Design Project: Smart-Green Storm Sewer Drainage System

Introduction. The objective of this project is to design a smart-green drainage system for a small community near Worcester, Massachusetts. The community is located on a high quality lake that serves as its water supply, so the drainage system must be designed to minimize pollution of the lake caused by stormwater discharge.

This project is organized into three primary design components: storm sewer design, pond design, and spillway and stilling basin design. Connected to this system is a sanitary treatment facility, however, design of this facility falls outside the scope of the project.

This design employs Best Management Practices (BMPs) to minimize pollution of the lake caused by stormwater discharge. Grassed ditches parallel every street, and two grassed swales occupy the southern and eastern sections of the community. These grassed waterways help cleanse the stormwater of pollutants as it flows toward the treatment pond.

There are several BMPs that may be employed for the purpose of reducing the level of pollutants in stormwater. However, many of these BMPs pertain to individual parcels of land, and implementation of these practices is a responsibility of the citizens.

Appendix A presents the design of the storm sewer, Appendix B presents the design of the pond, and Appendix C displays the spillway and stilling basin design.

Methodology. The first step of this project was to design the storm sewer located beneath Highway A (See *Map View of Community* in Appendix A for visual description of the region). For this analysis, Highway A was divided into four distinct sections and each intersection (node) was labeled using letters A through E. Each side of Highway A has a commercial zone that is 100 meters wide, and the remainder of the community is zoned low-density residential. As stipulated in the project specifications, the storm sewer was designed to carry flow of magnitude of that generated by a 10-year storm.

The first step of the storm sewer design process was to plot rainfall intensity vs. storm duration for each the 2-, 10-, and 50-year design storms (See *Storm Sewer Design: Rainfall Intensity vs. Storm Duration [Data and Graph]* in Appendix A). The second step was to prepare a longitudinal profile of Highway A that shows the natural terrain, graded terrain, location of manholes, and slope of the sewer pipe. The longitudinal profile also shows the diameters and depths of flow in the pipe by section; however, this information was not obtained until the fourth step of the storm sewer design process. See *Storm Sewer Design: Highway A Longitudinal Profile [Data and Graph]* in Appendix A.

The third step of the storm sewer design process was to study the topography of the community and determine the area that drains to the sewer (*Map View of Community Transparent Overlay* in Appendix A displays this drainage area). The fourth and last step of the storm sewer design process was to prepare a computational table to determine the sewer pipe diameter, flow depth, and flow velocity. In order to determine these parameters, several pieces of information had to be first obtained, including: the percent of the community commercially zoned vs. residentially zoned; the runoff coefficient (section-specific); the maximum Time of Concentration; the design rainfall intensity, flow, velocity, and diameter; and the full flow, velocity, and diameter. *Storm Sewer Design: Computational Table* (presented in Appendix A) fully displays and describes these calculations.

The second step of this project was to design the pond into which the storm sewer flows. The first step of the pond design process was to develop data for construction of the rainfall hyetograph (rainfall intensity vs. time). Normalized Rainfall data was taken from Table 7.2.2 of the textbook and interpolated to fit a convenient time interval of 10 minutes. Given the storm duration, the total rainfall for a 50-year storm was read from the *Rainfall Intensity vs. Storm Duration Graph* (located in Appendix A). Cumulative and incremental rainfall data was then developed, along with corresponding cumulative and incremental rainfall intensity data. The rainfall hyetograph was then constructed, completing the first step of the pond design process. Appendix B displays *Pond Design: Rainfall Hyetograph* and corresponding data, along with a summary of calculations.

The second step of the pond design process was to develop the excess rainfall hyetograph. This was accomplished by first estimating the area of the watershed (the area that naturally drains to the pond). The runoff curve number was then found with the aid of Table 4.5 in the packet, which lists various land use descriptions and corresponding curve numbers. The curve number for the entire community is a weighted average of the community commercial and residential curve numbers. Based on this curve number, the storage capacity of the watershed was determined. Based on this storage capacity, the cumulative and incremental excess rainfall was determined and the excess rainfall hyetograph constructed. Appendix B displays *Pond Design: Excess Rainfall Hyetograph* and corresponding data, along with a summary of calculations.

The third step of the pond design process was to develop the unit flow hydrograph. This was accomplished by first studying the topography of the watershed to determine the average slope and average overland flow length. Based on these two values, the average overland lag time was calculated and added to the average channel lag time (which was found using previously determined channel lengths and velocities) to yield the average lag time. Based on the average lag time, the time of concentration, rainfall pulse, peak time, base time, and unit hydrograph peak flow were determined. The unit flow hydrograph was then constructed, completing the third step of the pond design process. Appendix B displays *Pond Design: Unit Flow Hydrograph* and corresponding data, along with a summary of calculations.

The fourth step of the pond design process was to develop the runoff flow hydrograph. This was accomplished by reading from the unit flow hydrograph the flow magnitude for each successive rainfall pulse between the start time (time zero) and end time (base time). These incremental unit flow magnitudes were multiplied by the Incremental Excess Rainfall value for each time interval for the entire storm duration, to produce the Partial Runoff Flow data. The Partial Runoff Flow data was summed and plotted versus time to produce the Runoff Flow Hydrograph. The Runoff Flow Hydrograph was completed by adding a line (proportional to the magnitude of the peak flow) that shows the Maximum Allowable Total Runoff Flow vs. Time. The area of the graph between the Maximum Allowable Total Runoff Flow vs. Time line and the Total Runoff Flow vs. Time line was measured and recorded, as it represents the pond volume required by the 50-year design storm. Appendix B displays *Pond Design: Runoff Flow Hydrograph* and corresponding data, along with a summary of calculations.

The fifth step of the pond design process was to determine the pond volume required by the 2-year design storm. This was accomplished by repeating the first two steps of the pond design process for a 2-year design storm (without plotting the data), using the same curve number. The Cumulative Excess Rainfall for a 2-year design storm was multiplied by the watershed area to yield the pond volume required by the 2-year design storm. Appendix B displays *Pond Design: 2-Year Design Storm Cumulative Excess Rainfall Calculation*.

The sixth step of the pond design process was to add the pond volume required by the 50-year design storm to the pond volume required by the 2-year design storm to yield the total required pond volume.

The seventh step of the pond design process was to determine the maximum surface area of the pond (based on the total required pond volume). Knowing the depth of the pond and the slope of its sides, this was accomplished by considering the pond as the base of a cone and using the principles of geometry to determine the surface and base diameters. Based on the surface diameter, the maximum surface area was found. Appendix B contains a summary of these calculations.

The eighth step of the pond design process was to determine the design storm-specific pond depths due to each the 2- and 50-year design storm runoff volumes. This was accomplished using the dimensions obtained in the previous step, along with the principles of geometry. Appendix B contains a summary of these calculations.

The ninth and final step of the pond design process was to determine the pond surface area due to the 2-year design storm runoff volume. This was accomplished using the dimensions obtained in the previous two steps, along with the similar triangles principle of geometry. The surface diameter was determined, which yielded the surface area. Appendix B contains a summary of these calculations.

Appendix B also contains two sketches of the pond as it was designed – side and map view.

The third and final step of this project was to design the spillway and stilling basin. By design, if the volume of inflow exceeds the capacity of the pond, the excess volume will travel over the spillway into the stilling basin. Design of the spillway was accomplished by first doubling the peak runoff flow to yield the design runoff flow. Secondly, the critical depth was calculated and the spillway crest elevation obtained. Third, the flow depth above the spillway crest was computed, along with the spillway crest height. Lastly, the water depth and velocity at the toe were found. Appendix C contains a summary of these calculations.

The first step of the stilling basin design was to calculate the Froude number. The second step was to find the depth of flow after the hydraulic jump. Using this information, along with the spillway design information developed previously, the depth and length of the stilling basin were determined. Appendix C contains a summary of these calculations.

Appendix C also contains two sketches of the spillway and stilling basin as they were designed – side and map view.

Results and Discussion. The following table summarizes the design of the storm sewer:

Summary of Storm Sewer Design

10-Year Design Storm						
Section Identification		Length (m)	Slope	Diameter (m)	Flow Depth (m)	Flow Velocity (m/s)
Start Node	End Node					
A	B	392.765	0.001	1.65	1.16	1.14
B	C	321.335	0.001	1.95	1.38	1.29
C	D	178.575	0.001	2.10	1.49	1.36
D	E	107.145	0.001	2.10	1.55	1.38

This design satisfies all specifications contained in the project outline. The slope of the pipe is consistent along its entire length, and as recommended, plummets 1 vertical meter per horizontal kilometer. The diameter of the pipe increases with the flow rate in order to keep the flow depth in the pipe approximately constant.

The flow velocity is also approximately constant for the entire storm sewer, and fits within the specified acceptable range (0.9 – 3 meters/second).

Construction of the longitudinal profile required some engineering creativity. The project outline specified that the sewer pipe must exceed the freezing depth of 1.5 meters below ground surface, but also must exceed the maximum pond surface elevation of 206 meters above sea level. The rolling hills topography of Highway A made meeting these two requirements simultaneously impossible without some regrading of the natural terrain. Most of the terrain above the first section of pipe was regraded with fill of average depth 0.75 meters, and some terrain above the second section of pipe was regraded with fill of average depth 0.25 meters. The remainder of the terrain was not altered. (Note: In an actual design, it would likely be practical to cut the excess terrain above the third and fourth sections of the pipe in order to fill the terrain above the first two sections of the pipe.)

The following table summarizes the design of the pond:

Summary of Pond Design

Design Storm	Necessary Volume (m^3)	Surface Area (m^2)	Diameter (m)		Depth (m)	Bank Slope
			Surface	Base		
2-Year	10,445	6282.24	89.436	83.778	0.943	⅓
50-Year	24,735	8135.75	101.778	89.436	2.057	⅓
Sum	35,180				3	

As with the design of the storm sewer, similar success was experienced with the design of the pond. As designed, the depth of the pond is 3 meters, and the banks of the pond rise 1 meter for every three meters traveled horizontally.

The design of the pond is based on the combined volume of the 2- and 50-year design storm runoff. For this community, the total rainfall for a 2-year design storm of duration 6 hours is 28 millimeters. The total rainfall for a 50-year design storm of duration 6 hours is 96 millimeters, and the total rainfall for a 100-year design storm of duration 6 hours is 114.3 millimeters. This trends shows that highly frequent storms have a much smaller magnitude than highly infrequent storms.

All data developed for design of the pond was used as calculated, with the exception of the rainfall pulse value. The rainfall pulse was calculated to be 3.97 minutes, however, this value is unnecessarily small. A rainfall pulse of 10 minutes was used instead, since it still provides a high degree of accuracy and produces a data set of manageable size.

The following two tables summarize the design of the spillway and stilling basin:

Summary of Spillway Design

Length (m)	Width (m)	Height (m)	Flow Depth (m)		Velocity at Toe (m/s)
			Above Crest	At Toe	
2.5	10	4	1	0.2065	9.685

Summary of Stilling Basin Design

Length (m)	Width (m)	Depth (m)
14	10	0.42

The design of the spillway and stilling basin was very straightforward, and little engineering creativity was required. It should be noted that the results shown in the two tables above are not based on the as-calculated peak runoff flow (6.3567 m^3/second), but rather on the alternative peak runoff flow (10 m^3/second) suggested in project outline. The as-calculated peak runoff flow value produced a basin depth that was not desirable (only 3 centimeters) compared to the basin depth produced by the alternative peak runoff flow (42 centimeters).

Conclusion. The objective of this project was to design a smart-green drainage system for a small community near Worcester, Massachusetts. This objective was accomplished successfully and with minimal difficulty. By this design, which employs Best Management Practices, the high quality lake adjacent to the community will not be polluted by stormwater discharge.

This project was organized into three primary design components: storm sewer design, pond design, and spillway and stilling basin design. Consult Appendix A for comprehensive storm sewer design calculations, Appendix B for comprehensive pond design calculations, and Appendix C for comprehensive spillway and stilling basin design calculations.

References.

Mays, Larry W. *Water Resources Engineering*. First edition: John Wiley & Sons, Inc., 2001. pg. 222. [textbook]

Novotny, Vladimir. *Water Quality: Diffuse Pollution and Watershed Management*. Second edition: John Wiley & Sons, Inc. Northeastern University, Boston, MA. pp. 138-46, 161-96. [packet]