfall, but due to the aging infrastructure, the cracks in the pipes allow stormwater to seep into the sanitary sewers[8]. When heavy rainfall occurs, the valve to overflow pipes is opened to prevent basement backups. There are two reclamation facilities in Milwaukee County, Jones Island and South Shore, which clean the sewage and release it to Lake Michigan. These facilities can clean about six hundred million gallons of sewage a day combined[9]. When more sewage enters the sewers than the facilities can handle, overflow occurs.

2.2. deep tunnel

The Deep Tunnel was built in order to store excess sewage until the treatment plants can clean it. There are three stages to the construction of the Deep Tunnel. The first phase was completed in 1993, the second phase commonly referred to as the Northwest Side Deep Tunnel (NWSDT) was completed in 2005, and the third phase known as the 27th Street Deep Tunnel is under construction with expectations for its completion by 2011. The first phase of the Deep Tunnel stores both combined and separate sewage while the NWSDT stores only separate sewage. Phase three will be an addition to the Deep Tunnel. Currently the Deep Tunnel can store about 494 million gallons, but with the completion of phase three, it will be able to store 520 million gallons of untreated sewage. The Deep Tunnel is located 135-300 feet underground with diameters ranging from 17-32 feet [10]. It is important for the public to understand that the Deep Tunnel plays a huge role in reducing pollution of Lake Michigan by storing the high concentrations of poor quality water that initially occurs when it rains. As time increases, the water quality improves due to dilution, and this is what overflows into the lake[11].

2.3. models

Scientific modeling allows difficult concepts to be represented as a simple system that is easily understood. 3-D models can bring clarity to a complex set of relationships and may spark the interest of the public more so than a two-dimensional representation. This research explored a method which produced a model that allows the viewers to have a hands-on experience and gain a deeper understanding while engaging them to learn the fundamental workings of the Deep Tunnel more readily.

2.4. rapid prototyping

Rapid prototyping (RP) is a process by which a model of a part or assembly is produced using three-dimensional computer aided design data. The computer model is sliced into thin cross sections and sent to a machine which builds the model layer upon layer. Rapid prototyping is also known as additive manufacturing and solid freeform fabrication. Using RP for this research has helped to save time and has been convenient in producing an accurate model[12]. This research uses a rapid prototyping process known as stereolithography (SLA) to create a final model. The SLA process involves a laser that hardens a liquid photopolymer into the desired shape layer by layer,[13] as illustrated in Figure 2. As the laser traces over a layer, the resin begins to cure. The platform drops down and another layer is drawn on top of the finished layer and this process is repeated until the model is built.

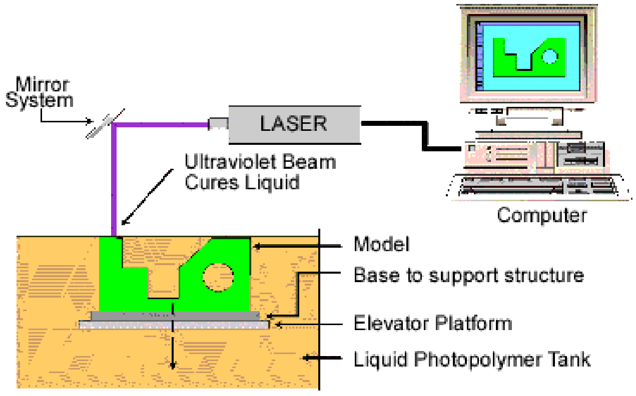

Figure 2. The SLA Process[14].

2.5. spiral timer

A spiral timer is a container filled with two immiscible liquids of different densities. As the denser liquid drips out of the top, it forms into a sphere and spirals down to the bottom compartment as shown in Figure 3. The concept of a spiral timer was used in the Deep Tunnel model to slow down the flow of fluids enough to follow the fluid motion.

Figure 3. Spiral timer.

3. Methodology

Many experiments were done prior to the creation of the Deep Tunnel model in order to determine the motion of the fluids, size of the nozzles, and the fluids to use.

3.1. acrylic model

An acrylic model was produced using acrylic plates and a laser cutter as shown in Figure 4. First a two-dimensional AutoCAD file was made which was then laser-cut into one of the acrylic plates (in black). Two translucent acrylic plates were then bonded to both sides of the cut acrylic. The two liquids used for test purposes were mineral oil and colored water. The model was filled with mineral oil up to ½ inch below the top and then dyed water was dropped from the top opening through a syringe. The water formed a sphere as it was in the oil but had a tendency to stick to the walls of the acrylic instead of sliding down the incline.

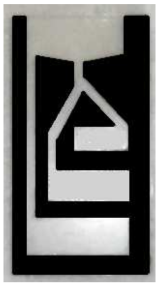

Figure 4. Acrylic model.

Superhydrophobic coating was researched because it was a solution to the adhesion of water to surfaces. Superhydrophobic coating transforms a surface to cause water droplets to bead off completely because the water droplets have contact angles of 150 degrees or higher. It is a relatively new idea and therefore is currently being tested in laboratory settings. A superhydrophobic coating developed at Sandia National Laboratories was investigated since it provides optical clarity and can be applied using a variety of methods that are practical for the complex geometry of this application[15]. Unfortunately, a sample of it was not able to be obtained for these tests.

3.2. spiral timer model

A spiral timer was drawn in SolidWorks® and then sent to the Rapid Prototyping Center (RPC) to build using the SLA process, Figure 5. A spiral timer was created because it was relatively quick to model and allowed easy revisions to the geometry and fluid choice for this project. The fluids used in the first experiment were mineral oil and water dyed with blue food coloring. Due to the initial diameter size of the nozzles, the fluids were not able to drip through the nozzle. A drill was used to increase the diameter of the nozzles from 0.03" to 0.062". The fluids were then able to flow through the nozzles but were not forming uniform spheres. It appeared that the high viscosity of the mineral oil was allowing a stream of water to exit through the nozzles. Mineral spirit was then used in place of mineral oil and experiments showed that although this worked better, uniform spheres of water was still not attained. Glycerin was then mixed with water in a 3:1 ratio to increase the density which also inadvertently increased the viscosity. Using this mixture with mineral spirit produced uniform spheres that spiraled down to the bottom. Due to the potential hazard of mineral spirit in certain settings, the clear fluid was switched back to mineral oil. Mineral oil was filled up to the top reservoir and then the water/glycerin mixture filled the top reservoir. Due to high surface tensions, there was no fluid flow. When the bottom reservoir was emptied and filled with air, the air bubbles would flow to the top which allowed water to flow to the bottom in uniform spheres. This demonstrated a transfer of fluids. Finally, the diameter of the nozzles leading to the top and bottom reservoirs, inlet nozzle, was increased to 0.078" to quickly allow the fluids to enter the reservoirs.

Figure 5. Rapid prototyped spiral timer.

The multiple experiments run on the spiral timer helped to make the next steps in creating the Deep Tunnel model. The tests resulted in the increase of the nozzle diameters and eventually, making the diameter of the inlet nozzle to be greater than the outlet. Also, mixing glycerol and water increased the density of the mixture which helped form the uniform droplets of water. Finally air was required to create the fluid motion. All these findings were applied to the deep tunnel model.

3.3. deep tunnel model

The workings of the Deep Tunnel was modeled in SolidWorks® and then sent to the Rapid Prototyping Center (RPC) to be created using the SLA process, Figure 6. The model was made in one piece with the exception of small holes made in each reservoir in order to clean the leftover resin out. Plugs were also built to seal these holes in the end. The model is 9.5" x 9.5" with varying depth. Each experiment required tape and the plugs to temporarily seal the openings. Plates with a magnet embedded in them were placed in the water reclamation facility reservoir, one at the top and one at the bottom. The plate was used to vary the rate of fluid entering and leaving the water reclamation facility. The plates were placed over the holes of the pipes with only a slight crack to allow water to slowly trickle into the facility and then trickle out to Lake Michigan. Three metal balls were placed in the top reservoir and were secured because the top of the nozzles were designed to cup the balls. Three magnets were placed on the front of the model, one for each ball, to adjust whether the ball is blocking the flow of fluid or not. To demonstrate the workings of the Deep Tunnel, a combined sewer system was used and sanitary sewage was not included because it enters the reclamation facilities at a relatively constant rate of 120-160 million gallons a day[16]. Also, the Deep Tunnel displayed in the model references to the Inline Storage System or phase 1. This is because phase 2 only handles separated sewage[17] and thus has not been included. Phase 1 can store about 400 million gallons of sewage[18]. Three different situations were used in order to demonstrate the workings of the Deep Tunnel.

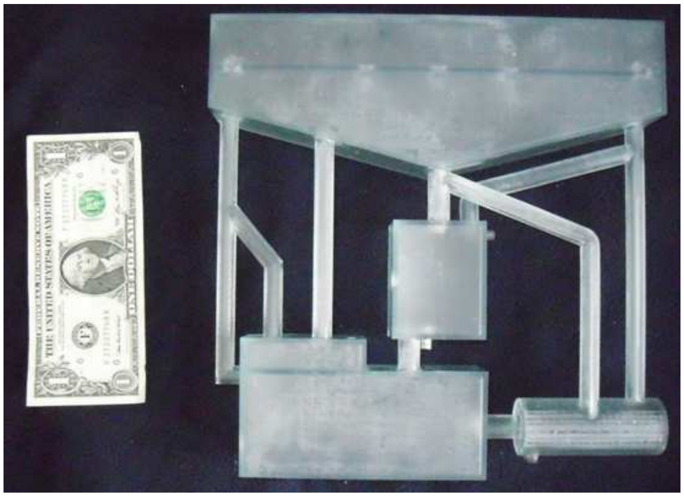

Figure 6. Deep tunnel model.

3.3.1. situation 1- light to medium rainfall

The water reclamation facilities in Milwaukee can handle about 600 million gallons of sewage a day and whether there is overflow is highly dependant on this rate. Since about 150 million gallons of wastewater a day is being cleaned in the reclamation facility, this leaves only about 450 million gallons a day for stormwater. Situation 1 shows rainfall that is substantially less than 450 million gallons a day. As shown in Figure 7, the water reclamation facilities can handle this rate of rainfall and none of it is diverted into the deep tunnel.

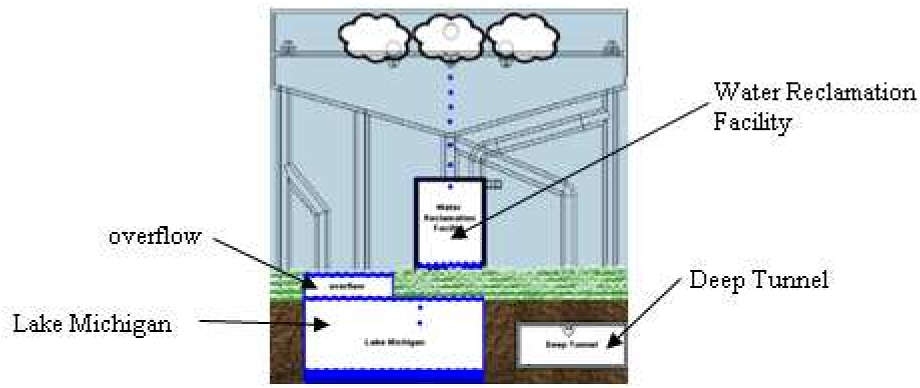

Figure 7. Situation 1.

It was simple to demonstrate situation 1, but other problems were discovered in the process. Emptying the rain reservoir at the top took a very long time. This problem can be eliminated by adjusting the depth of the reservoirs. Also, droplets of the water/glycerin mixture would occasionally stick to the surface of the RP material. It is important to note that once the metal ball has been lifted, the surface tension of the surrounding fluid has been broken and even when the ball is placed back on top of the nozzle, the mixture will continue to flow out.

3.3.2. situation 2 - heavy rainfall

Situation 2 occurs when stormwater entering the pipes is greater than 450 million gallons a day and at the same time, the Deep Tunnel can handle the excess wastewater since the total wastewater is less than 400 million gallons. As shown in Figure 8, the water reclamation facility cannot handle the rainfall because the rate of rain is too great so the stormwater is diverted to the Deep Tunnel.

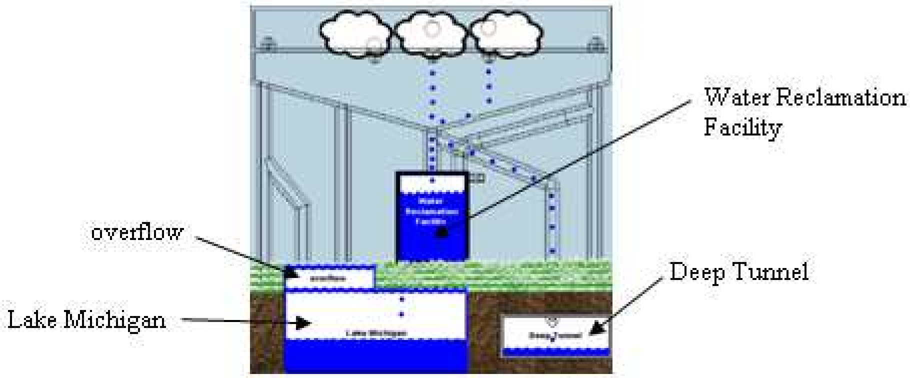

Figure 8. Situation 2.

Situation 2 could not be demonstrated. After situation 1, the model was flipped upside down and the water mixture flowed back once again to the top reservoir. There was difficulty in getting all the mixture back into the top reservoir due to the lack of pressure difference between the inlet and outlet nozzles. A possible solution would be to increase the length of the nozzle leading into the rain reservoir. When two of the nozzles were opened, the rate of rainfall increased. A plate was used to block the water/glycerin mixture from entering too quickly just as an orifice is used to ensure that a certain rate of sewage is entering the water reclamation facilities in Milwaukee.[19] When sewage entering the pipes exceeds this rate, some of the sewage is diverted to the Deep Tunnel. In the model, the plate only allows a specific rate of water to enter the facility. As this rate is exceeded, the water starts to flood in the pipe on top of the facility until it leaks down into the Deep Tunnel reservoir. Although this did occur during the experiment, the water reclamation facility was cleaning the water too quickly and the reservoir was not even a quarter full when the mixture was diverted to the Deep Tunnel. An adjustment to decrease the volume of the reclamation facility would fix this problem. It would also be beneficial to include valves into the RP model.

3.3.3. situation 3 - very heavy rainfall

Situation 3 demonstrates a rare situation in which stormwater is entering the pipes at a rate greater than 450 million gallons a day and fills up the Deep Tunnel. In this situation both the reclamation facility and the deep tunnel is overwhelmed and overflow occurs as shown in Figure 9.

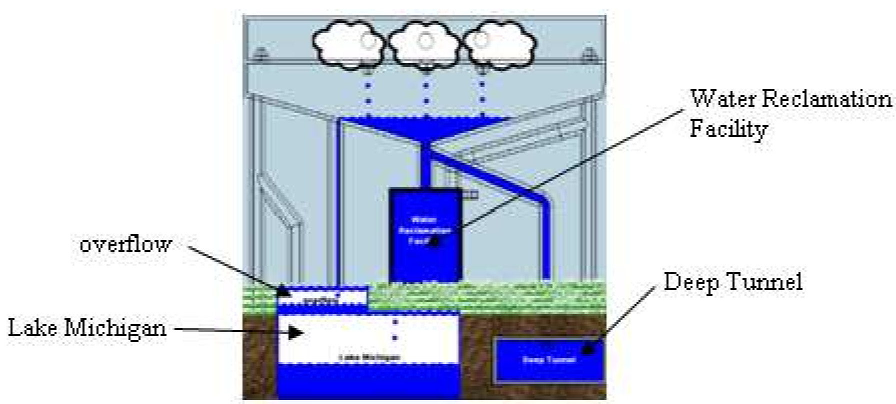

Figure 9. Situation 3.

Experiments run on the model were successful in demonstrating situation 3. The only problem was, just as in situation 2, the water reclamation facility did not fill up before the mixture overflowed. Also, decreasing the depth would quickly ensure that overflow occurs for situation 3 but the volume of the reservoirs must not be too small such that overflow occurs in situation 2.

4. Conclusion

Based on the prototypes made during this research, rapid prototyping is a great technology to use to help visualize subsurface hydrology. Rapid prototyping was able to create a quick model within days instead of weeks which allowed many tests to be run and for this research to be conducted. Using the SLA process and DSL Somos® WaterShed® resin produced prototypes that were colorless and transparent once sanded down and lacquered. It was also very important that the prototypes were water resistant since liquids would be kept in there for long periods of time. The particular resin used in this research had less than half a percent of water absorption[20] therefore making it practical for the Deep Tunnel model.

A model of the workings of the Deep Tunnel was not able to be successfully created, but much progress was made and with more time, it is possible for a working model to be built. Further research should be conducted to investigate how to prevent adhesion of water to the surface of the RP material. Superhydrophobic coatings were looked into, but unfortunately, was not able to be incorporated into the model. Also, a better way to vary the rate of flow of the liquids in the RP model should be examined in future research.

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