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# The Design and Construction of the Wachusett Dam: Owner Perspective and Contemporary Considerations

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Submitted by:

Samantha Evans

Kevin Sifuentes

Approved by:

Professor Guillermo Salazar, Advisor

Professor Paul Marrone, Advisor

## Abstract

The Wachusett Dam is located in Clinton, Massachusetts, and was constructed beginning in 1895. This project reviews the original construction of the dam as documented in archival photographs and reports and develops the construction schedule for the work directly managed by the owner up to October 1, 1901. It then, analyzes the productivity of modern equipment in the excavation at the bottom of the dam and compares the results with the ones observed more than 100 years ago. The design of the dam's hydraulic components is also reviewed.

## Executive Summary


Introduction

The Wachusett Dam is located in Clinton, Massachusetts. It was constructed between 1895 and 1905. The project was initiated by the owner, the Metropolitan Water Board, who directly managed the construction of the dam up to October 1, 1900 when the McArthur Brothers Company was contracted to complete the dam. This project reviewed in detail the construction of the initial phase which consisted of redirecting the river flow, assembling temporary structures to transport water to the residents of Boston, and preparing the land for the construction of the dam including excavation, moving materials to site, and building coffer dams. These major tasks were subdivided into a more detailed work breakdown structure.

This project reviewed the original construction of the dam between 1898 and 1901 as documented in archival photographs and reports and developed the construction schedule using modern project management software. It then, analyzed the productivity of modern equipment in the excavation at the bottom of the dam and compares the results with the ones observed more than 100 years ago.

The design of the dam's hydraulic components was also reviewed.

Background

The purpose of the Wachusett Dam is to store water to be delivered to the residents of Boston. Between the addition of indoor plumbing and the large quantities of people moving to the city for jobs, the population of Boston more than doubled between 1870 and 1900 (Marchione, n.d.). This caused panic by the city as the water supply that they had was not even close to being enough. As of 1895, Boston was consuming around 80 million gallons of water a day, but the water system at that time could only support 83 million gallons a day (Marchione, n.d.). There was a dire need for a new system to handle the water supply in the Metropolitan Area.

In order to find a solution to this problem, the Metropolitan Water Board was formed in 1895 and given the task of finding a solution to the urgent problem. They worked closely with engineers to determine three potential options. The first option involved constructing an aqueduct from Lake Winnipesaukee in New Hampshire. The second option consisted of capturing water from the Merrimack River. The third option, the one they decided to pursue, was to create a dam at the south branch of the Nashua River at a narrow pass in Clinton (Wachusett Dam, 2006).

The Chief Engineer placed on the project of constructing the Wachusett Dam was Frederick P. Stearns, who later was elected as President of the American Society of Civil Engineers because of his accomplishments on this project. He also continued on to help with the design of the Panama Canal. Because of Stearns, the plan for construction was titled Stearns Plan. It involved the construction of a dam on the Nashua River with the intent to create a reservoir that could hold 63 billion gallons of water. This would be enough water to more than double the water supply to Boston, which is why the plan was adopted on June 5, 1895 (Marchione, n.d.).

Original Construction Schedule

This work was motivated by an interest in not only the construction processes of the early 1900s, but also an interest in how construction has changed over time. By analyzing the construction timeline and processes, a large amount of knowledge was gained regarding both interests. The approach taken when researching dates for the construction of the Wachusett Dam was organized by the information available. This was done in order to analyze in detail the construction process used at the time. Certain activities had readily available dates in the Annual Reports. This was not true for all activities, but those that had explicit dates were identified before the dates of other activities since they were the most accurate. After all the activities with explicit dates were filed into the spreadsheet and schedule, the vague ones were researched. These are the dates that indicate a general time of year instead of specific dates. The last dates that were added to the schedule were those with minimal information in terms of duration or either start or finish dates. These activities could be approximated through the pictures, but this did not produce an extremely accurate timeline. Our goal was to have the schedule as accurate as possible, which is why the vague and estimated dates were analyzed towards the end of the research to result in an accurate sequence of construction activities.

Some of the exact dates of activities could be found through Annual Reports of the Metropolitan Water Board, but many were not documented. At this point, images of construction were used to estimate dates. Although the images could not show exact dates that tasks were completed, they allowed for estimations in terms of a month in which it was completed or at least allowed for predecessors and successors to be established. The concrete dates were added to the schedule first, followed by dates found using the photos, and then educated guesses were made for the remainder of the activities.

Productivity Analysis

The main goal when analyzing the productivity of modern excavation methods was to investigate what impact the contemporary methods and equipment could have on the construction schedule with the same activities that took place 120 years ago. This gave us a better understanding of the changes that have occurred in construction since 1900. It also gave us a better understanding of how the duration of activities could differ between the two schedules.

The group of activities that were focused on related to the deep excavation of the site since this process had fairly detailed records that could be used to compare it to modern day techniques.

Using available drawings, the dimensions of the area that had been excavated were estimated. The approximate shape of the excavation is an inverted trapezoidal prism. This drawing was used to find the width of the prism. This was calculated to be 950 feet. The length of the prism was approximately 700 feet. The total volume that was excavated was 1,008,841.94 cubic yards. This consisted of layers of rock, clay and gravel, and sand and gravel.

After figuring out the volume of soil that needed to be displaced using modern methods, the first step was to determine which method of excavation and equipment would be the most efficient to use for each layer. Originally, a combination of horses and steam carts were used to bring the soil out of the dam, but the actual digging was done using shovels. The most common method that is used today involves the use of an excavator or backhoe to dig and the use of a dump truck or several to transport the soil to a site down the road. This method should allow for the excavation to be completed in 133 days rather than 364 days.

Design Review

The capstone component of this project involved conducting a design review related to the hydraulic aspects of the dam. This design review determined the performance capabilities of the original design by analyzing the water flow velocity and pressures throughout different points of the pipeline system from the moment in which the water entered the system at the top of the dam to when it exits in the pool, located in the downstream side, at the very bottom of the dam system. Water from the dam flows into the river that carries water away. This analysis was used to gain an understanding of both hydrology in general and the rationale that went into the construction of the dam.

Calculating the velocities in this section helped ensure that there was a general understanding of the purpose and use of the dam. Since all values were calculated using the maximum flow, the design of the dam could be evaluated at this level. This is an extreme situation, which is why it allows for the design to be truly tested. The initial velocity, right before water enters the dam, is 0 ft/sec and the final velocity, when the water arrives in the pool, is also 0 ft/sec. Analyzing the water at different points throughout the dam allowed for the understanding as to how this happens. This information created a frame for future calculations. Using a spreadsheet allowed for flexibility. If different dimensions were to be tested, all values would automatically be calculated to see if this is a practical proposition.

Presentations

A large portion of this project relied on the ability to not only conduct research and apply the skills that have been learned, but also the ability to communicate and the application of these skills to a variety of audiences including those with a non-technical background. There was one main presentation throughout this project that helped expand the group's ability to cater information to the audience present.

Presenting to the Clinton Historical Society and general public was informative as it gave the opportunity to practice communicating with a group that has a mixture of technical and non-technical backgrounds. The general feedback received was that the presentation was informative and generally well received. The points that could have been improved were related to the difficulty there is in communicating technical data to a majority of non-technical audience members. This specifically refers to the final section about the pool. This section was filled with a large amount of technical language, so it could have been explained better for the non-technical audience.

Conclusion

The focus of this project was on developing an understanding and documenting the construction process for the Wachusett Dam. This was done through extensive research and calculations. The creation of the schedule took place in incremental steps. Beyond creating a schedule, the excavation for the construction of the dam and the design review of the hydraulic components were further broken down in order to adopt an engineering mindset related to this construction project. This created a design review to check that the dam was efficiently designed and to determine if any changes should have been made to the overall structure or construction process. The analysis showed that this construction would be more efficiently performed today, but despite this efficiency, the dam is still standing today, which indicates that the methods used were reliable and could still be used.

**Acknowledgements**

This project would not have been possible without the help of Professors Paul Marrone and Guillermo Salazar. The professors advised this project and were available as resources when gathering the necessary information. We would like to thank them for all of the time and feedback they provided throughout the course of this project. Another important reference was John Gregoire from the Massachusetts Water Resources Authority. He facilitated a field trip into the gatehouse at the Wachusett Dam which aided in the understanding of the dam. We would also like to thank Professor Paul Mathisen for answering questions and helping us understand the water flow throughout the dam.

## Capstone Design Statement

This project analyzes the construction schedule of the Wachusett Dam as well as the pipeline design used in the dam itself. The series of pipes involved in the dam were analyzed to determine the velocity of water at each point as well as the pressure. These values were calculated using Bernoulli's equation, the continuity equation, and the Darcy-Weisbach equation. This review was then used to ensure that the pipes were constructed to account for maximum water flow with an appropriate factor of safety. The project meets the standards put in place by both Worcester Polytechnic Institute (WPI) and the Accreditation Board for Engineering and Technology (ABET). The WPI standard is described as a capstone design requirement. This involves compiling knowledge that has been learned in other classes in order to add an engineering component to the project. This requirement was created in order to comply with the standards created by the ABET. By meeting these standards, WPI meets the criteria for Accredited Engineering Programs.

The standards for Accredited Engineering Programs are formatted in a way that lists the capabilities that a student should have by the time they graduate. The capstone design requirement put in place by WPI meets Criterion 3, Section 2. This states that students should be able to "apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors (Criteria, 2019)."

The specific components of this project have been broken up to show how it meets this requirement.

- Public Health, Safety, and Welfare: This project involves the design of reservoirs and pipelines, both of which come into contact with drinking water. Through the analysis of the original pipeline design and the modernization of this process, public health and safety standards were considered and reviewed.
- Global Factors: Considering the global potential for this design has created additional opportunities for development. The team researched dams globally and incorporated processes used in other countries to improve the schedule design.
- Cultural Factors: Cultural factors, such as cultural diversity of the workforce, were originally considered in the initial construction. These factors were preserved in the final design in order to preserve the culture of the region.
- Social Factors: One main source of information for this project was the records from the Metropolitan Water Board. By reading these records, the team was able to gain an understanding of some regulations that were in place at the time of construction. The modern design has incorporated the current regulations and also combines the needs of all stakeholders despite their social status.
- Environmental Factors: The design of this project allowed the team to consider environmental aspects into the design. An example of this is in the modernization of the pipeline construction task. This task is fairly straightforward, but by looking into more environmentally friendly materials and methods of construction, the team was able to gain a better understanding of sustainable construction.
- Economic factors: One of the goals of this project was to create a modern process that costs less due to increased efficiency. This process allowed the team to become familiar with costs relating not only to labor and materials from the 1900s, but also with these factors today.

## Engineering Licensure

In order to be recognized as a professional engineer, one must obtain a Professional Engineering License. This holds them to the standards set in place by their respective Engineering Board or Society. These standards not only include government standards, but also ethical standards. A Professional Engineering License is awarded by the Board of Licensed Engineers in each state.

The first step in obtaining a Professional Engineering License is to pass the Fundamentals of Engineering (FE) Exam. This exam is typically taken during the last year of college, or shortly after. Following this exam, individuals are classified as Engineers in Training (EIT). During this time period, they will spend five years working under other engineers. At the close of this five-year period, the individual can take the final exam, the Professional Engineering (PE) exam. Passing this exam grants them a Professional Engineering License.

Before all of this can be completed, an individual should attend an accredited university, such as Worcester Polytechnic Institute (WPI). At WPI, a student would need to be enrolled in the Civil and Environmental Engineering program. This step allows the individual to gain the knowledge that will be tested in both exams. The topics of the exams vary for each specific field, but they cover all areas of that field.

Those that have a Professional Engineering license are trusted with a large amount of responsibility over not only projects, but the safety of millions of people. This is why there are standards set in place to regulate their actions.

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## 1. Introduction

The Wachusett Dam, which was constructed in the late 1800s and early 1900s, is shown in Figure 1. Its primary function is to supply water to residents of Boston, Massachusetts. The construction process is documented in engineering reports as well as photographs, which provided an opportunity to learn and appreciate how the dam was built with resources and technology of the late 19th century and early 20th century and compare those with current construction methods using technology and concepts of the early 21st century. The original construction process was labor intensive and was completed with limited technology, which is very impressive.

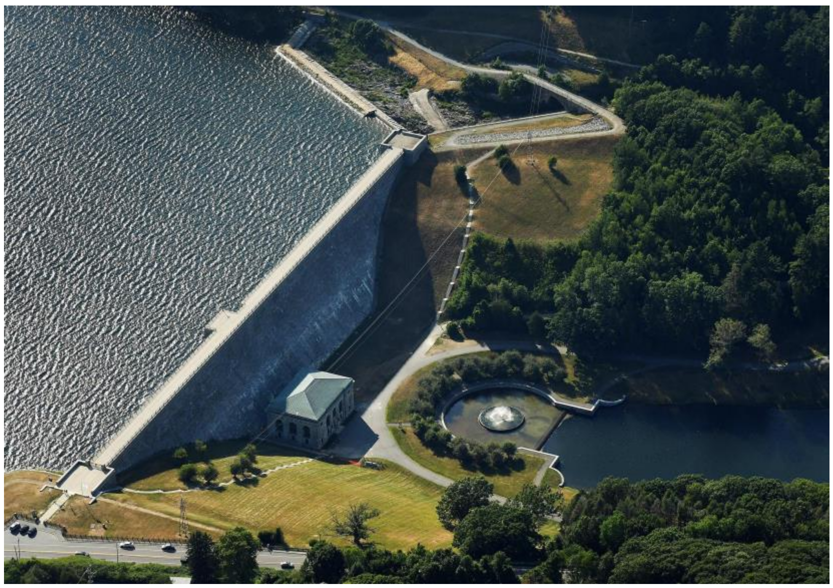

Figure 1: The Wachusett Dam from Tuoti, G. (2017, February 17). California crisis brings attention to Massachusetts dams. Retrieved from https://www.wickedlocal.com/news/20170216/california-crisis-brings-attention-to-massachusetts-dams

When studying the Wachusett Dam, it is easy to find general records regarding the construction process, the current state of the dam, and photographs of the process. There is not much information available in terms of the timeline. There are some dates mentioned in the annual reports, but not many specific dates.

The purpose of this project was to document the time and sequence of execution of the original design and construction using modern scheduling software. Following this, modern construction technology and practices were incorporated to create a productivity analysis that showed the differences that would ensue if the Wachusett Dam was constructed today. This was completed for the activities relating to deep excavation. This project combined data collected in previous years with data that was collected through research.

The scope of this project was to focus on the first half of the construction which took place primarily between 1898 and 1901. The construction focused on moving the water rather than forming the dam itself. This process involved the use of flumes and other structures to move the water away from the construction area. There were also many pumping systems that had to be constructed to allow the water to be sent to the residents of Boston, which took priority over the construction. The main purpose of this construction was to prepare for the construction of the dam. It was mostly related to site prep. The main components include the construction of temporary works, excavation, moving materials to site, and creating the coffer dams.

The owner of the dam, the Metropolitan Water Board, was responsible for the tasks mentioned above. Once the site was prepped, and outside contractor was hired to construct the dam itself. A second group has conducted a similar analysis of the second half of the construction process, which included the construction of the dam.

In terms of the project itself, a large portion of the work was creating a construction schedule to document the one used when this process began. The difficult portion of this task was finding the resources that were needed. There is no published schedule of construction of the Wachusett Dam and there are not many documents with specific timelines. This information was collected mainly from the Metropolitan Water Board since they owned the dam at the time of construction.

Specific goals and outcomes for this project include:

- Examine the difference in excavation practices from the time the dam was constructed to 2020.
- Create a construction schedule for the past construction software applications.
- Present to the Clinton Historical Society.
- Conduct a design review on the water systems within the dam.

This project was conducted by two separate groups, each containing between two and three students. These groups were given similar tasks but used individual methods to carry out the project. This group focused on the preliminary stages of construction, which took place from 1895, when the plan was established, to 1900, when the contract was signed and construction began on the dam itself, which is where the other group began.

The overall findings included a gain in knowledge and understanding relating to all of the above objectives. By researching and analyzing the construction schedule and methods, this group was able to better understand project management and general construction processes. The design review allowed for additional understanding of hydrology and the factors that contribute to the design of piping systems.

## 2. Background

Not only is the history relative to the Wachusett Dam relevant to this project, but also the history of dams in general. The Wachusett Dam is one of the first large dams built in Massachusetts and helped establish the context for constructing this type of facilities. The following section also contains other pertinent information related to the background research on the structure of the project. This includes a stakeholder analysis as well as a needs analysis. Both of these are relevant as they assess the needs of the project to ensure that all stakeholders are considered.

### 2.1 History of Dams in Massachusetts

The concept of constructing a dam was something that those living and working in Massachusetts were familiar with. Dams had been constructed around New England from the beginning of colonization. The first dam constructed in the area was a dam at a timber mill in South Windham, Maine. This dam was constructed in 1623. Over time, certain things have changed regarding the construction process, such as the tools used and organization, but the function features of a dam and construction schedule followed has remained similar. The changes include the use of different materials and the purpose of the dams themselves. When dams were first constructed, they were often made out of timber, which eventually progressed to stone, earth and concrete.  Originally, the purpose of most dams in Massachusetts was to be used by mills as a source of hydropower, but they have been shifted to public use for the purpose of water supply and recreation (Kempe, n.d.).

One main factor of dam construction that has changed is the knowledge and construction techniques behind it. This can be seen through the decrease in structural failure of dams over time. The first major fam failure was in 1874, and involved the dam in Williamsburg, MA. This failure killed 144 people and also caused over $1 million in damages. Another well-known dam failure was in Johnstown, PA in 1889 and caused the death of 2,200 people, which is still the largest casualty rate for a dam failure in the United States (Kempe, n.d.).

These dam failures are very serious, but in the 19th century, communication was not as easy, so unless the failures were local, many people were not aware of them. Many people living in New England were affected by the failure of the Croton dam in New York. This dam failed in 1842 while it was being constructed. Other dams that failed in the area include the 1867 failure of Hartford’s dam during a flood event. This dam was also under construction at the time of failure. In all of these cases, the mechanisms of failure were different and could include factors such as, issues with the soil composition and inadequate spillway capacity (Kempe, n.d.).

The dams above were analyzed since the date of construction is similar to that of the Wachusett Dam. This allowed for analysis of construction techniques at that time and gaining an understanding of what other areas were doing to create better dams.

### 2.2 Old water sources:

The water crisis in Boston began in the 1850s when the population increased by over 30% (Marchione, n.d.). The water system that was being used by Boston at the time was the Cochituate System, which consisted of Lake Cochituate and the Cochituate Aqueduct that connected Lake Cochituate with the Brookline Reservoir, could not handle this increase in population. In 1859, a major break occurred in the system, specifically in the Cochituate Aqueduct in Needham, Massachusetts. This break caused all water services to be shut down and could have caused major issues with water supply had there been a fire or any other emergency event. After this event, the Chestnut Hill Reservoir was proposed and accepted via a bill in April of 1865. This marked the beginning of water system adjustments in the Boston area as it was closely followed by the construction of the Bradlee Basin in 1870, which could hold 550 million gallons of water (Marchione, n.d.).

One major contributor to the changes in the water systems is the development of research linking the cleanliness of drinking water to different diseases. This paired with the need for water to keep up with the population with the need to ensure the community is staying healthy. The Public Health community had enough evidence in 1882 to decide that risky supplies of water were to blame for the high death rates of that time. This created a philosophy of sanitary engineering that would continue to grow in the future (Kempe, n.d.).

With the addition of indoor plumbing came an additional need for water. To make matters worse, rising populations in cities made it hard for the already limited water sources to meet the demand. Figure 2 shows the original water sources used by local cities. In this figure, it is clear that there are very few water sources compared to those that currently exist. This shows an average of one water source per city and most of them were natural bodies of water.

| State | City | Geographical Limitations | Early Source | 1850 Source |
|---|---|---|---|---|
| MA | Boston<br>Cambridge<br>Worcester<br>New Bedford<br>Fall River<br>Springfield | Coastal peninsula, poor river water quality<br>On Charles River, poor river water quality<br>On Blackstone River, mills upstream<br>Coastal city<br>Coastal city<br>On Connecticut River, mills upstream | 1652 Springs<br>1837 Springs<br>1798 Springs<br><br><br>1843 Reservoir | Lake Cochituate<br>Fresh Pond<br>Bell Pond<br>Acushnet River<br>Watuppa Lake<br>4 Sm. Reservoirs |
| RI | Newport<br>Providence | Island, little surface water<br>Coastal city, mills upstream | <br>1772 Springs | Ponds<br>Springs |
| CT | Hartford<br>New Haven<br>Bridgeport | Adjacent to Connecticut<br>Coastal city<br>Coastal city | <br><br>1818 Springs | Connecticut River<br>Mill River<br>Springs |
| NH | Manchester<br>Nashua | On Merrimack, mills upstream<br>On Merrimack, mills upstream | | Lake Massabesic<br>Pennichuck Brk |
| ME | Portland | Coastal City | 1812 Pond | Pond & Springs |
| VT | Burlington | On large lake | | Lake Champlain |

Figure 2: Water Development by Kempe, M. (n.d.). Chapter 2 – The Search for Water – Growth and Water Source Development. Retrieved from http://www.mwra.state.ma.us/04water/html/historypaper/ch2.pdf

**2.3 New found need for a dam:**

There can be several reasons why a dam is constructed. One reason could be that there is a need to store a large quantity of water, another could be that water needs to be prevented from traveling in a certain direction, and another could even be for the purpose of recreation. The purpose of the Wachusett Dam is to store water to be delivered to the residents of Boston. Between the addition of indoor plumbing and the large quantities of people moving to the city for jobs, the population of Boston more than doubled between 1870 and 1900 (Marchione, n.d.). This caused panic by the city as the water supply that they had was not even close to being enough. As of 1895, Boston was consuming around 80 million gallons of water a day, but the current water system could only support 83 million gallons a day (Marchione, n.d.). There was a dire need for a new system to handle the water supply in the Metropolitan Area.

In order to find a solution to this problem, the Metropolitan Water Board was formed in 1895 and given the task of finding a solution to the urgent problem. They worked closely with engineers to determine three potential options. The first option involved constructing an aqueduct from Lake Winnipesaukee in New Hampshire. The second option consisted of capturing water from the Merrimack River. The third option, the one they decided to pursue, was to create a dam at the south branch of the Nashua River at a narrow pass in Clinton (Wachusett Dam, 2006).

The Chief Engineer placed on the project of constructing the Wachusett Dam was Frederick P. Stearns, who later was elected as President of the American Society of Civil Engineers because of his accomplishments on this project. He also continued on to help with the design of the Panama Canal. Because of Stearns, the plan for construction was titled Stearns Plan. It involved the construction of a dam on the Nashua River with the intent to create a reservoir that could hold 63 billion gallons of water. This would be enough water to more than double the water supply to Boston, which is why the plan was adopted on June 5, 1895 (Marchione, n.d.).

### 2.4 Summary

Understanding the history of dams and learning about the construction techniques used not only helped create the construction schedule but helped build a foundation on the modern construction component of the project.

# 3. Methodology

## 3.1 General Overview

The portion of the construction of the Wachusett Dam focused on the preliminary work that took place under the direct supervision and responsibility of the owner. This work was conducted under the direction of the Metropolitan Water Board and the employees that they hired. The actual construction of the dam was not explored specifically by this group, but general knowledge was obtained. The dates of construction that were researched were from approximately 1895, when the plan for construction was created, to October 1, 1900, which was when the contract with McArthur Brothers Company regarding the completion date of construction was confirmed. This timeline consists of redirecting the existing water, assembling temporary structures to transport water to the residents of Boston, and preparing the land for the construction of the dam. Each task listed below was subdivided into a work breakdown structure to ensure that all steps were documented in the schedule.

In order to complete this project, a majority of the information was taken from records kept by the Metropolitan Water Board. These records are detailed in regard to the yearly construction of the dam. From these records, general dates as well as specific methods were compiled. The information that could not be found in the yearly reports was extracted from the chief engineer reports that are published. Other than the published records, published images were used to see exactly what the records discussed, which helped with visualization as well as estimation of dates based on when the photos were taken. There were two field trips conducted in order to get a better idea of the dam and the area surrounding it. Software such as PRIMAVERA was used to create schedules.

Some of the resources needed to execute this work included:

- Metropolitan Water Board Records (1898-1901)
- Metropolitan Water Board Images (1898-1901)
- General Field trip to the Wachusett Dam
- Field trip to the Wachusett Dam (focused on the Turbine Powerhouse)
- Other published articles from several websites

These resources were used to find all the information needed for this project including the scheduling portion and the general information needed in regard to the construction itself.

## 3.2 Project Objectives

In order to break down the project, specific goals and objectives were created.

Specific Goals:

- To accurately document existing construction dates and processes to the best of our ability.
- To apply modern technology utilizing engineering concepts.
- To create a new schedule that would analyze the time and cost of construction while introducing modern construction processes to some activities.

These goals mirror the objectives given at the beginning of the project. The objectives are:

- To use information collected through research to re-create the design and construction schedule at the time of the dam construction.
- To the extent possible, incorporate modern construction technology and practices to create a schedule of a portion of the same project as if the dam would be built in 2019.

This project relies on adherence to the objectives and tasks listed above. Since it is a very detailed and complex project, these tasks will help guide the project and make sure that it is completed correctly. Without the formation of tasks and objectives, parts of the project may not be completed, or the project may not be organized in the best way.

Using these goals and the outcomes of the Use Cases in Section 3.5.3, requirements for the system were created. The requirements for this system are as follows.

1. Different activity codes should be used for every activity across both groups.
2. Both groups should decide on a method of naming activities.
3. MWRA should have funds set aside in case issues occur with the schedule
4. There should be a liability disclosure included with the schedule if they are distributed to be used by any other parties.

These are specific requirements regarding the organization and applications of the system. The requirements below detail the requirements of the physical system.

1. The schedule should include all tasks from the original construction of the Wachusett Dam.
2. The modern construction schedule should incorporate an aspect of modern construction technology to increase the efficiency in terms of time and cost.

Systems Engineering Methods are extremely helpful in designing projects and ensuring that they are carried out in efficient ways, which is why they have been used in this project. The main methods used in this project were Stakeholder Analysis, Needs Analysis, and CONOPS. These methods all allowed for reflection on the project itself and allowed for adjustments to be made to create a better project overall. Each method was beneficial in its own way, but by combining all of them, the project was able to develop a systems engineering approach to differentiate it from other similar projects.

## 3.3 Stakeholder Analysis Introduction

Stakeholder analysis was crucial to this project because it established who the project would be designed to satisfy and would further lead to the needs analysis performed later in the project. By identifying stakeholders, the rest of the planning process could continue, and an accurate system could be created.

### 3.3.1 Stakeholder Analysis

The stakeholder analysis that was conducted for this project specifically was beneficial in that it put all of those that had a relationship with the project into perspective. By performing this analysis, the specific needs of the Commonwealth of Massachusetts, Residents of Boston, and the Massachusetts Water Resource Authority were identified. These are all important stakeholders in this project that would not have been considered without a stakeholder analysis.

Table 1: Stakeholder Analysis

| | Title | Description | Role | Priority | Needs/Goals |
|---|---|---|---|---|---|
| SH .01 | Commonwealth of Massachusetts, Metropolitan Water Board | Owner of the dam at the time of construction. They may be interested in the findings of the project and may be able to use the cost analysis to save money in the future. They may want to preserve the integrity of the dam | Indirect, possible negative | 3 | Their previous goal was to build the Wachusett Dam. |
| SH .02 | Residents of Boston | They use the water that comes from the Wachusett Reservoir, which is controlled by the Wachusett Dam. | Indirect, neutral | 2 | To have clean water. |
| SH .03 | Massachusetts Water Resources Authority (MWRA) | Provides water services to the Boston area. They currently control and maintain the Wachusett Dam. | Direct, positive | 2 | To maintain the Wachusett Dam. |

Table 1 provides a detailed description of all stakeholders and their roles in this project. It also identifies their role in the project as well as their priority and needs. Those with a positive role see the process of working on the project and have a positive impact, but those with a negative role see the outcome and may be negatively impacted. It was important to identify those stakeholders that have a higher priority. This helps later in the needs analysis and in creating the final system. This process properly leads into the needs analysis by helping to link the needs with the stakeholders involved.

3.3.2 Needs Analysis

Needs analysis is used to identify the needs that a project must satisfy. Given this information, needs are prioritized according to those that are more crucial than others. The needs that are identified with a priority of 1 are the most important to the system, while those that are prioritized as a 3 are less important. These needs might be incorporated into the system, while those prioritized as a 1 will be incorporated into the system. Table 2 summarizes the results of the needs analysis that was performed for this project.

Table 2: Needs Analysis

| | Title | Description | Traceability | Priority |
|---|---|---|---|---|
| N.01 | Clearly identify a construction timeline | Should provide a schedule that could be followed to recreate construction of the dam. | This reflects the needs of the project as it requires a schedule. | 1 |
| N.02 | Maintain a similar structure | The current structure of the Wachusett Dam is working well, so a similar structure would be beneficial, but it should be created using modern technology or modern approaches. | This reflects the needs of the Metropolitan Water Board as they may want to preserve the old structure. | 3 |
| N.03 | Use sustainable resources at a low cost | Sustainable resources would positively impact the overall footprint of the project and would also positively reflect the Massachusetts Water Resource Association (MWRA), who owns the dam. | This reflects the needs of the MWRA as they care about sustainability and their reputation. | 3 |
| N.04 | Should not disturb the water supply to Boston residents | The new construction of the dam should not prevent water from getting to Boston Residents. | This reflects the needs of the residents of Boston as they need water. | 1 |
| N.05 | Be easier and faster to build than the previous construction | The new construction should take less time and less manual work than the previous construction. | This reflects the needs of the MWRA and both advisors as they are all concerned about the final outcome including the cost analysis. | 2 |
| N.06 | Cost Less | The project should cost less (in today's standard) than the previous construction. | This reflects the needs of the project as it allows for cost analysis. | 2 |

The most important needs discovered were those relating to the structure of the project itself as well as the prioritized stakeholders. These needs indicated that there is a schedule needed and that the water for the residents of Boston should not be interrupted during the construction itself. These needs, along with the other needs listed in Table 2 provide helpful guidelines to creating the system for this project. They are especially helpful because there are separate needs for each section of the project. For the section relating to the schedule, N.01 describes the specific needs. For the section relating to the construction listed in the updated schedule, N.02, N.03, and N.04 described the needs that are important. For the last section of this project, which is the cost-time analysis, the needs that are relevant are N.05 and N.06. The distribution of these needs throughout the entire project will ensure that all steps of the project are related back to the stakeholders and their needs.

### 3.3.3 Summary

The needs for the project are those relating to the construction schedule of the Wachusett Dam. These needs include:

- The system shall provide a schedule that could be followed to recreate construction of the dam.
- The system shall recreate the Wachusett Dam using a similar structure, but with the application of modern construction technology to some activities.
- The system shall create a new construction schedule that does not prevent the administering of water to the residents of Boston.
- The system shall take less time and less manual work than the previous construction.
- The system shall cost less, when calculated to account for inflation over time, than the previous construction.

All of these needs can be traced back to the stakeholders identified in the stakeholder analysis, which was used in determining their priority.

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### 3.4 CONOPS

The concept of operations (CONOPS) is crucial to every project and system design because it defines the use of the system as well as constraints and additional needs for the system. This process also allows sufficient documentation for the methodology of a project. Two main features of CONOPS are verification and validation. These portions of the process allow the user to indicate that the correct system has been created and that the system was also created correctly. This indicates that the system meets the needs of all stakeholders and is operational.

#### 3.4.1 Priority Statement

The priority of this project was to create a schedule detailing the construction of the Wachusett Dam that took place in prior to 1901. Following this, modern construction technology was applied to that schedule and a design review was conducted on the hydrology of the dam.

#### 3.4.3 Context Diagram

The context diagram in Figure 3 includes the project, creating a construction schedule and applying modern technologies to mimic the construction, as well as the people and things that interact with it and those that the project interacts with. The people listed include all stakeholders as well as some additional people that have a smaller role. Listed next to each item are both the effect it has on the project and the effects the project has on the entity. An example is that the Environment imposes regulations on the project, which could change the structure and timeline, but the project could impact the environment my means of pollution or disruption of plant life. The relationships are also explained for the advisors, the MWRA, Boston Residents, Clinton Residents, the Clinton Planning Board, and the Historical Society. Each of these groups has a different impact on the project.

The Clinton Planning Board, the advisors, the Boston Residents, the MWRA, and the Clinton Residents all have control over the project. They can either vote to approve the schedule or have a say in how the schedule turns out. The environment and the historical society also have a say in the matter, but this comes in the form of regulations rather than a vote most of the time. The project also impacts these parties. The advisors are given additional work by the project because they are responsible for grading assignments and ensuring that the project is completed properly. The MWRA will be benefited by the project because it will help them with future scheduling of a remodel of the dam, or of the construction of similar structures. The Clinton and Boston residents may have problems with the schedule because it would present the opportunities for possible disruption in water services and the introduction of traffic delays. There are more parties that could be impacted by this project and that could have an impact, but those shown in Figure 3 are the main parties.

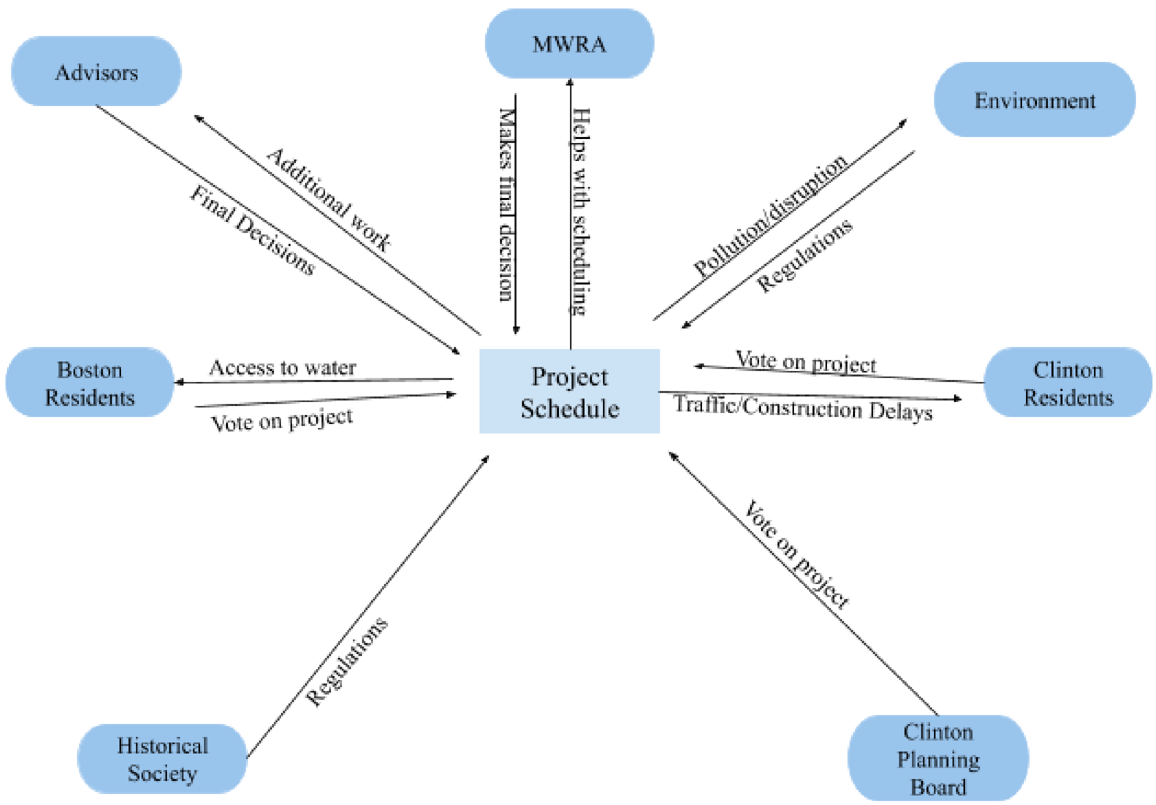


Figure 3: Context Diagram

### 3.5 Gap Analysis

The major similarity between the system that will be created, which is the original construction schedule, and other systems that exist is that since we are recreating an existing system, it already exists. The main gap that is present is the lack of specific records about the construction schedule and the lack of modern technology, which is why this was added. There are also similar schedules that exist that introduce modern technology in regard to building dams in general, but not for this specific dam.

The first source used was the Metropolitan Water Board Records. These document the timeline of the construction of the Wachusett Dam. Although they do not contain an explicit schedule, they were the main resource for dates and tasks completed. These records have general dates and are written yearly in order to create a summary of what happened that year. At the very least, years that some of the tasks were completed could be found by using these records.

The next source that was helpful in performing this gap analysis was an article published by the U.S. Army Corps. This source detailed the construction of a more recent dam, constructed in 1966. This dam is called the Dworshak Dam and it is located in Ahsahka, Idaho. This dam was built by the U.S. Army Corps of Engineers. The construction plan was recorded in detail and was used to gain general knowledge about dam construction today. Although this does not necessarily show a project schedule, it lists details that would make it easy to generate one. The document linked below also contains important general information regarding the construction of a dam that may be helpful. Since there is such a large gap in the knowledge of using recent technology to construct dams, the technology used in constructing this dam could have been used instead (DWORSHAK, 2015).

The third source that was used detailed another main gap in the current knowledge. This source describes the new approach to dams. They are being removed. A very small percentage are being used for beneficial reasons like water storage for the purpose of supplying running water in the future. Instead, dams are being used as recreation areas. This is not necessarily a negative use for dams, but it is taking up space and using water that could be used for other needs. Since there are not many dams being constructed today due to smaller need for water reservoirs, there is not a current documented approach to constructing them. This leaves a gap as there is new technology that could be applied to this construction, but has not as of this moment (Lieb, 2015).

The overall gaps that exist in this project are the gap in modern technology being applied to the construction of dams, the gap in a lack of specific information relating to scheduling construction of the Wachusett Dam, and the gap that exists in the actual construction of the Wachusett Dam that took place. This gap contains the lack of technology used at all as well as the lack of record of said technology.

Table 3 provides a summary of the gaps in the current research that were found in this gap analysis.

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Table 3: Gap Analysis

| Current State | Desired Future State | Gap | Risk(s) | Development Plan |
|---|---|---|---|---|
| There are general records posted on a yearly basis that contain notes from all construction projects near Boston. | Detailed notes on the technology used in constructing the dam in order to compare it to technology that exists today. | There is a lack of records for the technology used in Constructing the Wachusett Dam | Some of the technology used may need to be made up using an educated guess | Research will be done into similar dams constructed at that time. |
| There are a few dates listed that are associated with the construction of the dam. | A detailed construction schedule that includes accurate dates. | There are a lack or dates and records relating to the duration of tasks related to the construction. | Dates may have to be estimated, which would decrease accuracy. | Research will be done into other construction processes to find the estimated duration and that will be used to properly estimate the dates. |
| There are not many dams being constructed today. | An application of modern technology in the construction of dams. | There is a lack of testing of modern technology for the specific purpose of dam construction. | Modern technology may not be designed to create dams in the way that they are currently built. | Research will be done regarding modern construction technology and the potential applications. |

### 3.5.1 System Constraints

The main system constraint is that the schedule that was created, cannot be tested. Aspects of the schedule can be tested in terms of validation and verification, but the entire schedule cannot be physically tested during the scope of this project. Since it cannot be fully tested, the schedule was not 100% accurate. In order to create a schedule with 100% accuracy, components of the construction would need to be physically tested to ensure that they are completed within the allotted time. This uncertainty is due to a lack of published information that exists on the design and construction of the Wachusett Dam. Another constraint on the system is that it needs to be completed by early March 2020.

3.5.2 Design Constraints

This project does not contain many design constraints. The main design constraint is that the schedules produced by Team A and Team B need to correspond in order to allow future work on the project. The schedules need to be able to be put together to form one large schedule for the original construction.

3.5.3 Use Cases

Use Cases are important as they provide information relating to the gaps in a project. By testing out different scenarios, gaps can be better seen, and work can be done to fill the gaps in information.

Use Case Identifier: WD_01

Use Case Name: Application of Modern Schedule in Construction of a New Dam

Primary Actor(s): Massachusetts Water Resource Authority (MWRA) | Project Manager(s)

Participating Actor(s): Construction workers

Initiating Condition(s): MWRA has started constructing a dam in Massachusetts while using the modern construction schedule created. MWRA finds error in the schedule causing the project to be delayed and costing them $250,000.

UC Description:

I. Construction workers are working on the preliminary portion of construction
II. Construction workers discover the need for an additional water pump in order to ensure that water can get to the residents of a nearby city
III. The water pump would require the construction of a pipeline, which is expensive
IV. The project managers alert the MWRA of the issue
V. The MWRA uses their liability insurance along with the additional funds they had set aside previously to pay for the construction of the pipeline
VI. The project continues following the late start schedule due to delays in the planned schedule

Alternative(s):

- (V. alternative) the MWRA pays for the repair using a loan or other funds since they did not purchase insurance or set aside funds
- (VI. alternative) the project continues following a new delayed schedule since the late start schedule was already being utilized.

Exit Conditions:

- Pipeline is created and issue is resolved using money from a loan taken out by the MWRA.
- Issue is resolved, but the project is slightly delayed.

Needs/Requirements Discovered:

1. MWRA should have funds set aside in case issues occur with the schedule

2. There should be a liability disclosure included with the schedule if they are distributed to be used by any other parties.

Models/Studies Needed:

1. Model construction to the best of our abilities

Use Case Identifier:WD_02

Use Case Name: Use of Schedule in Future Projects

Primary Actor(s): Future Students

Participating Actor(s): Prof. Marrone | Prof. Salazar

Initiating Condition(s): The students are working on their MQP, which builds off of the construction schedules of the two groups. The students try to assemble the two schedules in order to build one large schedule, but the formatting does not allow for the assembly to happen. The students need to individually input all of the work created by both groups.

UC Description:

I. Students are working on expanding the construction schedules to include the preliminary planning and the finishing of the areas surrounding the Wachusett Dam

II. Students decide to merge all of the schedules that have been created.

III. Primavera does not allow for the files to be merged because the activity codes are the same on multiple activities.

IV. The students must individually input activities, leaving them with less time to expand the research.

Alternative(s):

- (III alternative) the students are left with missing activities due to the same codes being used for tasks on both projects.
- (IV alternative) the students must input half of the tasks since half of the activity codes can be kept the same.

Exit Conditions:

- Student has to repeat the process of combining the schedules and delete the current schedule.
- Student inputs half of tasks.

Needs/Requirements Discovered:

1. Different activity codes should be used for every activity across both groups.
2. Both groups should decide on a method of naming activities.

Models/Studies Needed:

1. Model the combination of schedules using Primavera.

3.5.4 Summary of System Support

In order to create this system, training was needed to be able to use the software, so this could be beneficial to those using the system in the future. This, however, is not required as many project managers already have training in this software. The software also has the ability to export information to other, better known, platforms such as excel. The ideal training provided to the user would be:

- Primavera training
- Microsoft Excel training
- Basic construction management training

3.5.5 Summary of Studies Needed

There are not many studies that exist that involve re-creating construction scheduled for projects from the early 1900s. Those that do exist do not give exact dates, which was not as helpful for this project. Some studies needed are:

- A study detailing the methods involved in construction of a dam
- A study describing the specific timeline of dam construction
- A current study detailing the methods used in dam construction

## 3.6 MQP Project Schedule

The first step in this project was to create a Primavera schedule detailing the assignments due throughout the year. This schedule covered the individual assignments due throughout the first semester as well as the overall structure of the MQP. The purpose of this schedule was to better organize the project as a whole. A picture of the schedule produced is shown in Figure 4. It was helpful to have the schedule in Primavera so that it could be easily referenced while completing assignments.

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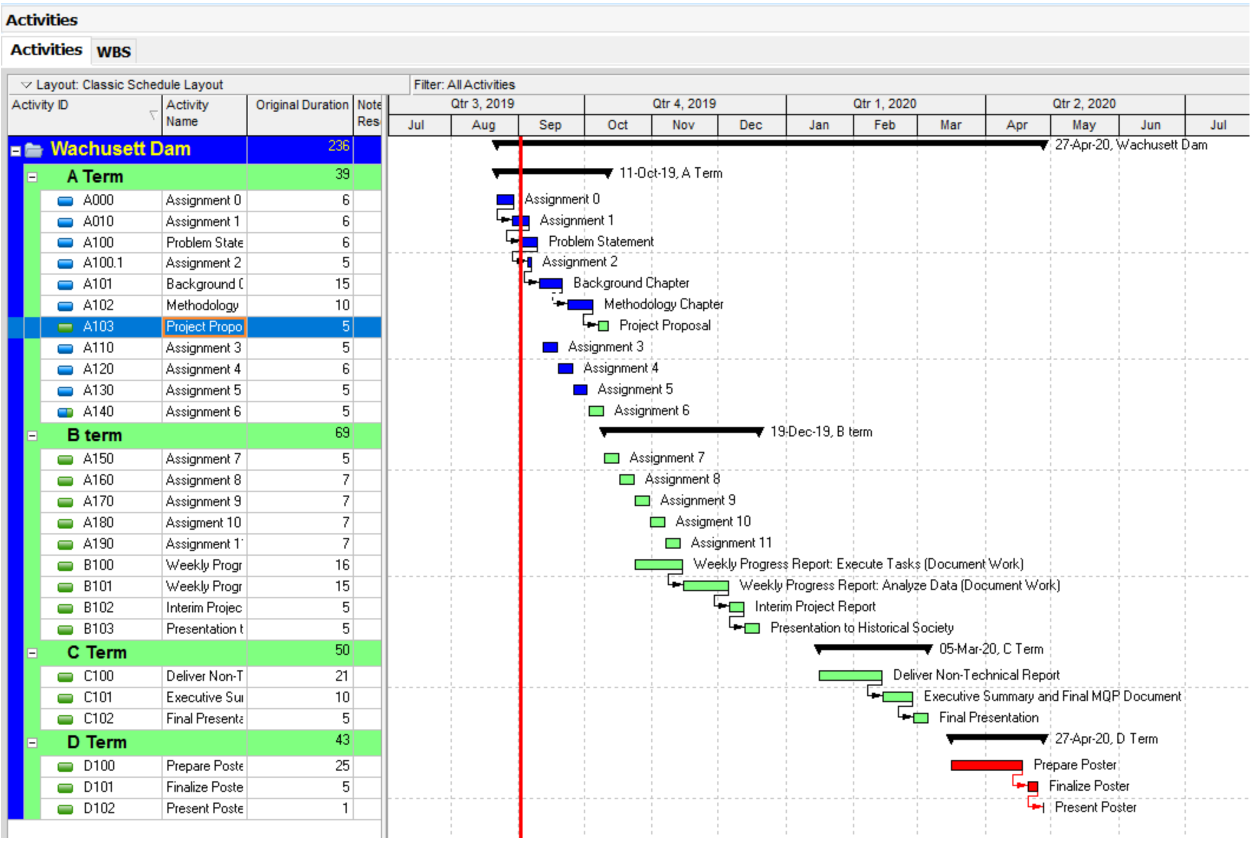


Figure 4: MQP Schedule

### 3.7 Picture Analysis

The pictures taken at the site of construction were very useful in uncovering more information relating to the timeline of construction. These pictures are very detailed and provide a snapshot of the project at a certain date. From there, dates were filled into the schedule. An example of an image taken at the time of construction is shown in Figure 5.

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Figure 5: Picture 1416: (Dec 16, 1897) from Photograph, Wachusett Dam Construction, June 20, 1898: Exhibits: Institute Archives & Special Collections. (2003, July).

In this picture, it is evident that the large flume (Flume 1) has been constructed. This can be seen as the large structure towards the back of the image. Right above the flume, the Gate House is still being constructed. The Coffer Dam can also be seen in this image. It is clear that it is almost finished since there are people working near it, possible working on the soil fill. This image also shows that the centrifugal pump and gate are in place and there is also a platform for the boiler that has been constructed. Overall, this one image has placed five tasks in relation to December 16, 1897.

Although the images could not show exact dates that tasks were completed, they allowed for estimations in terms of a month in which it was completed or at least allowed for predecessors and successors to be established. Some of the exact dates could be found through Annual Reports of the Metropolitan Water Board, but many were not documented. The concrete dates were added to the schedule first, followed by dates found using the photos, and then educated guesses were made.

**3.8 Engineering Reports**

The Metropolitan Water Board Records were the sources with the most information. These reports provided the chief engineer reports as well as general details about the construction of the Wachusett Dam. The general details of construction are in the section by the Metropolitan Water Board, while the more specific information is in the section written by the Chief Engineer. These reports are more detailed in terms of dates and help break the project down into years. Even if a date was not listed for a particular activity, if it was mentioned, progress was made on it in that year. These records also provide a large amount of background information and other information regarding water use at this time. The project only focuses on the projects completed in one section of the reports, but there are many other sections with important projects in Massachusetts.

### 3.9 Field Trips

Throughout the project, this team has visited the site of the Wachusett Dam twice. The first time was a general walking field trip where we were able to see the dam in person and learn more information. This was helpful to put the size of the dam into perspective. It is very easy to underestimate the size of the dam when only looking at the pictures, but in person, the magnitude is evident. The second field trip involved a more in-depth look at the Wachusett Dam and the functions it serves. This information was helpful for both teams, but more so for Team B, as they are responsible for ensuring that the dam works as it should.

The second field trip also helped provide explanation that could benefit this group in the capstone design aspect of this project. The trip provided a more in depth look at how the dam functions and explained the system of pipes that is used.

### 3.10 Programs Used

At the beginning of the project, dates were being uploaded to primavera as soon as they were found. This was convenient in that it allowed for all of the information to be tracked in primavera right away. It was tedious because it did not allow for the recording of citations or other relevant information.

The most efficient way that our team found to complete this project was through the use of spreadsheets. This helped us ensure that all the data that needed to be collected was and that all of the information that we had was tracked in terms of citations and any additional information that could be needed later in the project. A picture of the spreadsheet that we used is located in Figure 6. This spreadsheet held all of the research we completed and was able to be used as a reference when uploading dates to primavera.

After all of the dates were found and uploaded into the spreadsheet shown in Figure 6, they were exported to primavera. This ensured that the schedule was kept in one primavera file and was complete.

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| Activity | Specific | Start | End | Link of Picture | Citation | Notes | Resources | Cost |
|---|---|---|---|---|---|---|---|---|
| Drain Mill Pond | Phase 1 - Take Down of Lanc. Mill Dam (First 6') | 06/01/1897 | 06/19/1897 | | | | | |
| | Phase 2 - Take Down of Lanc Mill Dam (Remaining Struct.) | 08/02/1897 | 08/28/1897 | | | | | |
| Mill Supply Pipe | Exc. of Pipe Trenches | 06/14/1897 | 06/23/1897 | | | | | |
| | Installation of Mill Supply Pipe | 06/23/1897 | 07/31/1897 | | | | | |
| | Installation of Centrifugal Pump & Boiler | 07/25/1897 | 07/30/1897 | | | | | |
| Coffer Dam | Drive Temp. Support Piles | 07/31/1897 | | | | | | |
| | Erect Temp. Bracing Frame | | | | | | | |
| | Install Sheet Piles to Grade | | | | | | | |
| | Inside Grade Exc. and Inst. of Internal Bracing | | | | | | | |
| | Backfill Inside Sheet Piles | | | | | | | |
| | Drive Piles Inside Coffer Dam | | | | | | | |
| | Place Rock Fill and Support Course | | 10/20/1897 | | | River was turned through large flume on Nov 4 | | |
| Flume 1 & 2 | Sawmill Machinery / Facility | | | | | | | |
| | Assemble of Wooden Frames | | | | | | | |
| | Exc. of Trenches for Flumes | 09/01/1897 | | | | | | |
| | Erect Gate House for Large Flume | | 12/18/1897 | | | | | |
| | Finished Temp. Flume 1 (Large) | 09/15/1897 | 01/30/1898 | | | | | |
| | Finish Temp. Flume 2 (Small) | 09/15/1897 | 02/12/1898 | | | | | |
| | Install Gate System for flumes | | 12/18/1898 | | | | done | |
| Temp. Conduit | Install Wodden Legs & Platform Across (From Boiler Room to Opposite End) | | | | | | | |
| | Install Temp. Conduit | | 03/14/1898 | | | Is it refering to the pipe for the Mill Supply | | |
| Deep Excavagtion (by horse) | Materials on Site (Horse & Wagon) | | | | | | | |
| | Install Car Hist Ramp and Cableway | | | | | | | |
| Shape the Granite | Exc. for Foundation of Main Dam | | | | | | | |
| | Exc. of Granite (Change of Order) | 10/19/1899 | | | | | | |

Figure 6: Project Spreadsheet

Uploading two or three dates at a time to primavera was a tedious task and did not allow the team to collaborate as much as desired. By working in a shared spreadsheet, we have been able to collaborate more and better record information. All of the information was uploaded to primavera when it needed to be, but not as often as it previously was.

### 3.11 Progress

The approach that our team took when researching dates for the construction of the Wachusett Dam was organized by the information available. Certain activities had readily available dates in the sources above. This was not true for all activities, but those that had concrete dates were identified before the others. After all of these dates were filed into the spreadsheet and schedule, the vague dates were researched. These are the dates that say a general time of year instead of specific dates. For these dates, the rule that we followed was that when the reports listed that the activity was completed at the end of a year, the date was listed as December 31st. A similar strategy was used for when the reports said that an activity was started at the beginning of the year. In this case, the date was identified as January 1st. The last dates that were added to the schedule were those that we could not find any information on in terms of duration or either start or finish dates. These activities could be approximated through the pictures, but this did not produce an extremely accurate timeline. Our goal was to have the schedule as accurate as possible, which is why the vague and estimated dates were saved towards the end of the research.

In the final term of this project, a work plan was created to ensure that the project would be completed on time. This is located in Table 4. This plan breaks down the work that needed to be completed by week and was updated throughout the term to better fit the needs of the project. The main focus in this term was working on the capstone design portion of the project and finishing the paper. Another component that was completed was creating a modern excavation schedule based on the original construction.

Table 4: C Term Work Plan

| Week: | Dates: | Tasks: |
|---|---|---|
| Over Break | 12/13-1/15 | ● Finish original construction section of the paper.<br>● Export dates to Primavera.<br>● Continue gathering information for capstone design. |
| 1 | 1/15-1/22 | ● Continue gathering material for the capstone design. This material includes dimensions and current velocities.<br>● Add to the capstone portion of the paper.<br>● Begin modern schedule research |
| 2 | 1/22-1/29 | ● Start calculations<br>● Evaluate the impact of the modern schedule. |
| 3 | 1/29-2/5 | ● Continue working on calculations.<br>● Finish modern construction schedule section |
| 4 | 2/5-2/12 | ● Check over calculations with Prof. Mathisen.<br>● Finish calculations.<br>● Start looking into the conclusions section. |
| 5 | 2/12-2/19 | ● Make any changes that are needed for the calculations.<br>● Finish capstone section of the paper.<br>● Finish section on modern schedule in the report. |
| 6 | 2/19-2/26 | ● Write executive summary and edit abstract.<br>● Write conclusions section. |
| 7 | 2/26-3/4 | ● Final edits of the paper and schedule.<br>● Start thinking about the poster. |

**3.12 Issues Found**

Throughout this project a few minor issues were found. The main issue that happened was relating to primavera. Since primavera is a scheduling software created fairly recently, it does not have the option to schedule in the 1800s. This means that our portion of the project could not be properly documented. The main solutions to this were either to shift all of the schedule up and relate it to the 1900s instead, or to find a specific year in the future that has the same dates as the first year of this project. This means that if the first day of construction was on the second Monday of July in 1897, the first day of construction on the altered schedule would also be on the second Monday of July but would only have a different year.

Another minor issue was the lack of preliminary knowledge that the group had relating to hydrology. In order to ensure that this portion of the project was properly completed, Professor Paul Mathisen was consulted. Professor Paul Mathisen teaches hydrology, so he was a useful resource on this topic.

### 3.13 Presentations

The first presentation made was to the Clinton Historical Society. In order to prepare for this presentation, each member first submitted a recording of their section of the presentation. The group then met to rehearse in front of the advisors after addressing all feedback.

The second presentation was to the advisors of this project, Professors Salazar and Marrone. This presentation took place towards the end of the project and allowed both teams to present the entirety of their findings as well as prepare for the final presentation.

The final presentation was on April 24th, which is Project Presentation Day. This is when most MQP groups present their projects to the WPI community.

All three presentations helped the team develop a better understanding of the project through the preparation. Being able to explain the dam construction process as well as the other components of the project tested the knowledge that the team had. This was further tested when presenting to a non-technical audience.

### 3.14 Summary

Breaking down the concept of operations for a system is beneficial in that it allows for the project to be broken down and analyzed. By creating a context diagram to sum up all available information, the project can be analyzed visually as well. This process is crucial to the complete development of a functional system. This along will all of the various methods used to research allowed for a thorough understanding of the Wachusett Dam construction. This knowledge was applied to not only the construction schedule itself, but also the application of modern technology and the capstone design.

# 4. Original Construction Schedule

## 4.1 Introduction

The first step of this project involved research into the schedule used in constructing the Wachusett Dam. There is not much information published about this schedule, which created a challenge, but also is the purpose of this project. Many construction projects have published schedules so, by creating one for this construction, documentation will be created.

## 4.2 Tasks

Before the schedule could be created, the construction project had to be broken into tasks. This way, the project itself was more manageable and dates could be specific to tasks. The tasks included were each part of a general activity. These activities were: Draining the Mill Pond, the Mill Supply Pipe, the Coffer Dam, Flumes 1 and 2, Temporary Conduit, the Second Coffer Dam, Deep Excavation (by horse), Shaping the Granite, Flumes 3 and 4, Pump-sets with Steam, Deep Excavation (by steam), and Bond/Landtaking. These activities each had tasks associated with them. These tasks served as steps to complete the activity. By figuring out the dates of each task, the approximate dates of the activities can be estimated.

While researching the dates of these tasks, resources and costs were also noted. This was beneficial when comparing this schedule to the modern schedule that was created after. Most of this information was found in the Annual Reports of the Metropolitan Water Board.

## 4.3 Programs Used

At the beginning of the project, dates were being uploaded to primavera as soon as they were found. This was convenient in that it allowed for all of the information to be tracked in primavera right away. It was tedious because it did not allow for the recording of citations or other relevant information.

The most efficient way that our team found to complete this project was through the use of spreadsheets. This helped us ensure that all the data that needed to be collected was and that all of the information that we had was tracked in terms of citations and any additional information that could be needed later in the project. A picture of the spreadsheet that we used is located in Figure 17. This spreadsheet held all of the research we completed and was able to be used as a reference when uploading dates to primavera.

After all of the dates were found and uploaded into the spreadsheet shown in Figure 17, they were exported to primavera. This ensured that the schedule was kept in one primavera file and was complete.

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| | Specific | Start | End | Link of Picture | Citation | Notes | Resources Used |
|---|---|---|---|---|---|---|---|
| Drain Mill Pond (MQP.01) | Phase 1 - Take Down of Lanc. Mill Dam (First 6') | 06/01/1897 | 06/19/1897 | | AR97-48 | | |
| | Phase 2 - Take Down of Lanc Mill Dam (Remaining Struct.) | 08/02/1897 | 08/28/1897 | | AR97-49 | | |
| Mill Supply Pipe (MQP.02) | Exc. of Pipe Trenches | 06/14/1897 | 06/23/1897 | | AR97-48 | | |
| | Installation of Mill Supply Pipe | 06/23/1897 | 07/31/1897 | | AR97-49 | | |
| | Installation of Centrifugal Pump & Boiler | 07/25/1897 | 07/30/1897 | | AR 97-? | | |
| Coffer Dam (MQP.03) | Drive Temp. Support Piles | 07/31/1897 | 08/15/1897 | | AR97-? | | |
| | Erect Temp. Bracing Frame | 08/15/1897 | 8/29/1897 | | | | |
| | Install Sheet Piles to Grade | 8/31/1897 | 9/12/1897 | | Photo 1247 | Pile driver on site | |
| | Inside Grade Exc. and Inst. of Internal Bracing | 9/14/1897 | 9/26/1897 | | | | |
| | Backfill Inside Sheet Piles | 9/26/1897 | 9/30/1897 | | | | |
| | Drive Piles Inside Coffer Dam | 10/01/1897 | 10/16/1897 | | | | |
| | Place fill and Support Course | 10/16/1897 | 10/20/1897 | | Photo 1416 Coffer dam done | River was turned through large flume on Nov 4 | 209 men, 35 horses (largest number) |

Figure 7: Updated Project Spreadsheet

Uploading two or three dates at a time to primavera was a tedious task and did not allow the team to collaborate as much as desired. By working in a shared spreadsheet, we have been able to collaborate more and better record information. All of the information was uploaded to primavera when it needed to be, but not as often as it previously was.

A helpful feature of primavera is the ability to create a work breakdown structure. This can be seen in Figure 8 below. This was helpful since it allowed the team to visualize the schedule in a different way. This was similar to the way it was set up in Figure 7 above. Being able to compare them helped to complete this portion of the project.

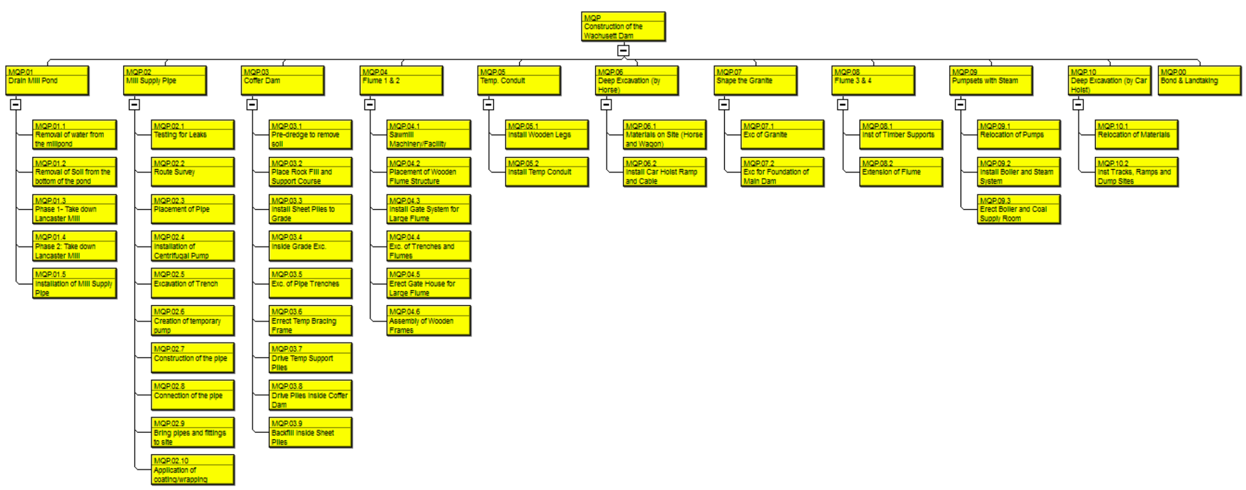


Figure 8: Work Breakdown Structure

### 4.4 Construction Process

The organization of the site can be seen in Figure 9 below. In order to perform the excavation, the water had to be moved. This was done by constructing coffer dams on either side of the area where the dam would be constructed. This empty space was excavated to create room for the dam and reservoir. The Temporary Conduit that can be seen is bringing the water to the residents of Boston.

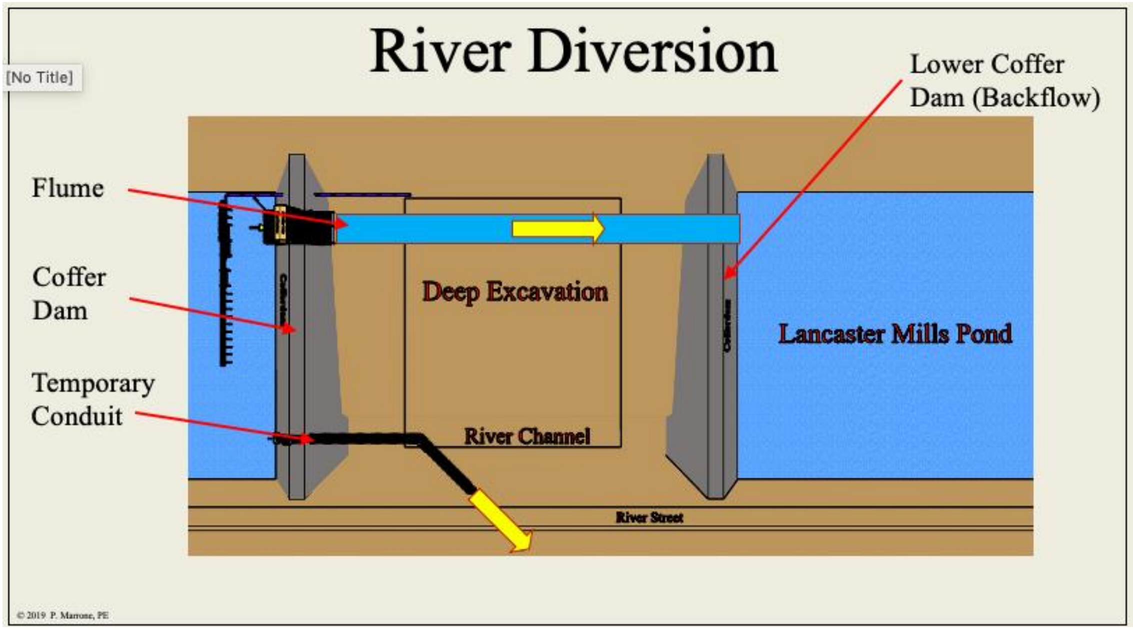


Figure 9: Site Layout

The first step in constructing the dam was to move the water. There was originally a mill pond that was connected to the river with a smaller dam, but this had to be taken down in two sections. The Metropolitan Water Board was allowed to take down the first six feet but had to wait to take down the rest until they were able to provide temporary water supply to the factory. After this was done, they were able to take down the rest of the mill pond. The activities associated with this can be seen in Figure 10 where they have been formatted into the CPM schedule.

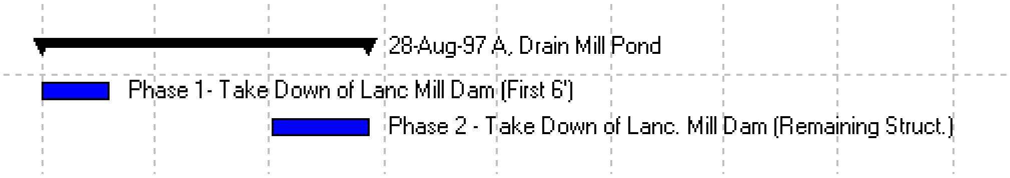


Figure 10: Mill Pond Schedule

The next step was to ensure that the Boston residents would have access to the water that they were promised. This water travels through the Temporary Conduit and through the Lancaster Mill Supply Pipe to the Wachusett Aqueduct in order to get to Boston. Figure 11 shows the construction process for the Temporary Conduit and Figure 12 shows the activities that went into constructing the supply pipe. When constructing the Temporary Conduit, a frame also had to be created in order to support the pipe. The flume was created in order to ensure that water could be directed into this pipe. The final step in this process was to connect the conduit to the aqueduct. When constructing the Mill Supply Pipe, the first step was to dig the trenches. The pipe was then installed. Around the same time, the boiler and steam systems were being installed in order to facilitate the future deep excavation.

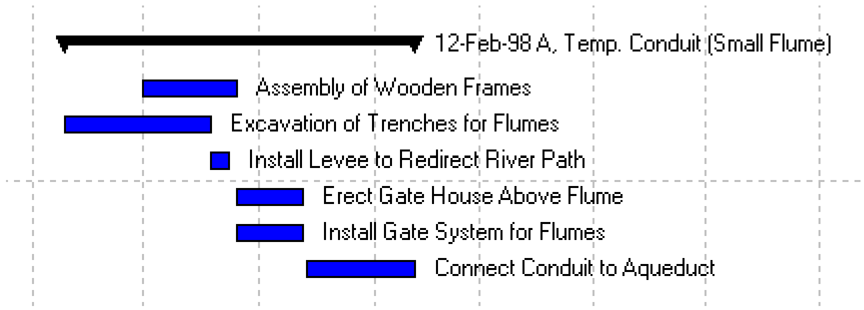


Figure 11: Temporary Conduit Schedule

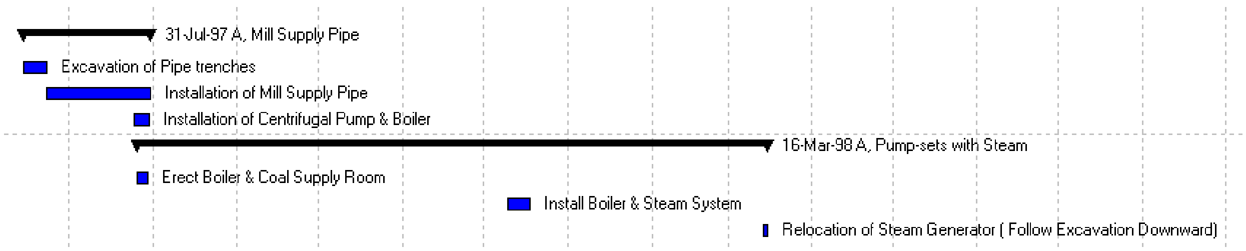


Figure 12: Mill Supply Pipe Schedule

After the supply pipe was constructed, the focus was shifted to constructing the main flume. This flume is the one seen in Figure 9 above. The flume was constructed before the coffer dams so that the water could be moved prior to construction on the surface. There were four flumes constructed in total that all connect, and all followed a similar schedule to the one shown in Figure 13. The first activity on this schedule is building the wooden frames. It exceeds the time frame for Flume 1 because after Flume 1 was built, the construction on the frame of Flume 2 began. In order to create the flume, trenches had to be dug and these wooden frames had to be installed. The gate systems were then installed in order to ensure that there was control of the water. The control of the water was needed in order to ensure that the water level was high enough to flow into the Temporary Conduit that was going to Boston.

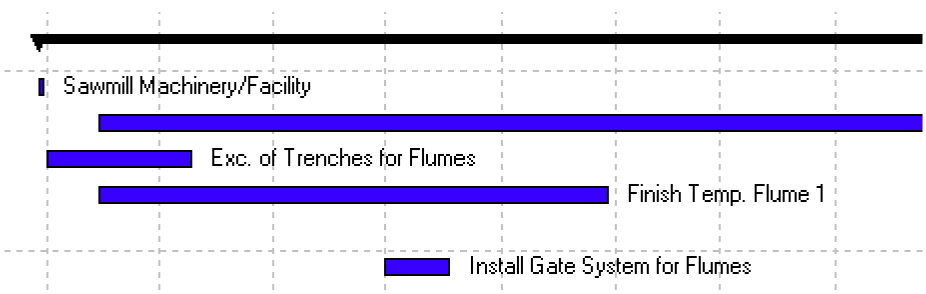


Figure 13: Flume 1 Construction Schedule

The construction of the remaining flumes did not go as planned. Large amounts of granite were found during the excavation process. This meant that they needed to construct Flume 4 before Flume 3. The granite was in the way of Flume 3, so the construction schedules of the two flumes overlapped. This can be seen in Figure 14.

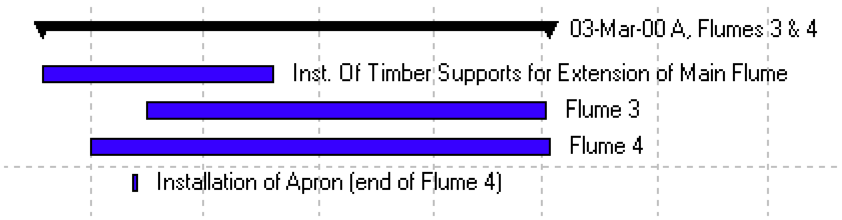


Figure 14: Flume 3 and 4 Construction Schedule

After the flumes were in place, the two Coffer Dams could be constructed. The construction schedule for the Coffer Dams can be seen in Figures 15 and 16. Both Coffer Dams had the same activities and time frame since it was the same structure being constructed in two different locations. The dams were constructed by creating temporary support piles, building a bracing frame, installing sheet piles, installing internal bracing, backfilling, driving piles, and filling the structure. These are all common steps in creating a structure similar to a Coffer Dam. The main difference between the two schedules is that they were completed 18 months apart.

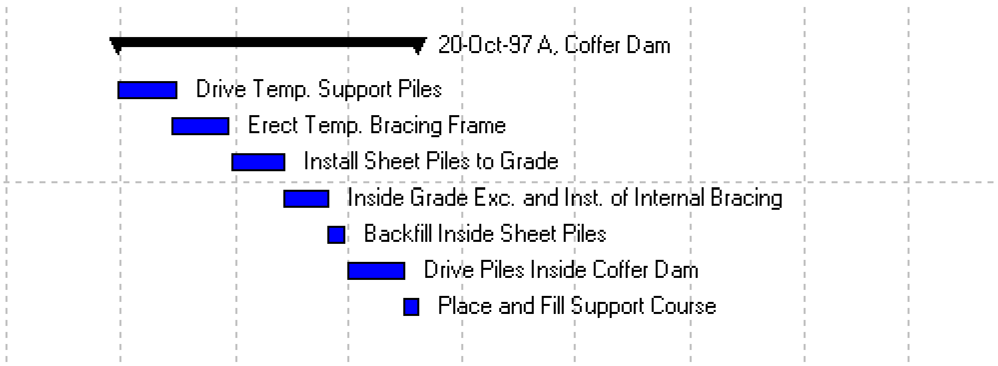


Figure 15: Coffer Dam 1 Construction Schedule

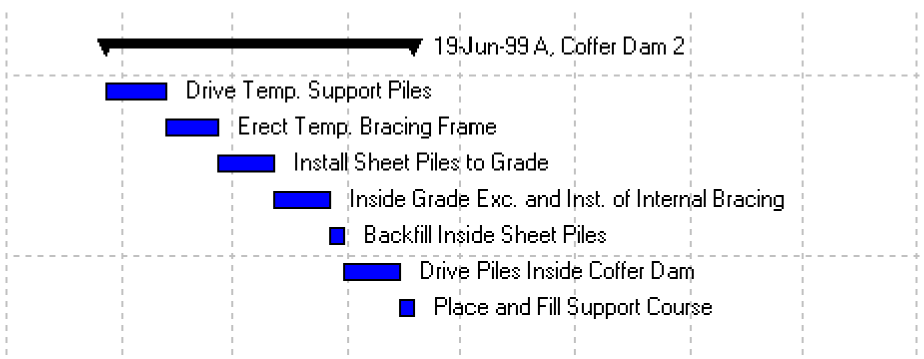


Figure 16: Coffer Dam 2 Construction Schedule

The excavation process was a complicated task because there was a mix of materials in the ground. The surface soils were excavated first, which can be seen in Figure 17. This was a shorter process, since the soil was fairly easy to move. After this, deep excavation began.

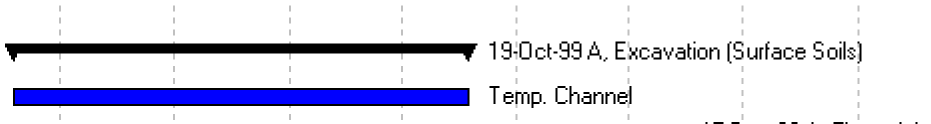


Figure 17: Surface Excavation Schedule

Deep excavation took place in two parts since the maximum depth that had to be excavated was 63 feet. The first excavation method was using horses. This can be seen in the lower activities in Figure 18. After this portion of the excavation was completed and the horses could no longer access the land that needed to be excavated, the car hoist system was installed and utilized. This involved the use of a rail and car system to move the soil.

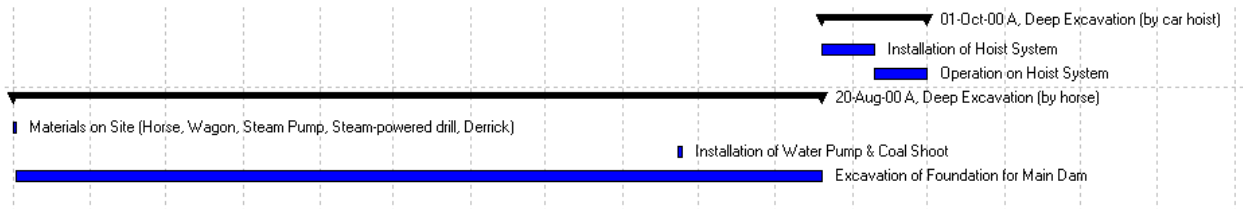


Figure 18: Deep Excavation Schedule

After all of this was complete, the dam itself could be constructed.

## 5. Productivity Analysis of Deep Excavation Using Modern Equipment and Methods

### 5.1 Introduction

The main goal when creating a new portion of a construction schedule was to investigate what impact the use of contemporary methods and equipment could have on the construction schedule with the same activities that took place 120 years ago. This gave us a better understanding of the changes that have occurred in construction since 1900. It also gave us a better understanding of how the duration of activities could differ between the two schedules.

The group of activities that were focused on for this analysis were those related to the deep excavation of the site since this process had fairly detailed records that could be used to compare it to modern day techniques.

### 5.2 Excavation Techniques

When the Wachusett Dam was constructed, two methods of excavation were used. These methods relate to the way that the soil was excavated, and the material was transported. In both situations, shovels were being used to dig. The first method was excavation by shovel and horse. This involved using horses as power to lift dirt out of the hole that was being created. In order to do this, the horses used ramps that were placed on one side of the excavation site. When the hole reached a depth that no longer allowed for the horses to travel in and out, steam powered carts were used in combination with a railroad. This railroad was constructed on a ramp to allow the steam powered carts to enter and exit the excavation site. The process can be seen in Figures 19 and 20. Figure 19 shows the horses being used to excavate the soil and Figure 20 shows the land towards the end of the excavation process. When the image in Figure 20 was taken, the horses were no longer being used as they could not climb out of the hole that had been dug. All of the material was brought to a site that was less than a mile away.

Figure 19: Excavation Techniques from Massachusetts Annual report of the Metropolitan Water Board. c.1 v.6 1900. Retrieved from https://babel.hathitrust.org/cgi/pt?id=chi.72624881&view=1up&seq=9

Figure 20: Excavated Site Photo 5230 from "Digital Commonwealth." www.digitalcommonwealth.org/.

In order to replicate this process using modern construction technology, a series of equipment will be used that includes backhoes, power shovels, loaders, drills, and dump trucks. These will serve the same purpose as the original equipment but will make the process more efficient.

The first step in determining a modern schedule for the excavation related to the dam was to figure out the amount of soil that was excavated. This was not in any of the available Annual Reports. In order to do this, another dam, that had more detailed records, was analyzed. The dam analyzed is the Sudbury Dam. This dam was constructed in the same time period as the Wachusett Dam and was also owned by the Metropolitan Water Board (Massachusetts, 1897). This was done to allow for a reasonable comparison in terms of productivity. The sites have many differences, which could minimize the effectiveness of the comparison, but it allowed for a rough estimate as to if the calculated duration was accurate. Although the original duration of excavation was determined for the Wachusett Dam, this was done using estimations that were based on photographs. Having a site to compare the duration and productivity rates to increase the accuracy of these predictions.

The second step in determining a modern schedule was to estimate the distribution of the soil. The method above can be used to find the average productivity in the early 1900s, but each layer that was found when excavating needs to be analyzed separately.

Using available drawings, the dimensions of the area that had been excavated were estimated. The approximate shape of the excavation is a trapezoidal prism. The trapezoid can be seen in Figure 21 below, outlined in red. This drawing was used to find the width of the prism. This was calculated to be 950 feet. The length of the prism was approximately 700 feet. These were used in combination with the height of 63 feet and the formula: $V = L(\frac{1}{2} * h(a+b))$. In this formula, L is the length of the trapezoidal prism, while the rest of the equation finds the area of the trapezoid. This involves adding the lengths of the two bases (a and b) and multiplying them by half of the height of the trapezoid (h). The total volume that was excavated was 1,008,841.94 cubic yards. This was found using a height of 63 feet. This prism consisted of 131,270.68 cubic yards of rock, found through the equation: V= 700ft*(½*13 ft(324.99ft+453.97ft)), 273,868.11 cubic yards of clay and gravel, found through the equation: V=700ft*(½*20ft(453.97ft+602.38ft)), and 603,703.15 cubic yards of sand and gravel, found through the equation: V=700ft*(½*30ft(602.38ft+950ft)). These calculations were made by creating smaller trapezoidal prisms for each layer. The bottom layer consists of a prism with a height of 13 feet. The second layer has a height of 20 feet and the top layer has a height of 30 feet. The slope was provided in the drawings and aided in the calculations.

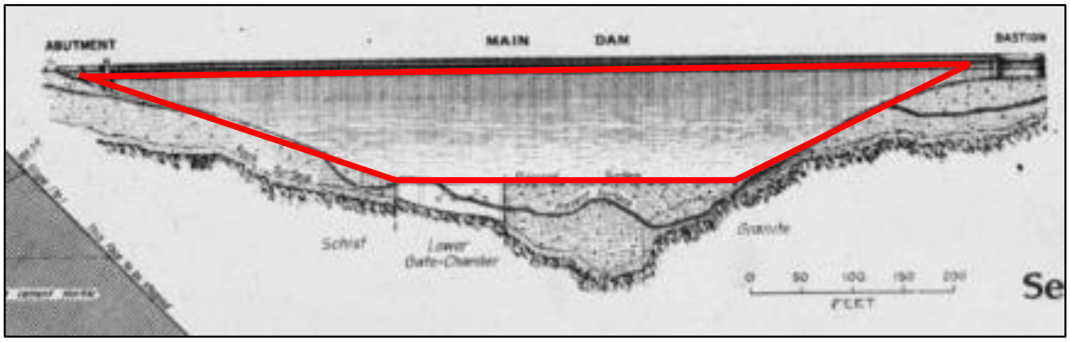


Figure 21: Width of the Dam Photo 8431 from "Digital Commonwealth." www.digitalcommonwealth.org/.

When excavating, the material is removed from a compacted state, which increases its volume and is known as swelling. The adjusted loose volume calculations were done using the respective swell percentages for each material. The adjusted volume of rock was 195,921.49 cubic yards, the volume of the clay and gravel mix was 320,425.69 cubic yards, and the volume of the sand and gravel mix was 676,147.53 cubic yards. These volumes can be compared in Table 5 below. The swell values present in this table was gathered from RS Means (Means Engineering Staff, 2009).

Table 5: Material Volumes

| **Material** | **Depth (ft)** | **Calculated Bank Volume (CY)** | **Swell (%)** | **Loose Volume (CY)** |
|---|---|---|---|---|
| Sand and Gravel | 30 | 603,703.15 | 12 | 676,147.53 |
| Clay and Gravel | 20 | 273,868.11 | 17 | 320,425.69 |
| Rock (Granite) | 13 | 131,270.68 | 49.25 | 195,921.49 |
| Total: | 63 | 1,008,841.94 | N/A | 1,192,494.71 |

### 5.3 Modern Applications

When looking at the records of the excavation of land pertaining to the Sudbury Dam, a rate of productivity was calculated. The exact distribution of soils is unknown for this construction project, but similar methods were used since it took place in the same time period. This was done through a comparison of cubic yards of soil excavated and the duration of the excavation. During a time period of

13 months, 1,580,000 cubic yards of soil was excavated (Massachusetts, 1897). This equates to 4,000 cubic yards per day. This rate was then used to compare the construction of the Wachusett Dam. Having a productivity rate was helpful in determining how exact the calculations were. A rough sketch of the site is shown in Figure 22 below. This sketch shows the starting point and the access point for all vehicles. The excavation site is shown in the blue rectangle in the center. All areas have been estimated.

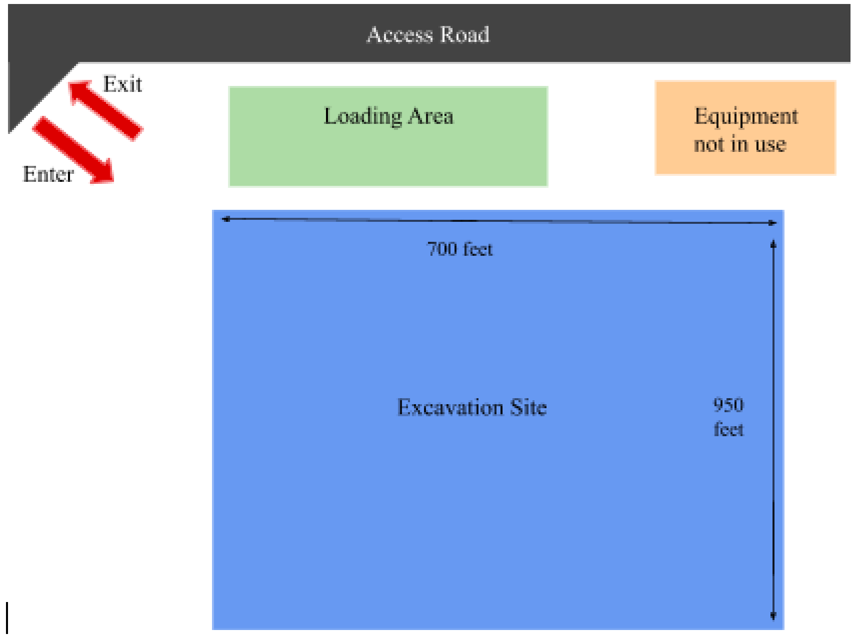


Figure 22: Site Sketch

Figure 23 shows this area in 2020. The area within the red rectangle is the same area that is displayed in Figure 22. This area now contains the dam and pool.

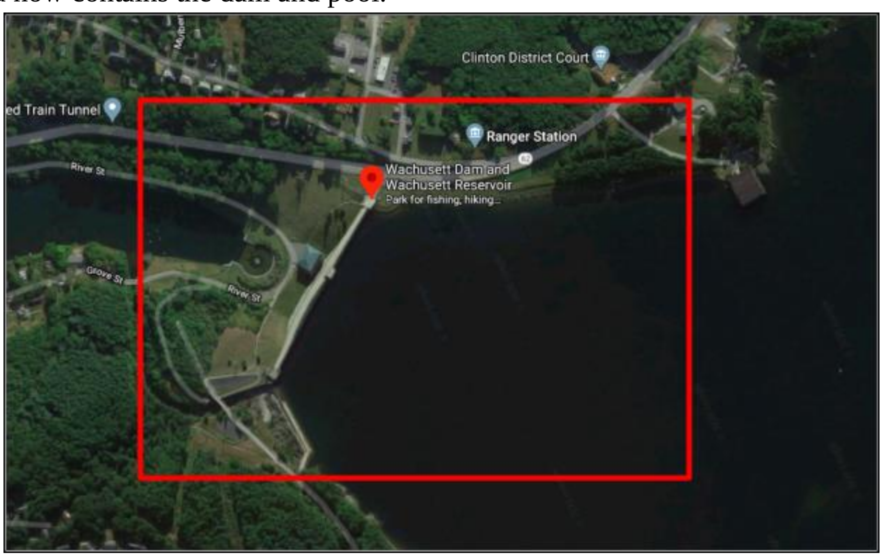


Figure 23: Site Today

After figuring out the volume of soil that needed to be displaced using modern methods, the first step was to determine which method would be used. The most practical method that is used today involves the use of an excavator or backhoe to dig and the use of a dump truck or several to transport the soil to a site down the street. An example of a backhoe can be seen in Figure 24 and an example of a dump truck can be seen in Figure 25. For these calculations, seven backhoes with a bucket volume of 4 loose cubic yards and 18 dump trucks with a capacity of 16 cubic yards of soil or 12 cubic yards of rock were used. This method would allow for the excavation to be completed in a fraction of the time. A backhoe is suitable to be used up to a depth of 15 feet.

Figure 24: Backhoe Example from "426F2.",
www.cat.com/en_ID/products/new/equipment/backhoe-loaders/side-shift/1000031542.html.

Figure 25: Dump Truck Example from "How Big Is a Dump Truck?" Wonderopolis,
www.wonderopolis.org/wonder/how-big-is-a-dump-truck.

After this, a power shovel, which can be seen in Figure 26, should be used for the remainder of the first layer and the second layer. Seven power shovels were needed for this portion of the excavation and they were estimated to have a bucket capacity of 4 loose cubic yards.

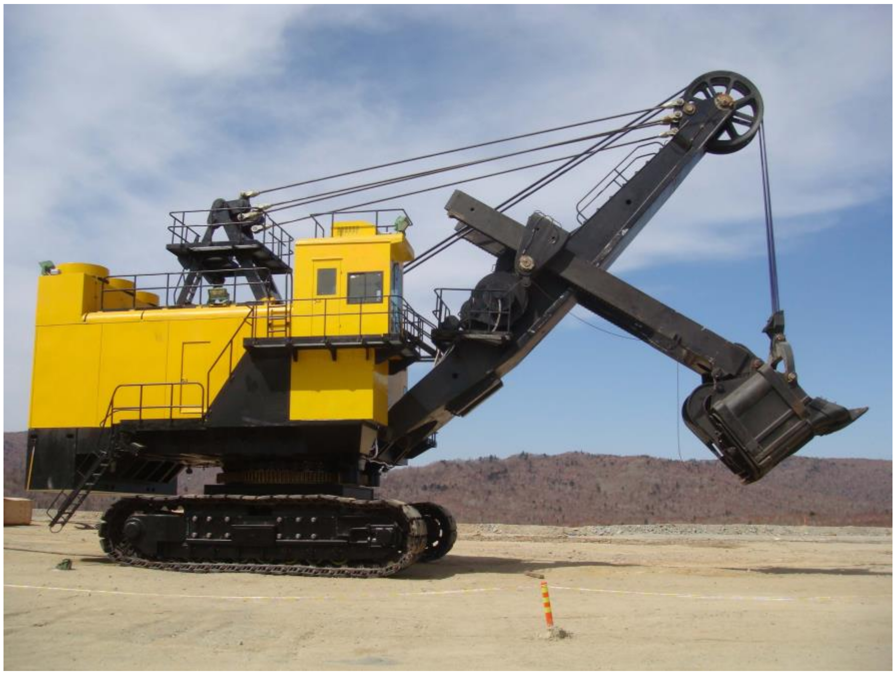

Figure 26: Power Shovel Example from “Power Shovel (Electric Mining Shovel).” Power Shovel (Electric Mining Shovel)_China Railway Science & Industry Group Corporation¡ªA CREC Member Company, www.crsic.cn/en/html/2013/11/180.html.

The third layer is made up of rock, which needs to be drilled and blasted before it can be removed. The drilling involves using a downhole drill, found in Figure 27, in order to create holes where explosives can be placed. The explosions cause the rock to break in order to make it easier to move. For this portion of the excavation, two drills were used, and they have productivity rates of 600 cubic feet per minute and operate at 250 pounds per square inch.

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Figure 27: Downhole Drill Example from "Blast Hole Drills." Furukawa Rock Drills | Furukawa Rock Drill Parts, www.canyonequipment.com/mobile/subcategory/rock-drilling/blast-hole-drills.

A loading tractor, seen in Figure 28, can then be used to remove the stone. Table 6 shows each piece of equipment with its productivity rate and total time needed. Calculations were completed using six loaders with bucket capacities of eight loose cubic yards.

Figure 28: Loading Tractor Example from "Volvo L60H Wheel Loader." Power Equipment Company, http://power-equip.com/product/volvo-l60h-wheel-loader/.

Table 6: Equipment Productivity

| Equipment: | Activity Used for: | Productivity Rate (CY/hr): | Daily Productivity (CY/day): | Number of Trips per Dump Truck per Day: | Quantity of Equipment: |
|---|---|---|---|---|---|
| Backhoe | Sand and Gravel | 365 | 2,920 | 10 | 7 |
| Power Shovel | Sand and Gravel | 460 | 3,680 | 13 | 7 |
| Power Shovel | Clay and Gravel | 375 | 3,000 | 11 | 7 |
| Loading Tractor | Rock | 520 | 4,160 | 20 | 6 |
| Drill | Rock | 12.25 yd/hr | 146.96 yards/day | N/A | 2 |
| Dump Truck | All | 48 | 384 | N/A | 18 |

All calculations were done assuming that each work day is nine hours and includes a one-hour lunch break. At this rate, the excavation would be completed in 133 days, rather than 364 days that it took in 1900. This is a difference of 231 days. In order to further shorten this construction project, additional drills could be used, or longer hours could be utilized. All calculations were completed in a spreadsheet which is also shown in Appendix H. The productivity rates were found using RS Means data.

There were several assumptions made when completing these calculations. The main assumptions were in regard to the daily productivity rates. These were calculated assuming 50-minute hours, 83% job efficiency, and 100% operator efficiency.

**5.4 Cost Comparison**

When comparing the cost of the original construction to a modern adaptation, the Sudbury Dam project was also used since it was well documented. For this project, as well as for the construction of the Wachusett Dam, outside contractors were hired in order to complete work such as the excavation. The contractors hired for the construction of the Sudbury Dam charged 14 cents per cubic yard (Massachusetts, 1897). If this same pricing was used for the Wachusett Dam, the total cost for the selected activities would have been $141,237.87. This was estimated by multiplying the total volume that was excavated by the cost per cubic yard.

In order to compare this to an approximate cost today, construction costs were estimated in the area. Since in the original construction, the contractors were hired by contract, these 14 cents accounted for all costs associated with the excavation. Currently, a similar contract would cost on average, $100 per cubic yard (Learn, n.d.). These costs cannot be directly compared due to inflation.

An inflation calculator was used to determine the equivalent of 14 cents today. This value equates to $4.35 in 2020 based on an average inflation rate of 2.83% per year (Inflation Rate, 1897). This is much smaller than the rate charged today, but the cost difference accounts for administrative needs that companies have today as well as the increased efficiency. Today, the project would be completed quicker and would require the use of machinery. This machinery not only costs a lot to purchase, but also requires maintenance that a contractor must pay for. The price increase accounts for the increase in efficiency that many projects need.

## 6. Design Review of the Hydraulic Components of the Dam

### 6.1 Overview

The capstone design component of this project involved conducting a design review related to the hydraulic aspects of the dam. This design review determined the performance capabilities of the original design by analyzing the water flow velocity and pressures throughout different points of the pipeline system from the moment in which the water entered the system to when it exits in the pool. This was used to gain an understanding of both hydrology in general and the rationale that went into the construction of the dam.

### 6.2 References

The information collected for the capstone design was found in drawings, which can be seen in Figures 29, 30, and 31. These drawings detail dimensions of the pipes located at the area of the Wachusett Dam. Figure 29 was used to find the initial dimensions of the first few pipes. This section details where the water enters the pipes and shows the flow to the pipes shown in Figure 30.

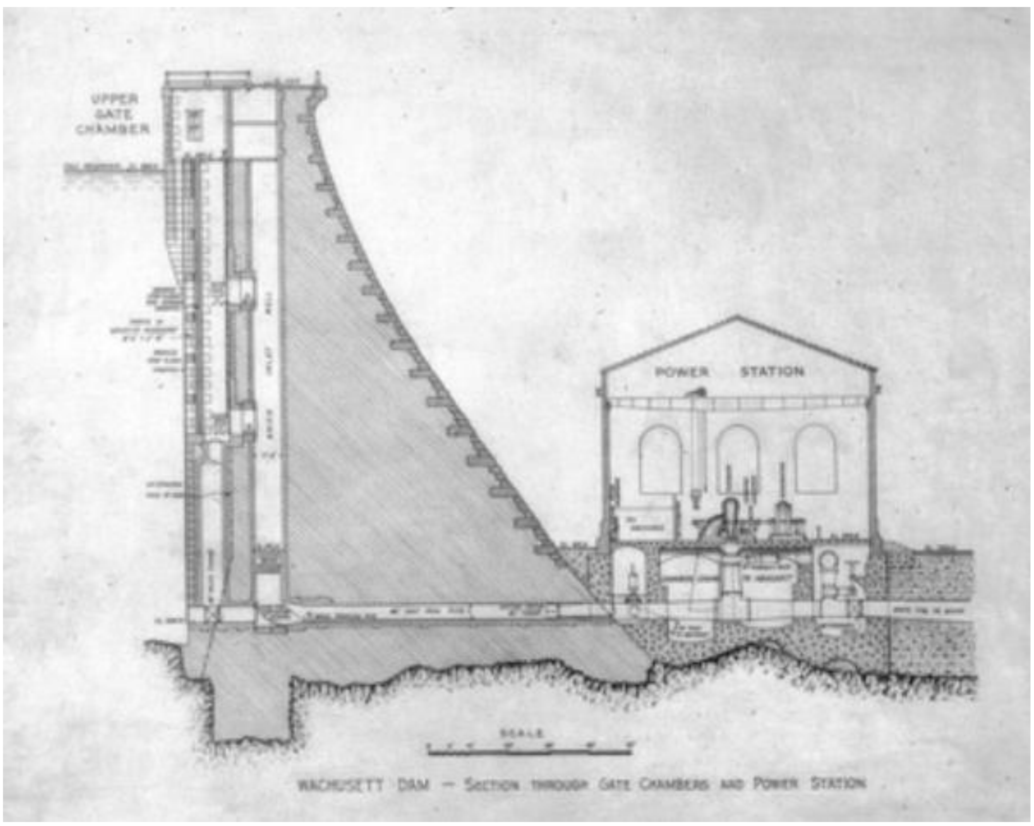


Figure 29: Starting Cross Section of the Dam Photo 08117 from "Digital Commonwealth." www.digitalcommonwealth.org/.

Figure 30 was used to collect most dimensions as it is well labeled. It shows the cross section of the dam and the pipes that run underground to the pool. The left side of this figure is shown in Figure 29, and the right side can be found in Figure 31.

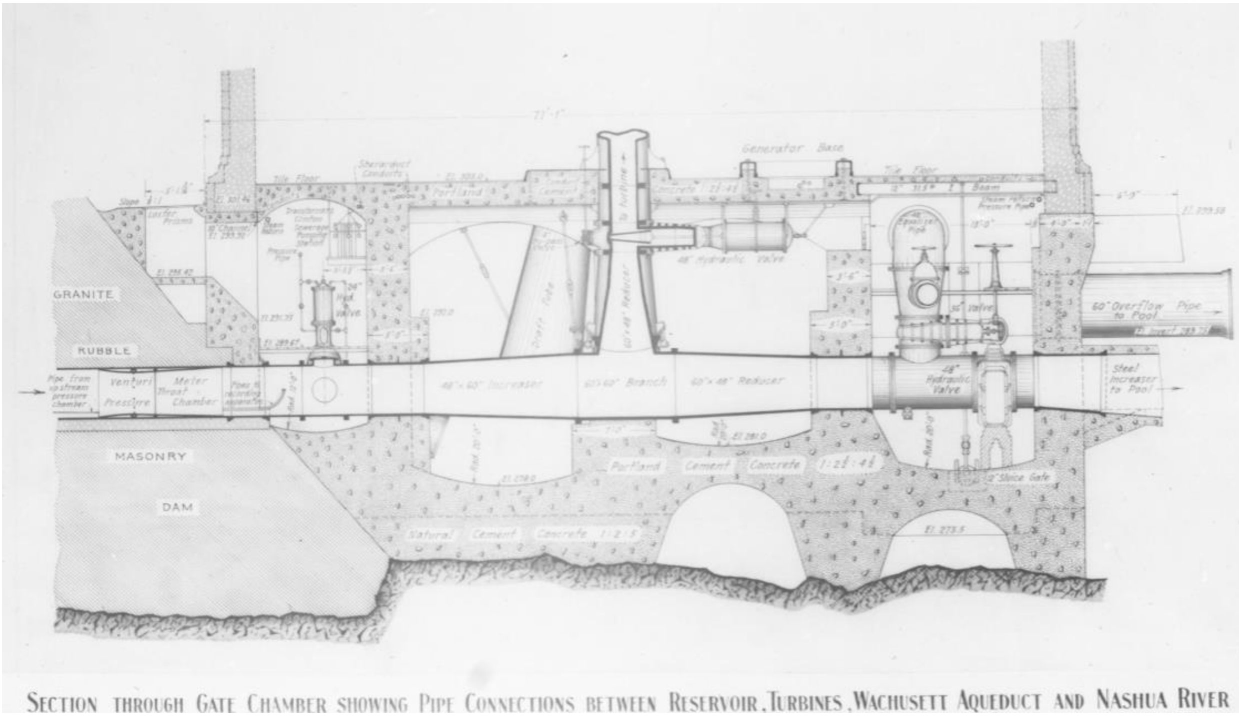


Figure 30: Cross Section of the Dam Photo 8542 from "Digital Commonwealth." www.digitalcommonwealth.org/.

The section of the dam in Figure 31 shows the area from the lower gate chamber to the pool. This is a very complicated section of the dam as it includes four separate conduits that meet at the pool. Once all water arrives at the pool, it has a velocity of 0 feet per second. In order to create this change in velocity, the pipes increase in size as they travel to and around the pool. This change can be seen in the section views at the bottom of Figure 31. These views provide all dimensions for each section of the conduits as they run into the pool.

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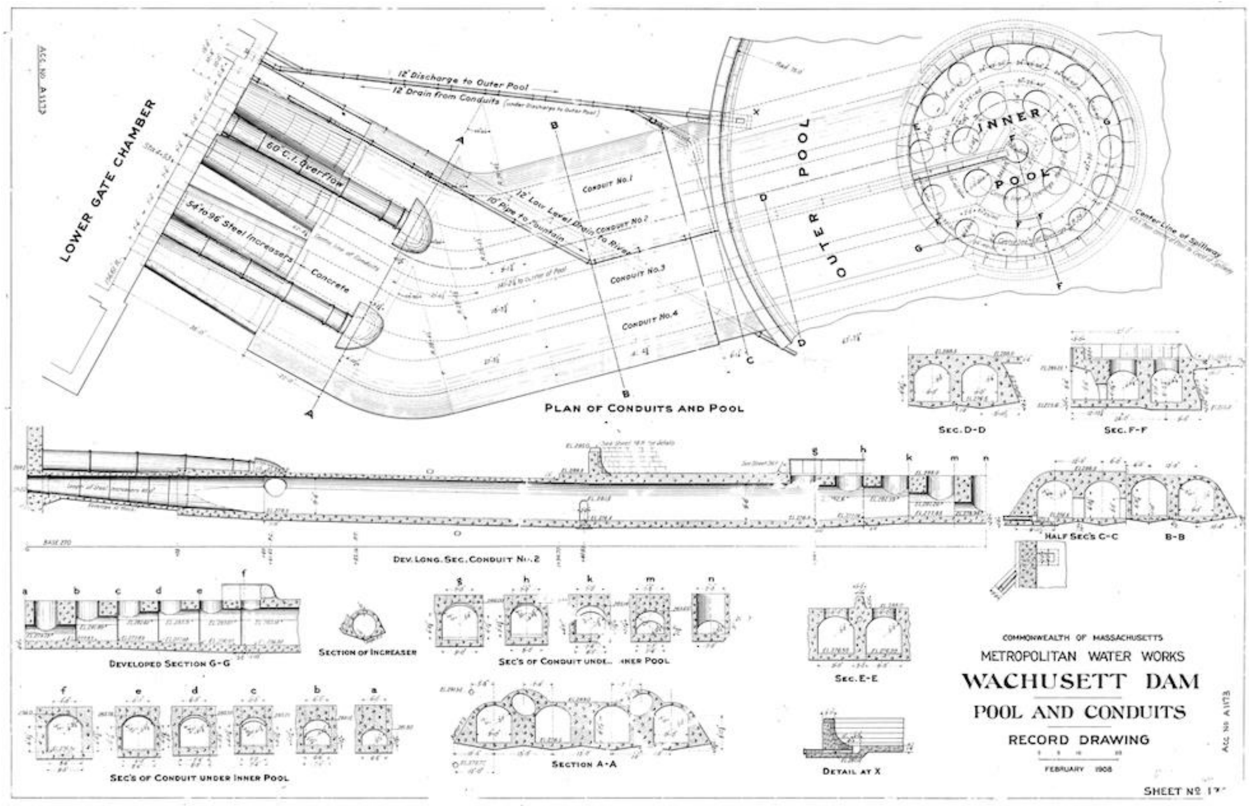


Figure 31: Pool and Conduit Plan

### 6.3 Approach

The first step in completing the capstone design portion of this project was to gather the information required. This involved reading about hydrology and finding the formulas that would be used in a design review. After the formulas were found, the next step involved finding the dimensions of the pipes. Not only were drawings such as the ones in Figures 29, 30, and 31 used, but Professor Marrone also provided some helpful information that he had found in his individual research.

The best way to structure this information was to keep all of it in a spreadsheet, which can be seen in Figure 32. This spreadsheet ensured that all formulas and calculations can be found at all points throughout the project (Appendix I). The spreadsheet tracked the flow, pressures and velocities in all sections of the pipe. By using the known variables, the velocity and ending pressure in the pipe can be calculated. This can then be used as the initial velocity and pressure of the next pipe segment. By using a spreadsheet, future calculations could also be made in terms of testing different dimensions. These calculations could be useful if the pipes were to be redesigned for a different flow rate. This would be very efficient using a spreadsheet.

The main equation used was Bernoulli's equation. This equation is:

$$P_1+(\frac{1}{2}*p(V_1)_2)+pgh_1=P_2+(\frac{1}{2}*p(V_2)_2)+pgh_2+f_p.$$

All variables are explained in Figure 31 below. Using this equation allowed for the comparison of the pressure ($P_1$) and velocity of water ($V_1$) in a pipe with a specified area to another pipe with a different area. This requires solving for the pressure ($P_2$) and velocity ($V_2$) of the second pipe. The last portion of the equation contains the friction factor ($f_p$). This was the last step that was calculated since the pipes were designed to provide little friction. Pipes are generally designed to prevent friction since it would decrease the efficiency of the pipe. Pipes are designed to transport water and friction limits the velocity at which that can happen.

Figure 32 not only shows the equations that were used for all calculations, but also defines the variables that were used. This shows the connectivity between variables such as Q=AV. This means that the flow rate is equal to the product of the area of the pipe and velocity of the water.

| Capstone Information: | | |
|---|---|---|
| **Find** | **Formula** | **Variables** |
| Cross Sectional Inside Pipe Area | A=pi(d/2)^2 | d= inside diameter |
| Cross Sectional Pipe Wall Area | Am=pi(d0/2)^2-pi(d/2)^2 | do= outside diameter |
| Weight of empty pipes | W=pAm | p=density of pipe material |
| Weight of liquid in pipes | Wl=plA | p1= density of liquid |
| Outside surface area of pipes | Ao=2pi(do/2) | |
| Inside surface area of pipes | Ai=2pi(d/2) | |
| Water velocity inside a pipe | V=0.408(Q/d^2) | Q=flow rate of water inside the pipe |
| Minimum pipe diameter | dmin=0.20655(sqrt(Q/P)) | P=design pressure of a pipeline |
| Pressure loss due to pipe friction | Ploss=4.53*L*((Q/C)^1.852)/(do^4.857)) | C=pipe coefficient ; L=pipe length |
| Flow rate | Q=AV | |
| Link: | http://irrigation.wsu.edu/Content/Calculators/General/Pipe-Velocity.php | |

| Values for C | |
|---|---|
| Material | C |
| PVC | 150 |
| Aluminum with Couplers | 120 |
| Galv. Steel/ Asb. Cement | 140 |
| Cast Iron/Old Steel | 100 |

Figure 32: Hydraulic Analysis Spreadsheet

An example of these calculations is seen in Figure 33. This shows the calculations used to find the velocity and pressure in the first conduit. This is the conduit running vertically on the left side in Figure 29. The initial values that were used in these calculations were a velocity and pressure of 0. These are due to the water being in the reservoir before it enters the brick inlet. The gravitational force was calculated as 32.17 ft/$sec^2$ and the density of water was also used (62.42 lbs/$ft^3$). Another value that was needed for this portion was the initial flow of the water. This flow was taken from the assumption that 600 million gallons of water flow through these pipes daily. When factoring the fact that there are 24 hours in a day, this equates to 232.08 $ft^3$/sec. This flow was originally plugged into the equation Q=VA. This equation calculated the initial velocity using the area. The velocity was 6.03 ft/sec and was then plugged into Bernoulli's equation to find the ending pressure. This can be seen in Figure 33 and was used to calculate the velocity and ending pressure in the next pipe.

Given:
Total flow ($Q_T$)= 600 million gallons/day
Initial Velocity ($V_1$)=0 ft/sec
Initial Pressure ($P_1$)=0 lbs/ft$^2$
Brick Inlet Height ($h_1$)= 395 ft
Brick Inlet diameter (d)= 7 ft
Density of water = 62.42 lbs/ft$^3$
Gravitational Force = 32.17 ft/sec$^2$
Brick Inlet Final Height ($h_2$)= 284 ft
Initial flow (Q)= 232.08 ft$^3$/sec

Calculations:

1. Solve for $V_2$

$Q=VA$

232.08 ft$^3$/sec=$V_2$*38.48 ft$^2$

$V_2$= 6.03 ft/sec

2. Bernoulli Equation:

$P_1+(½*p(V_1)^2)+pgh_1=P_2+(½*p(V_2)^2)+pgh_2+fp$

3. Adding Known Variables:

0 lbs/ft$^2$+ (½*62.42 lbs/ft$^3$(0 ft/sec)$^2$)+ 62.42 lbs/ft$^3$*32.17 ft/sec$^2$*395 ft = $P_2$+(½* 62.42 lbs/ft$^3$(6.03 ft/sec)$^2$)+62.42 lbs/ft$^3$*32.17 ft/sec$^2$*284 ft

4. Solve for $P_2$

$P_2$=219,850.42 lbs/ft$^2$

Figure 33: Calculations Example

### 6.4 Assumptions

Due to many unknown factors relating to the pipes themselves, several assumptions were made. The first assumption related to the water flow itself. The water flowing through these pipes would differ based on the water level of the dam, but these calculations were made with the assumption that the water was constantly flowing, causing the pipes to be full. Another assumption that was made was that all valves were closed in this process of the water flow. This allowed the calculations to be simplified and provided a singular path for the water.

One unknown factor that was excluded from calculations was the thickness of the pipes. This would not change the velocity of the water traveling through the pipes but would be an additional calculation that could determine the failure rate of the pipes.

### 6.5 Results

The results of this section are summarized in figures 34 through 37. These are the same figures shown above, but the velocities and pressures have been added to demonstrate the flow of water. The actual flow of water is demonstrated using the blue arrows. Figure 37 shows a zoomed in image of the conduits that run in the pool area to better depict the changes in velocities and pressures in that area.

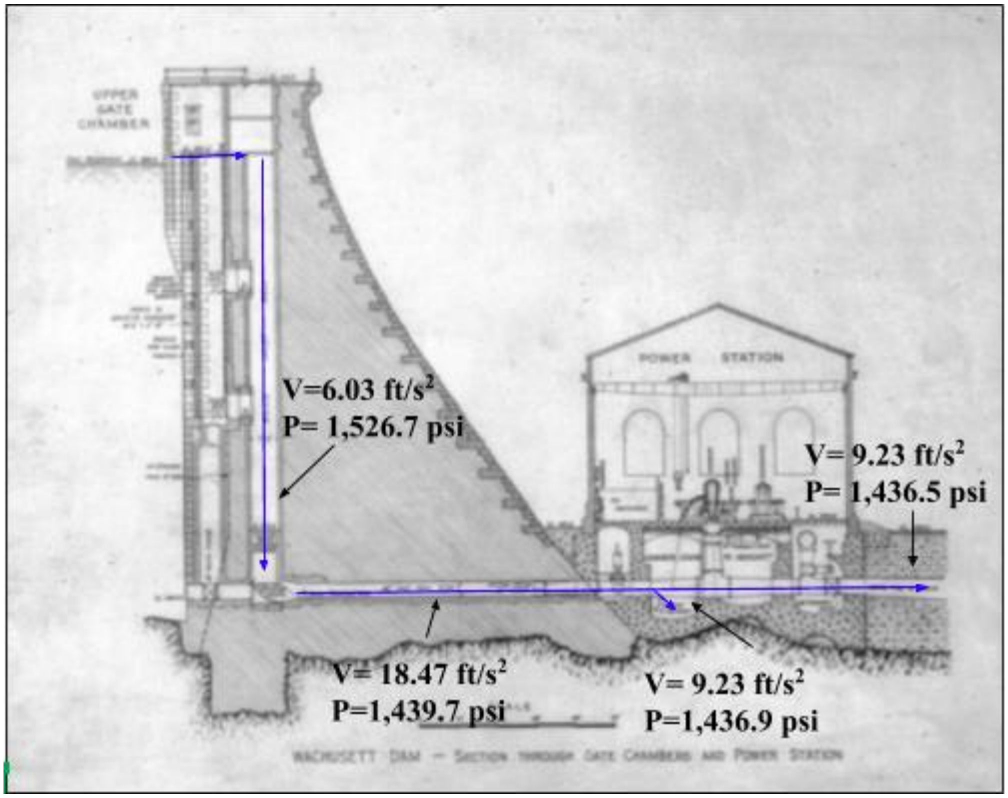


Figure 34: Starting Velocities and Pressures

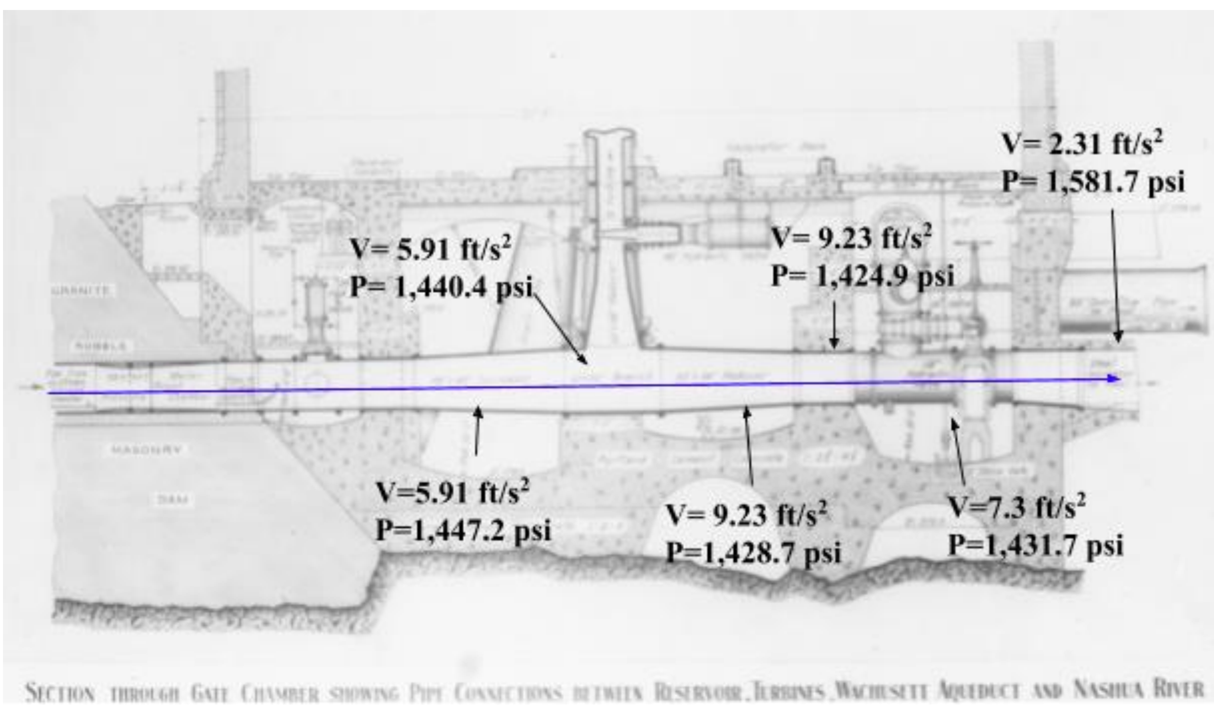


Figure 35: Additional Velocities and Pressures

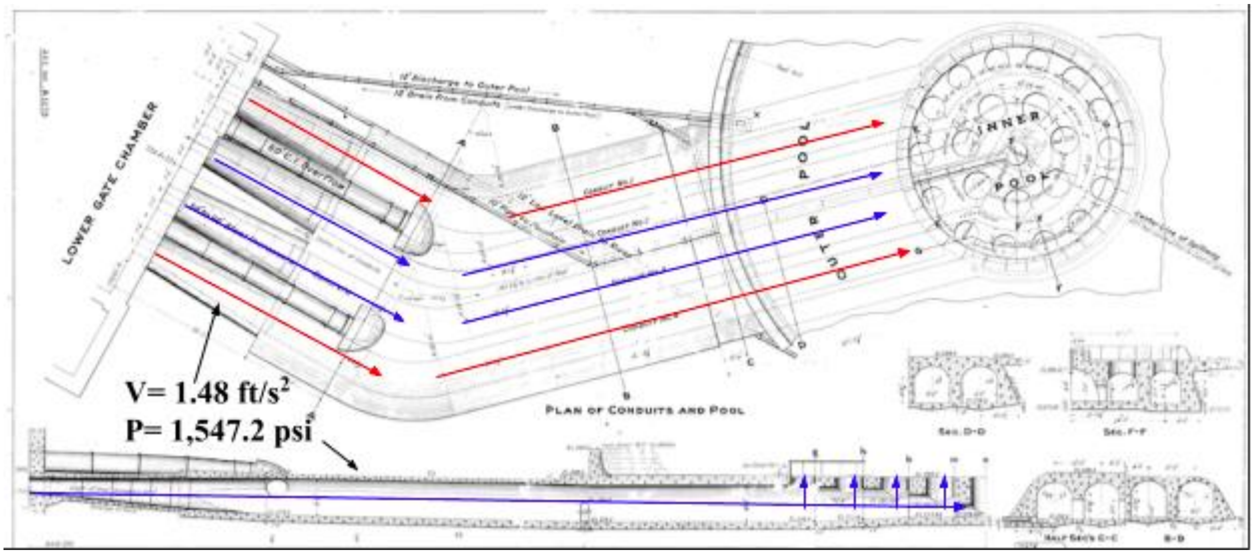

Figure 36: Conduit Velocities and Pressures

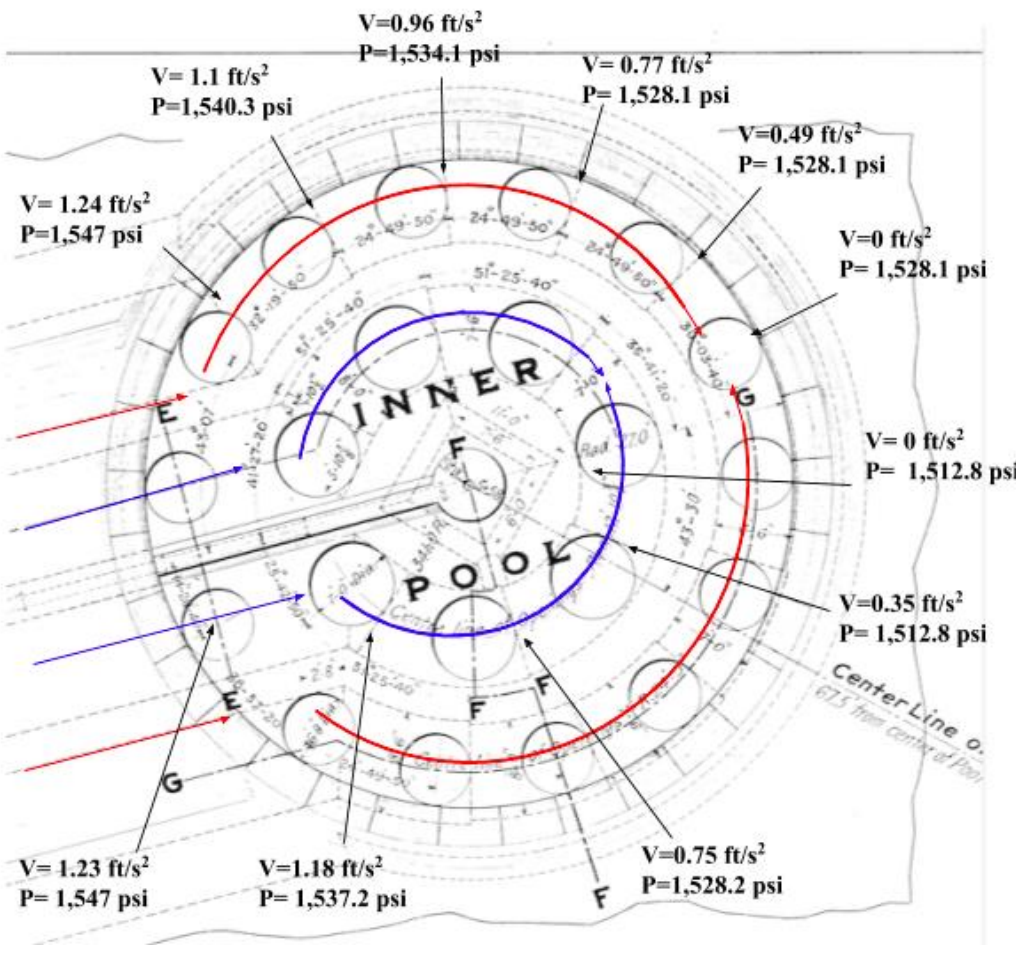

Figure 37: Pool Velocities and Pressures

Calculating the velocities in this section helped ensure that there was a general understanding of the purpose and use of the dam. Since all values were calculated using the maximum flow, the design of the dam could be evaluated at this level. This is an extreme situation, which is why it allows for the design to be truly tested. The initial velocity, right before water enters the dam, is 0 ft/sec and the final velocity, when the water arrives in the pool, is also 0 ft/sec. Analyzing the water at different points throughout the dam allowed for the understanding as to how this happens. When traveling throughout the dam, the maximum velocity was 18.47 ft/sec and the minimum velocity was 0 ft/sec. These calculations verified that the dam was designed to account for the maximum flow of water. This is apparent based not only on the calculations that were done, but also the presence of several overflow areas throughout the dam.

One area where the calculations were assessed for accuracy was the pressure. After all calculations were completed, the minimum and maximum pressures were compared to the graph shown in Figure 38. This graph indicates that typical maximum pressure values for similar pipes fall between 16,000 and 23,000 psi. These values decrease as the temperature increases. The maximum pressure for the Wachusett Dam hydraulic system is 222,770 pounds per square foot. This is equal to approximately 1,547 psi, which means that it is well within the limits of allowable pressure.

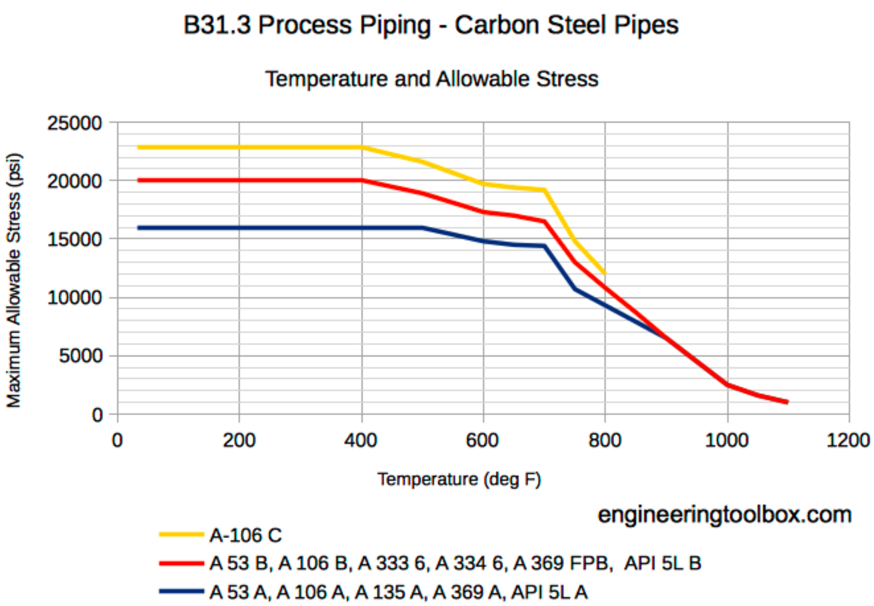


Figure 38: Pressure Capacity from “Process Pipes - Temperature and Allowable Stress.” Engineering ToolBox, www.engineeringtoolbox.com/temperature-allowable-stresses-pipes-d_1338.html.

Another test that was completed to confirm that the pressure values were reasonable was calculating the safety factors of the pipes. This can be seen in Table 7 below. This table shows the formula used to calculate the safety factors as well as the three safety factors that were calculated. These all are greater than one, which confirms that the pressures are realistic. If the values were less than one, the pipes would have a greater chance of breaking.

Table 7: Safety Factor Calculations

| Safety Factors for Pipes | | | |
|---|---|---|---|
| Formula | P = 2ST / (OD)(SF) | | |
| | 48" Cast Iron Pipe | Steel Increaser at (54") | Steel Increaser at (96") |
| Ultimate Tensile Strength (S) (psi) | 29007.00 | 60900.00 | 60900.00 |
| Pipe Wall Thickness (T) (in) | 2.00 | 2.00 | 2.00 |
| Fluid Pressure (P) (psi) | 1526.74 | 1431.66 | 1518.70 |
| Pipe Outside Diameter (OD) (in) | 50.00 | 54.00 | 96.00 |
| Safety Factor (SF) | 1.52 | 3.15 | 1.67 |

If this dam was designed today, it would most likely be constructed using pipes with similar, if not the same, measurements. The calculations used were most likely the same as those used when originally designing the hydraulic elements. The fact that the dam still stands, and functions today shows that the construction of the pipes was done in a way that meets the needs of the dam. This information created a frame for future calculations. Using a spreadsheet allowed for flexibility. If different dimensions were to be tested, all values would automatically be calculated to see if this is a practical proposition.

## 7. Presentations

### 7.1 Overview

A large portion of this project relied on the ability to not only conduct research and apply the skills that have been learned, but also the ability to communicate and the application of these skills to a variety of audiences including those with a non-technical background. There were three main presentations throughout this project that were each to a different group of people. This helped expand the group's ability to cater information to the audience present.

### 7.2 Presentation to the Historical Society

The first presentation was to the Clinton Historical Society. This presentation took place on December 10, 2019. The purpose of this presentation was to inform the Historical Society as well as the community about the research that both MQP teams had conducted so far. This community was specifically selected since the dam is located in Clinton, MA. This presentation was in the middle of the project, but still conveyed enough information to inform the community about technical aspects that made it possible to complete this project as well as the project in general. The title slide of this presentation can be seen in Figure 39.

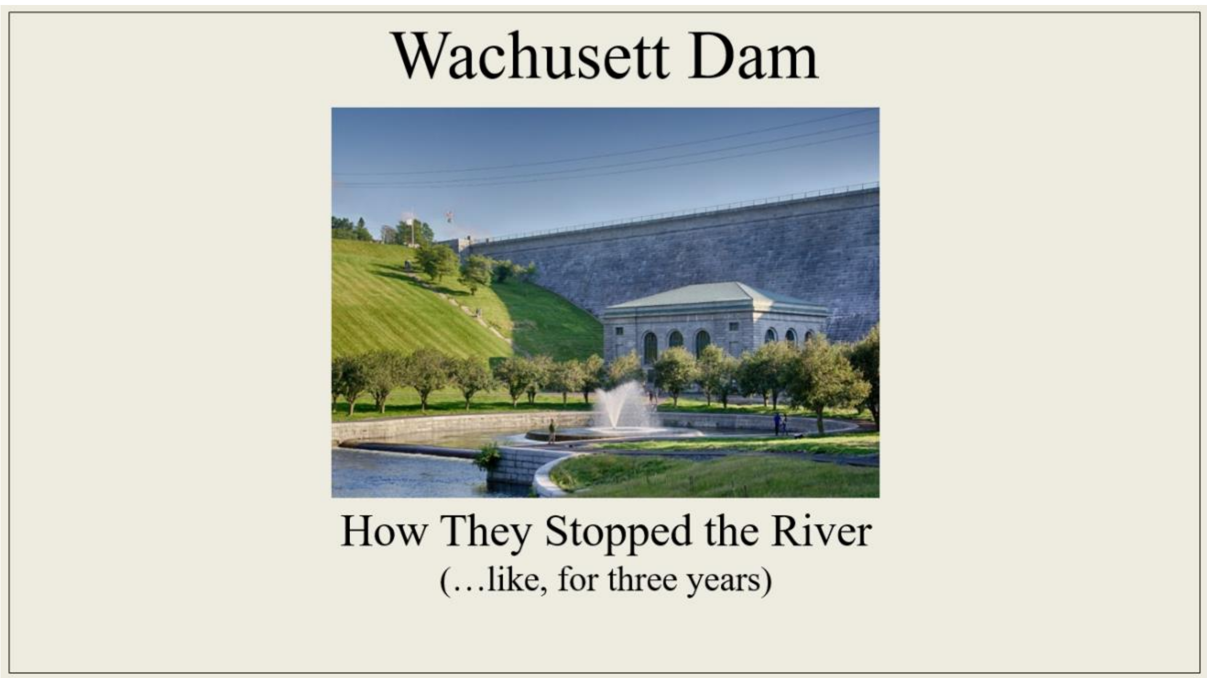


Figure 39: Title Slide

The presentation was divided into five sections so that each person in both Team A and Team B could present. In order to prepare for the presentation, all members recorded their own section and also practiced as a group. This team presented on site preparation and the bypass. The other sections were about the equipment on the site, the excavation, and the process piping. The site preparation section had 18 slides, the excavation section had 19 slides, the equipment section had 19 slides, the process piping section had 17 slides, and the bypass section had 23 slides. All of these slides can be seen in Appendix G as well as a few in Figures 40 through 43 below. Each figure includes a general description similar to the one that was given during the presentation.

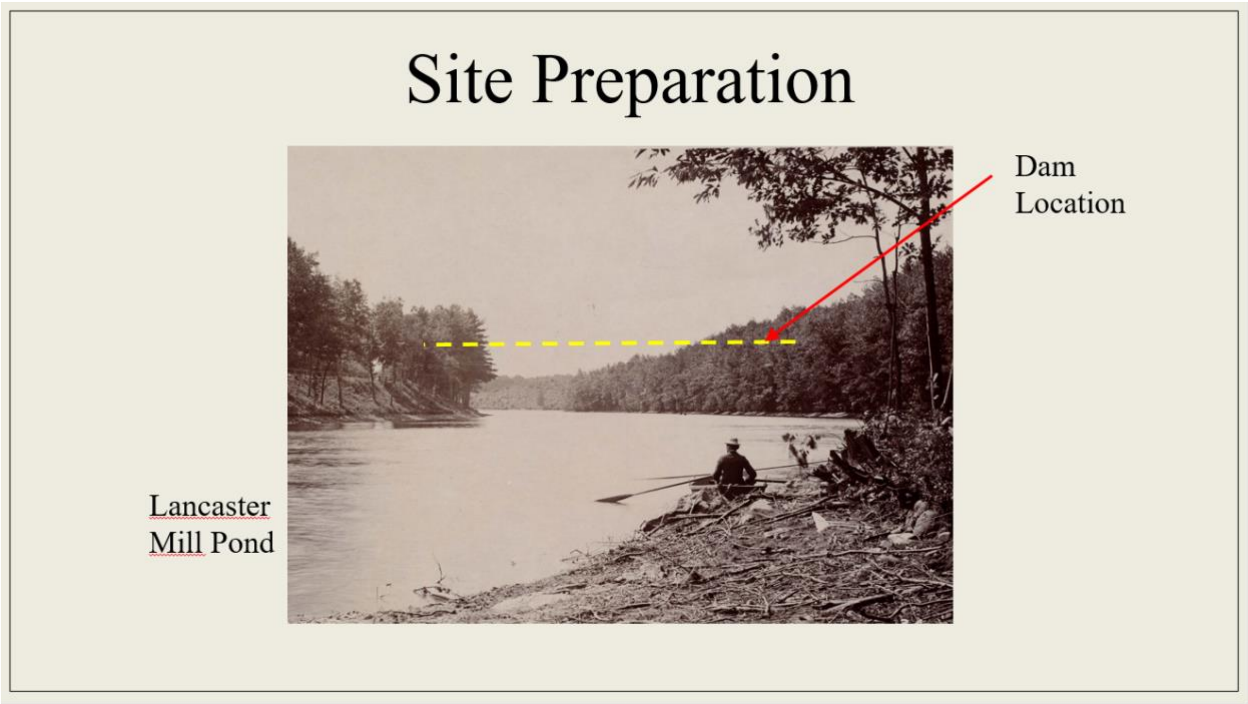


Figure 40: Site Preparation

Figure 40 portrays the location of the dam before it was constructed. This shows the river as had been prior to 1895. Figure 41 shows the next section that was presented, the excavation.

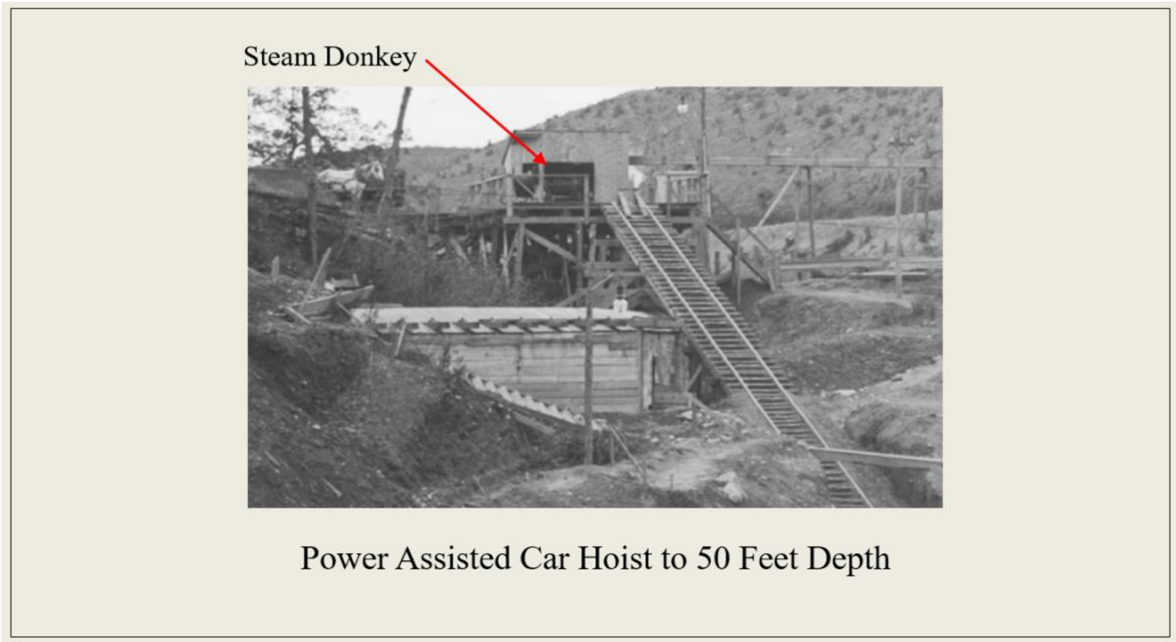


Figure 41: Excavation

The image in Figure 41 shows the steam donkey that was used to aid in the deep excavation of the site. This was used once the horses could no longer climb out of the excavation site. The excavation is further described in Section 5 of this report.

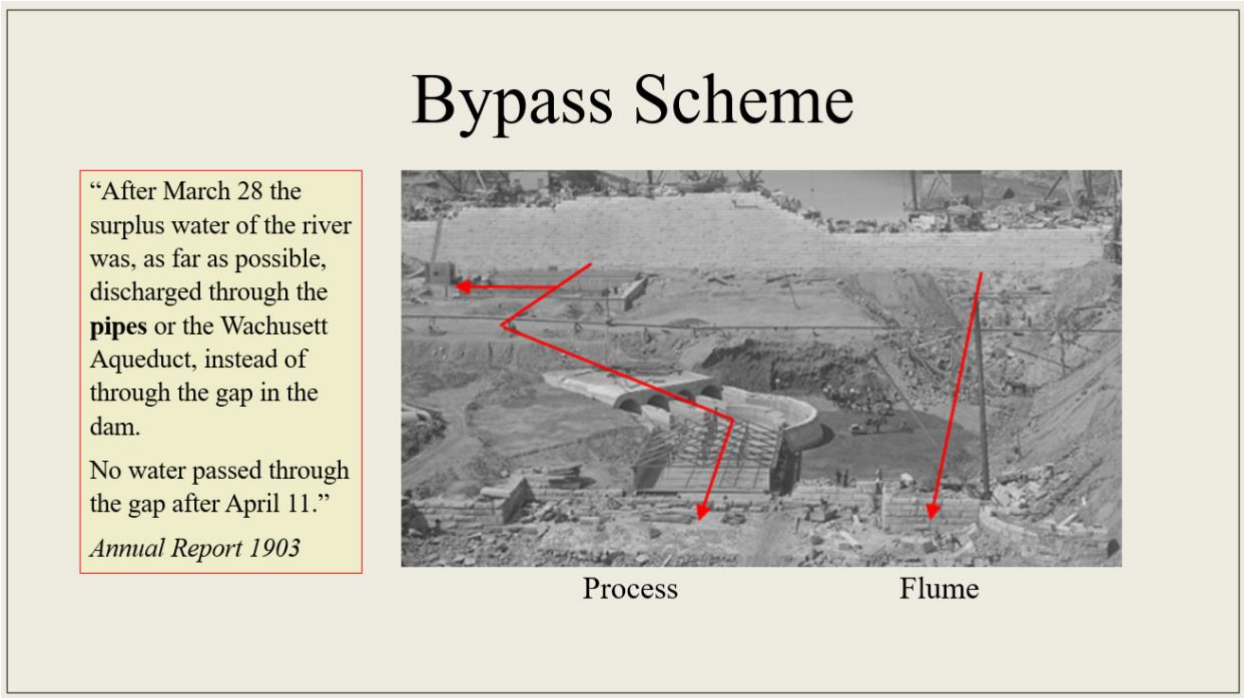


Figure 42: Bypass Scheme

Figure 42 shows the bypass process that was used during the construction of the dam. In order to build the dam itself, the water had to be moved. This was done through the use of flumes. The red arrows indicate the two paths that water could take, with the one on the left indicating where the water would go after the dam was constructed.

**This space has been intentionally left blank**

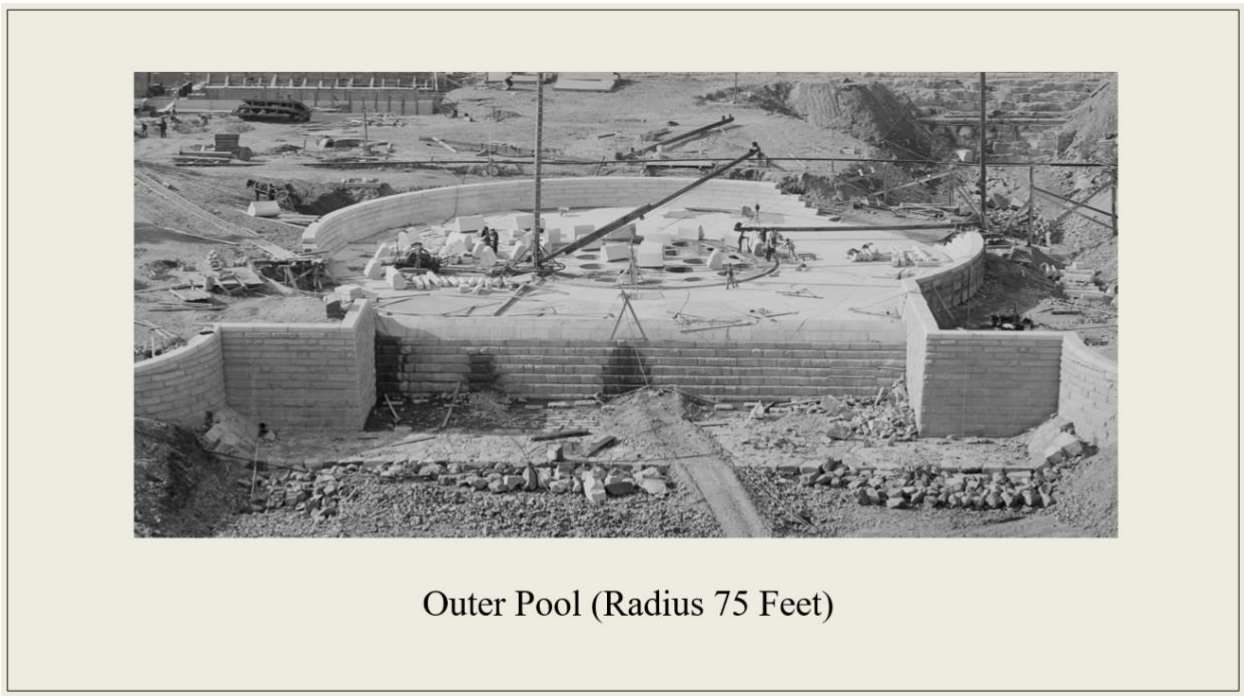


Figure 43: Pool Construction

Figure 43 displays the construction of the pool and shows the conduits where the water comes out. This pool contains a weir and an erosion control apron. The weir is structured at an angle that allows the water to increase its velocity before traveling to the river. The erosion control apron is used to prevent the ground at the start of the river from eroding due to the force of the water.

### 7.3 Feedback and Critique

Presenting to the Clinton Historical Society and general public was informative as it gave both teams the opportunity to practice communicating with a group that has a mixture of technical and non-technical backgrounds. The general feedback received was that the presentation was informative and generally well received. The points that could have been improved were the technical sections of the presentation. This specifically refers to the final section about the pool. This section was filled with a large amount of technical language, so it could have been explained better for the non-technical audience.

# 8. Conclusions and Recommendations

The Wachusett Dam was constructed in the late 1800s and early 1900s with the intent of providing water to the residents of Boston. This construction process was successfully completed but was not well documented. There are Annual Reports that detail some overall steps in the process, but there are not many details regarding dates of completed tasks. This MQP was created to fill this gap and create a construction schedule to explain the construction of a portion of the dam. This MQP was also split between two groups to ensure each group could create a detailed schedule for half of the construction. This group was assigned the pre-construction phase that focused on site preparation. Along with this schedule, the construction process was also analyzed in terms of practicality today and the hydraulic components. The excavation portion was analyzed to determine how the process would differ today. When analyzing the hydraulic portion, a design review was completed to analyze how the velocity of the water changes throughout the pipes.

In order to complete this project, many resources were used including the Annual Reports, mentioned above, and field trips to the dam. Another helpful source was the collection of photographs published by Digital Commonwealth. These photographs gave estimated dates for different phases of construction and were used to create a large portion of the schedule. By creating this collection of information relating to the Wachusett Dam, this team created an additional resource that could potentially be used in future projects.

Not only was the lack of specific information relating to the construction timeline a limitation, but the length of the project ended up being another limitation. This left this group with a list of things that we wish we could have completed. This list includes creating a modern construction schedule. In order to do this, each individual activity would be analyzed in a similar way as the excavation was analyzed in Section 5. Being able to calculate specific timelines in order to compare construction methods would have been very interesting and informative. This process would also require detailed research about each specific activity, which is why it was not something we were able to do in this time period.

Some additional things that had been proposed as ideas throughout this year could be used in future MQP projects. Professor Marrone has indicated that he hopes to advise other groups and continue using the Wachusett Dam as the subject of MQP projects. One of his ideas is to create a project that will finish the construction of the dam in a similar way to this project. Team A analyzed the site preparation phase, Team B analyzed the dam construction phase, and a future MQP could perform a similar analysis on the remaining masonry construction.

Another idea that Professor Marrone gave was to have a project that focused on the construction of the spillway, a portion of the reservoir designed to create controlled flooding in the case of a surplus of rain. A similar project could also focus on stripping the basin soil and constructing the dikes. Although these projects relate to the current one, there could be an additional project focused on combining the two schedules that have already been created. This could be a challenging task because there could be overlap in the dates used.

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# Appendices

## Appendix A: Activity Development

September 12-19

The first major area of research that we conducted was reading the annual reports from the Metropolitan Water Board. The reports that we focused on were from 1897 to 1900. All of these were read over in prior weeks in order to develop some general insight on the construction, but this week, we focused on the report from 1897. The goal was to find more specific dates in order to better adjust the schedule. While reading the report, any dates listed were noted and their relevance was evaluated. The dates that were important to our project were attached to a task in the Primavera schedule. While conducting this research, the comments made by Prof. Marrone were considered and changes were made to the schedule to allow it to comply with the recommendations given.

In the next few weeks, we will continue reading through the annual reports with the same approach, as we found it beneficial. We also will consult photographs and other sources that we found online. These sources were mainly used for the background section so far, but they may be helpful in the next few weeks.

September 20-27

This week the main research has been focused on the images collected. Along with the previous research, these images are provided guidelines for the schedule. A main focus this week has been on adjusting the schedule to better fit the work breakdown structure and the activity naming protocol previously discussed. Dates have been collected from both the pictures and the Metropolitan Water Board Records. Currently, the main focus is on the pictures, but since they take longer to analyze, this focus will remain into next week.

Some other goals that we have for next week are to finish the methods section to correspond with the work already completed and to finish analyzing the images that we currently have. This will allow us to find dates for many of the activities. We also will be able to use knowledge gained during the field trip to improve our methodology and background sections.

September 28-October 3

This week involved going on a field trip to the Wachusett Dam. This allowed our group to learn more and put the dam into perspective in regard to size and strength. While on the field trip, we were able to learn more from Professor Marrone about his research and the construction process. Some other research that has been done this week has been minor research into the activities that we still do not have dates for. The reason that this research was minor is that the main focus has been in regard to the formatting of the schedule. We have been trying to figure out how to include the citations in the schedule.

Some goals that we have for next week are to continue adding to the methods section as we research more as well as to fully fill in all citations on the schedule.

October 4-11

The main progress this week was with organization. This included organizing the paper as a whole as well as organizing the spreadsheet used to track dates. This spreadsheet will be our main source of organization as we will be compiling information here before anything is uploaded to primavera. This will allow us to clearly recognize what dates we still need to find. This week we also added to the methods section and included columns in the spreadsheet to start tracking resources and costs of the activities. This will be helpful later in the project.

Goals that we have for next week are to continue finding dates and making adjustments to the report. This will ensure that we are on the right track.

October 25-October 31

The progress this week consisted mainly of working on the structure of the report. This was a main focus because having a good structure will be beneficial as we continue adding information. We also focused on finding resources and additional dates for the schedule. Switching to an excel spreadsheet to keep track of this information has been very beneficial. We have also started thinking more about our capstone component.

Our goals for next week are to include more information in the methods section and continue adding dates and resources to the excel spreadsheet.

November 1-7

The progress this week built off of the previous work with Prof. Marrone. This work related to finding additional dates. There was not much progress on the paper since the group did not receive comments from the advisors. The work completed mostly involved expanding the sections that had been previously established.

Our goals for next week are to continue to look for dates and resources. We also would like to work on the paper more. Receiving comments from the advisors would help in this process.

November 8-14

The progress this week continued to focus on recording the last of the dates in the spreadsheet that has been utilized for organizational purposes. The comments received from the advisors were addressed and additional work was completed on sections 6 and 7.

The goals for next week are to finish collecting dates and prepare for the presentation. Once we receive the slides for the presentation, we will be able to further prepare for it.

November 15-21

This week most involved preparing for the presentation that will be in two weeks. This preparation involved creating a recording of each individual part, which will be merged prior to the first practice presentation.

The goals for next week are to plan out the capstone and further prepare for the presentation.

November 22-December 5

The progress this week included preparation for the presentation on December 10th. This preparation not only included individual preparation, but also a group practice presentation. The other progress involved finishing the excel sheet related to the construction schedule.

The goals for next week are to plan for C term and to put the construction schedule into Primavera.

December 6-13

The progress this week was focused on the paper. Some efforts were also dedicated to preparing to complete the capstone area of this project. The paper has been improved each week, but more progress was completed this week then in past weeks. This week also focused on the presentation.

The next few weeks are break, so we are planning on addressing any comments made on the paper and working on the capstone portion. We also intend to export the entire schedule to primavera.

December 13-January 17

During this time period, the focus was on improving the paper and understanding the tasks that needed to be completed before the project was complete. This preparation allowed for detailed questions to be asked at the first meeting of the term. Another large section of progress was finishing the original construction schedule. This still needs to be documented in the paper, but the primavera schedule was completed.

January 17-23

This week a large portion of the work was dedicated to the modern construction schedule. This portion of the work involved research and calculation in order to determine how the excavation would have been done today. It also involved documenting this process in the modern construction schedule section of the paper. This week we also got a better understanding of what was expected for the capstone development. This allowed us to refine the C term plan.

The goals for next week are to continue making substantial progress so that we can get a head start on the work for the term.

January 24-30

This week, progress was made on both the capstone and modern construction sections of the project. Both sections required more adjusting time than expected, but more work is being put into each section each week.

The goals for next week are to finish the modern construction section and make progress on the capstone section.

January 31-February 6

This week focused on a better understanding of the capstone portion of the project. This involved meeting with Prof. Mathisen in order to get a better idea of how to break down the hydrology calculations. By doing this, we were able to make more progress on the capstone portion of the paper.

The goals for next week include making additional progress on the capstone section of the project as well as addressing the comments given by the advisors.

February 7-13

This week a large portion of the progress focused on finishing the paper and the capstone portion of the project. These are some of the final steps in completing the project.

The goals for next week are to completely finish these two sections and also work on the executive summary.

February 14-20

This week focused on finishing all calculations and finishing the first draft of the paper. The term is almost over, so next week is going to be focused on finishing the paper and making any adjustments necessary.

**Appendix B: Field Trip Reports**

On September 28, 2019, both teams working on the Wachusett Dam MQP traveled to the dam itself along with the surrounding areas in order to get a better understanding of the size of the construction and the number of projects that contributed to the construction process. One main thing learned on this trip was more information about the Aqueduct and surrounding water areas. These include both the North and South Dike. Along with this information, we also learned about the placement of the railroad as well as other structures in the area.

Traveling to the site was helpful because it allowed us to put the size into perspective and get a better understanding of the layout of the construction. Before visiting the dam, we were unaware exactly where the North and South Dike were located in respect to the dam or the size of the dam itself. As much as the images and reports are helpful, visiting in person allowed us to understand the project better and ask any questions that we needed to. Shown in Figures 44 through 46 are pictures of the dam from the trip.

Figure 44: The Wachusett Dam Pond

The image in Figure 44 shows the pond in front of the dam itself. Seeing this was helpful because it allowed us to get a better idea of the size of all of the features in the dam. Figure 45 shows the view from on top of the dam. Without going on top of the dam, or at least near it, it is hard to really know how wide it is. Measurements can give an idea but being there puts it into perspective.

Figure 45: On Top of the Dam

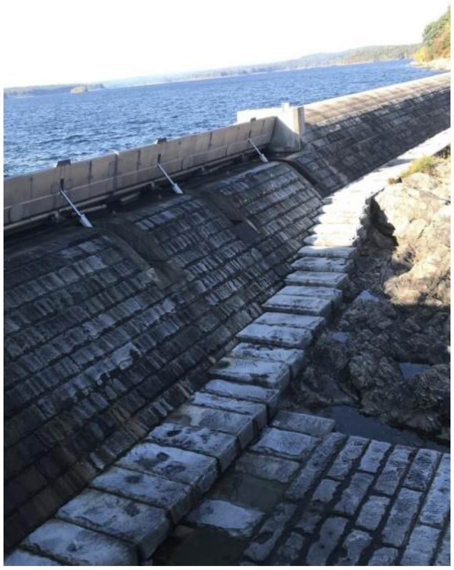


Figure 46: The Spillway

Figure 46 shows the spillway and the water in the reservoir. This was a very interesting thing to see on this field trip. We had not read much about the spillway or seen many details about it before visiting the dam, so we did not know what to expect.

On November 5, 2019, both teams returned to the dam to see how the dam functions and learn more about the dam in general. The general information learned was about the generators, the upper gate, how the water level is raised, and the use of gravity. This information provided a better insight on the project scope and how exactly each activity should be organized. Some figures are included below to help showcase the area of the dam that was toured.

Figure 47: Inside Look 1

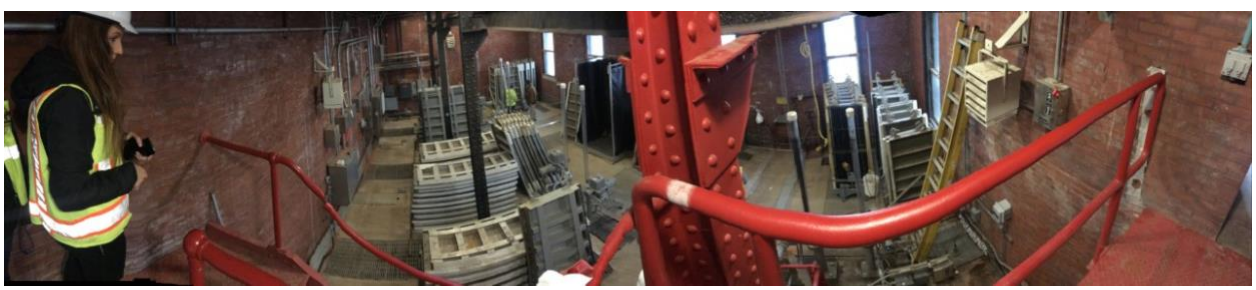


Figure 48: Inside Look 2

Both of the figures showcase the age of the dam and the technology that was used to construct the dam. Although this technology is not a part of the research conducted for this paper, it is interesting and contributes to the capstone design. One area where this field trip helped was in the analysis of the hydraulic aspects of the dam. Understanding the way, the turbines were set up was very helpful when reading the plans.

**Appendix C: Preliminary Research Table**

Notes from the Metropolitan Water Board Annual Reports:

These notes were used to start planning out the construction schedule.

| Date: | What Happened: | How long it lasted? |
|---|---|---|
| 1893 | The state legislature ordered the state board of health to make recommendations about how to increase the water supply | |
| 1895 | report (prepared by Chief Engineer Frederick P. Stearns) showed Boston was consuming nearly 80 million gallons of water a day even though the capacity of the current system was only 83 million gallons a day | |
| June 5, 1895 | Stearns Plan: construction of a dam on the Nashua River at Clinton that would create a reservoir that could hold 63 billion gallons of water. (adopted) | |
| 1898 | Building of the temporary dam | Completed in February 1898 |
| March 7 1898 | Gates to the temporary dam were opened | - |
| March 7 1898 | Last 3 miles of the open channel of the Wachusett Aqueduct were completed | |
| June 22 1898 | Act was passed saying that intercepting sewers should be built from the outlets to a point in the northerly part of Clinton adjoining High Street and the river (receiving basin should be built and a pumping station erected) | |
| 1898 | Considerable work was done to provide supplies of water to those who had wells or springs damaged by the construction of the aqueduct | |
| 1898 | Wachusett Aqueduct was substantially completed. Only a small amount of attention was needed in 1899. | 1899 |

| | | |
|---|---|---|
| | (digging of additional well and the extension of the pipeline) | |
| 1899 | Borings have been made near the site | |
| 1899 | The flume has been extended to cover the entire site of the dam | |
| 1899 | Considerable rock excavation in the bed and at the sides of the river has been made to obtain a suitable foundation for the dam (it has not been carried to as great a depth as it should) | |
| 1899 | Some of the quarries upon land of the Commonwealth near the dam have been opened (may be using stone from them for the construction) | |
| Early 1900 | The main features of the dam were decided upon. | |
| August 1900 | Plans for the dam were completed | |
| Early July 1900 | Day-labor force was organized and kept at work until the contract for the construction had been made | |
| Middle of October 1900 | Contractors have been working | |
| October 1 1900 | Contract was made with McArthur Brothers Company of Chicago (lowest of 11 bidders) | Stated contract should be completed on or before November 15, 1904 |
| 1901 | Progress has been made on the creation of air-compressor plant (building of cableways and installation of other portions of the plant for carrying on the necessary work of excavation) | |
| Early 1901 | Compressor plant completed | |
| | Progress of opening quarry and removing stone to be used in the construction of the dam | |

| | | |
|---|---|---|
| June 5 1901 | First stone was placed | |
| By the end of 1901 | Stone had been placed up to 40 feet above the rock bed | |
| January 25, 1901 | Wachusett Aqueduct began operation | |
| June 24, 1905 | Last stone was placed on the dam | |

**Appendix D: Notes on Photos from Construction**

These photos can be accessed on the Digital Commonwealth Website:
https://www.digitalcommonwealth.org/search?utf8=%E2%9C%93&search_field=all_fields&q=wachusett+dam

Picture 1416: (Dec 16, 1897)

- Placement of Flume 1 (large) structure is already in place
- Erection of Gate House for Large Flume still under construction
- Coffer Dam finished or almost finished (ppl in the background make me believe they might still be working on soil fill
- Centrifugal pump + gate for it in place
- What is that tank and ladder/tower? Pile driver?
- Platform from boiler to other end has been constructed

Picture 1422: (Dec 18, 1897)

- Gate house of Flume 1 looks done
- Boiler and Boiler room done? Far right side
- Structure of Flume 2 (small) is in place

Picture 1423: (Dec 18, 1897)

- Flume 2 (small) is not connected to aqueduct yet
- What is the stack pile of wood right on top of Flume 1's entrance?

Picture 1424: (Dec 18, 1897)

- Men in shovels on the far side of the picture. What does that mean?

Picture 1540: (Mar 14, 1898)

- Flume 2 (small) looks done + gate house above
- Temp Conduit/pipe installed

Picture 2964: (Nov 13, 1899)

- Extension of Main Flume (Flume 3 & 4?)
- Requires excavation that has been started

Picture 2965: (Nov 13, 1899)

- Extension being built from left and right and in between there is granite? That needs to be excavated

Picture 2967: (Nov 13, 1899)

- Power lines in the picture

Picture 2968: (Nov 13, 1899)

- Excavation of granite with steam pumpset?

Picture 2971: (Nov 16, 1899)

- Excavation still done with horses

Picture 2972: (Nov 16, 1899)

- Main flume with timber support
- Excavation of granite
- Cableway system in the picture

Picture 2974: (Nov 16, 1899)

- Excavation of granite with cableway system and box to place soil load in
- Boom lift on site?

Picture 3080: (Nov 20, 1899)

- Timbering in cut-off under main flume (Dec 20, 1899)

Pictures 3106 - 3111: (Mar 2, 1900)

- Main Flume 3 & 4 extension finished

Picture 3334: (Jul 25, 1899)

- Excavation at main dam site
- A lot of horses and men

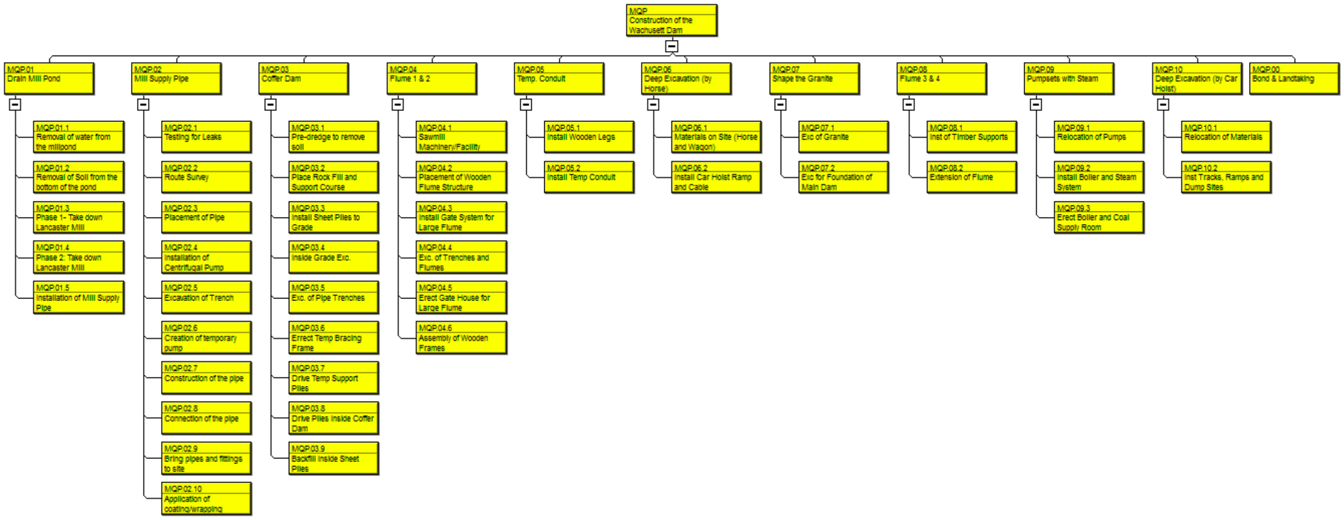
Picture 3337: (Jul 25, 1899)

- What are they dumping in the water with the cart?

Picture 3484: (Sep 08, 1900)

- Pump has been relocated along with boiler and steam system

## Appendix E: Work Breakdown Structure

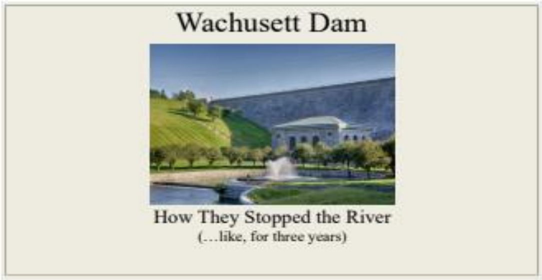


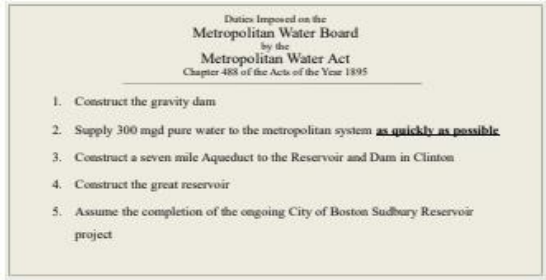
**Appendix F: Citation Organization**

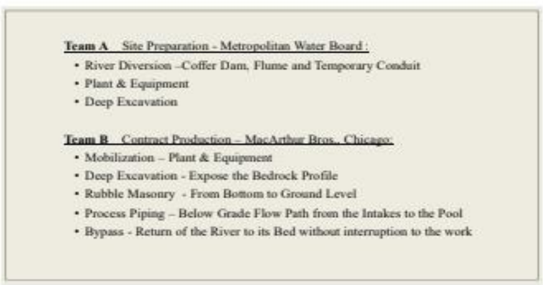
| Internal (Annual Reports and Photos): | External (Websites): |
|---|---|
| Massachusetts. (2016, December 27). Annual report of the Metropolitan Water Board. c.1 v.4 1898. Retrieved from https://babel.hathitrust.org/cgi/pt?id=chi.100868069&view=1up&seq=9 | 1897 - Wachusett Reservoir. (n.d.). Retrieved from http://www.mwra.com/04water/html/hist4.htm |
| Massachusetts. (2016, December 27). Annual report of the Metropolitan Water Board. c.1 v.5 1895. Retrieved from https://babel.hathitrust.org/cgi/pt?id=chi.100868124&view=1up&seq=7 | Clark, C. (2019, August 21). Learn Wachusett Dam's history. Retrieved from https://www.nashobavalleyvoice.com/2019/08/12/learn-wachusett-dams-history/ |
| Massachusetts. (2019, June 4). Annual report of the Metropolitan Water Board. c.1 v.3 1897. Retrieved from https://babel.hathitrust.org/cgi/pt?id=chi.100868001&view=1up&seq=7 | "DWORSHAK RESERVOIR PROJECT MASTER PLAN ." U.S. Army Corps of Engineers, U.S. Army, June 2015, www.nww.usace.army.mil/Portals/28/docs/dworshak/Dworshak%20Master%20Plan%20Final%207-9-15%20.pdf |
| Photograph, Wachusett Dam Construction, June 20, 1898: Exhibits: Institute Archives & Special Collections. (2003, July). Retrieved from https://libraries.mit.edu/archives/exhibits/wachusett/index.html | History of Wachusett Dam program is Sept. 7. (2019, August 20). Retrieved from https://www.telegram.com/item/20190820/history-of-wachusett-dam-program-is-sept-7 |
| | Kempe, M. (n.d.). Chapter 2 – The Search for Water – Growth and Water Source Development. Retrieved from http://www.mwra.state.ma.us/04water/html/historypaper/ch2.pdf |
| | Lieb, Anna. "The Undamming of America." PBS, Public Broadcasting Service, 12 Aug. 2015, www.pbs.org/wgbh/nova/article/dam-removals/. |
| | Marchione, W. P. (n.d.). Water for Greater Boston. Retrieved from |

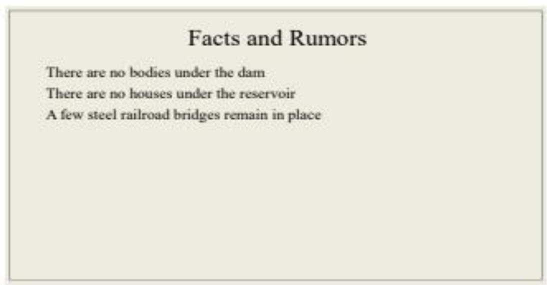
| | |
|---|---|
| | http://www.bahistory.org/HistoryWaterForBoston.html |
| | Wachusett Dam - 100 Years Old. (2006). Retrieved from https://archives.lib.state.ma.us/bitstream/handle/2452/41011/ocm48880163-12.pdf?sequence=1 |

## Appendix G: Presentation Slides



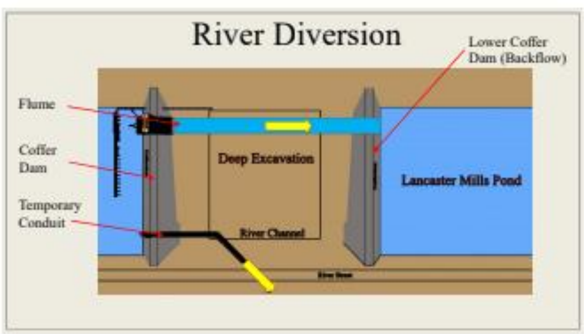



Moderator – Site Preparation

Our first speaker is STUDENT, will tell us about the substantial amount of work that was required to prepare the site for construction.

Until such time as a general contract could be prepared and to **gain on the Schedule**, the Metropolitan Water Board (MWB, or the Board) undertook to drain the millpond to provide a dry workspace, erect a large flume to carry the river waters safely past the workspace and to fulfill its mandate to provide Metropolitan Area with pure river water as early in the project as possible.

In the event, it became necessary for the Board to begin deep excavations with its own forces



Lancaster Mills Dam

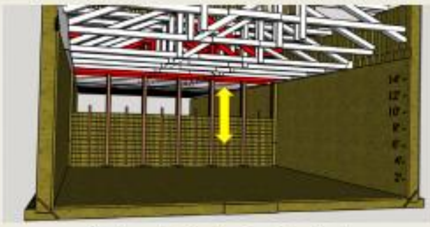
"In order to construct the temporary dam and to make the connection with the aqueduct, it was necessary to **down the dam** of the Lancaster Mills"
*Annual Report 1897*

Downed Lancaster Mills Dam 1897


Drained Lancaster Mills Pond


The Whole Flume (700 Feet Long)

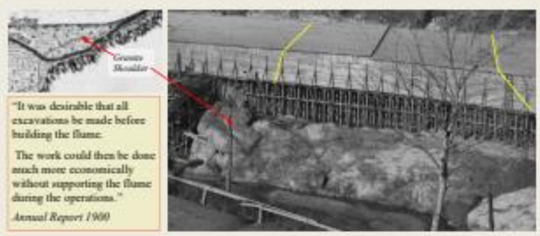

Flume Gatehouse (Low Water)



Gatehouse Interior showing Stop Planks

Removing Unsuitable Granite at Section 3


Flume, Section 4 built before Section 3




High Granite Profile Cleaned Before Building the Flume

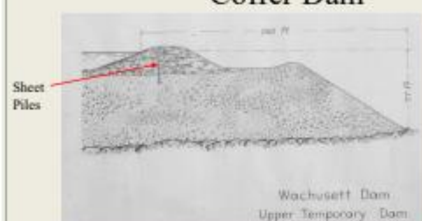
Flume Intake at Springtime High Water

Moving pretty fast

The River in a Box


Temporary Conduit provided Water to Metropolitan Area

# Coffer Dam




"A temporary dam has been constructed, just above the site of the great dam to be built, which is not only a necessary preliminary to the construction of the great dam, but is also sufficient to enable the diversion of the water of the river into the Wachusett Aqueduct."

*Annual Report 1897*


Upstream Coffer Dam


"The completion of the protective work at the main dam required the extension of the large flume about 500 feet, and the construction of a second dam of earth across the valley a short distance above the lower end of this flume, to protect the excavations for the main dam from **backwater**."

*Annual Report 1900*

Downstream Coffer Dam

Project Milestone - First Full Flow to Aqueduct 3.07.1898

Moderator - Deep Excavation

Finally, after all the preparation, a serious effort at deep excavation (and I mean deep) could be undertaken.

This task, undertaken by the Board and later taken up by the a contractor, involved the removal of all loose soils under the riverbed to expose the bedrock on which the was founded,

Our next STUDET will explain this important process.

# Deep Excavation

Rock Profile

High Granite

Initial Excavation of Riverbed by Team & Wagon 7.25.1900

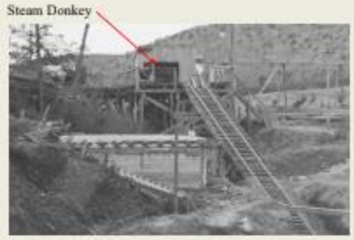
Teamster

Teams & Wagons to 25 Feet Depth

"W" Pattern of Tracks Gains Access to the whole excavation

Power Assisted Hoisting Ramp (20% slope)

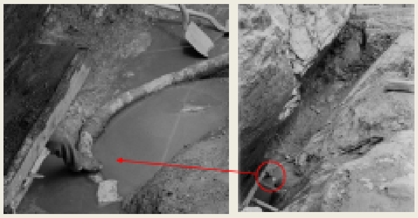

Power Assisted Hoist (+20%) atop Temporary Conduit




Power Assisted Car Hoist to 50 Feet Depth


Cableway Used to Reach Bottom on Excavation, 80 Feet Depth


Granite Interface with Schist 4.12.1901



Inclined Shaft (**the bottom**)

Moderator - Bypass

The problem of removing the wooden flumes passing through the structure while maintain control of the river remained

A scheme was devised to turn the river, without interruption, through the newly installed pipes back into the millpond

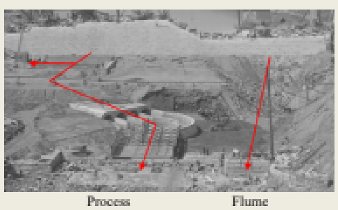
Our final speaker STUDENT will explain how this complicated task was accomplished.

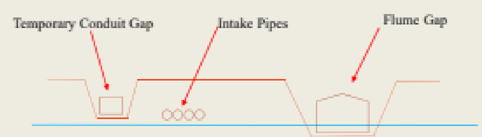
# Bypass Scheme

"After March 28 the surplus water of the river was, as far as possible, discharged through the **pipes** or the Wachusett Aqueduct, instead of through the gap in the dam.

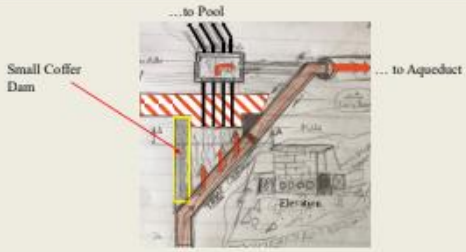
No water passed through the gap after April 11."

*Annual Report 1903*




Gaps in the Rubble Masonry




Temporary Conduit Bypass Scheme

Small Coffer Dam at Intakes

Bypass Scheme in Operation

"Water is introduced into the aqueduct by way of the pipes carried through the dam and the lower gate chamber.

The overflow from the river **passes over a portion of the dam,** which has been carried to a less height than the remainder of the structure.

The height of the water upstream is still regulated by the Gatehouse."

*Annual Report 1903*

Flow Across Rubble Masonry at Flume Gap

The Flume Gap and the Lancaster Mills Supply Pipe

Lancaster Mills Supply Pipe <u>Rerouted</u> through Lower Gate Chamber

Lancaster Mills Supply Pipe – Support Masts

Outer Pool (Radius 75 Feet)

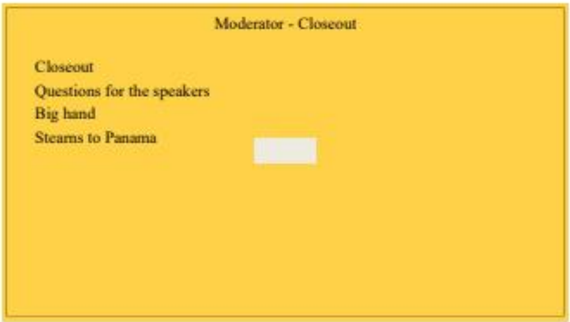

Pool, Weir and Erosion Control Apron 12.01.1903

Velocity in Pool (0 Ft/Sec) 4.08.1904

5.06.1919

With thanks to the staffs at the Metropolitan Water Resource Authority (MWRA) and the Department of Conservation and Recreation (DCR) for their continuing cooperation and assistance...

…and special thanks to
Mr. Frederic P. Stearns,
Chief Engineer,
whose genius remains
with us today


Moderator - Closeout
Closeout
Questions for the speakers
Big hand
Stearns to Panama


Your Speakers…
…in order of appearance
Kevin, Becca, Julia, Emma and Samantha
Thanks for having us

# Appendix H: Excavation Calculations

| Materials: | | | | | |
|---|---|---|---|---|---|
| **Material** | **Depth** | **Bank Volume** | **Load Factor** | **Swell %** | **Loose Volume** |
| Rock | 13 feet | 131,270.68 cubic yards | | 49.25373134 | 195821.4899 |
| Clay and gravel | 20 feet | 273,868.11 cubic yards | 0.85 | 17 | 320425.6887 |
| Sand and gravel | 30 feet | 603,703.15 cubic yards | 0.89 | 12 | 676147.528 |
| First 15 feet of sand and gravel | 15 feet | 340,509.122 cubic yards | 0.89 | 12 | 381370.2166 |
| | | 1008841.94 | | | 1192494.707 |

Assumptions: 50 minute hours, 83% job efficiency, 100% operator efficiency

| Equipment | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Equipment** | **Loose CY per Bucket** | **Number of Passes** | **CY per Truck** | **Portion of Excavation** | **Volume of Material** | **Productivity Rate** | **Total Daily Volume** | **Dump Truck Trips/day** | **Number of Dump Trucks** | **Number of Equipment** | **Adjusted Daily Volume** | **Number of days per Activity** | **Dump Truck Time per Activity** | **Dump Truck Time without overlap** | **Total Time per Activity** | **Rounded Time** |
| Dump Trucks | 4 | 3 or 4 | 12 (rock) or 16 | sand and gravel | 676147.528 | | | | | | | | | | | |
| Backhoe | 4 | | | (first 15 feet) | 381370.2166 | 365 CY/hour | 2920 | 182.5 | 16 | 7 | 20440 | 18.65803408 | 347.603562 | 19.31128122 | 37.96931531 | 34 |
| Power Shovel | 4 | | | sand and gravel | 294777.3114 | 460 CY/hour | 3680 | 230 | 16 | 7 | 25760 | 11.44321861 | 269.6772369 | 14.93651316 | 26.36973177 | 27 |
| Power Shovel | 4 | | | clay and gravel | 320425.6887 | 375 CY/hour | 3000 | 187.5 | 16 | 7 | 21080 | 15.25838613 | 282.0548642 | 16.22525912 | 31.48362525 | 32 |
| Loading Tractors (Wheel Loaders) | 8 | | | rock | 195821.4899 | 520 CY/hour | 4160 | 346.6666667 | 16 | 6 | 24960 | 7.849418666 | 232.4303083 | 12.91277924 | 20.7621949 | 21 |
| Drill | | | | | | | | | | | | | | | 61.24985842 | 62 |
| | | | | | | | | | | | | | | | Total Time: | 186 |
| | | | | | | | | | 48 | | | | | Dump Truck Time: | 63.37582175 | |
| | | | | | | | | | | | | | | | Dump Truck and Excavation can happen at the same time: | 132.6241683 |

133 days

| Timing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Timing** | **Amount of Material** | **Time per pass** | **Haul Distance** | **Time for Haul (9min/mi)** | **Dump Time** | **Return time (7 min/mi)** | **Spot under machine** | **Portion of Excavation** | | |
| Dump Truck | | 30 seconds | 1 mile | 9 | 2 minutes | 7 | 1 minutes | All | 21 | minutes per 16 CY of sand/gravel/day |
| | | | | | | | | | 20.5 | minutes per 12 CY of rock |

| Drilling | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Depth (ft)** | **Penetration Rate (ft/min)** | **Drilling Time (min)** | **Change Steel (min)** | **Blow Hole (min)** | **Move to Next Hole (min)** | **Align Steel (min)** | **Change Bit (min)** | **Total Time(min) per hole** | **Operating Rate (ft/min)** | **Production Efficiency (min/hr)** | **Hourly Production (ft/hr)** | **Daily Production (holes)** | **Number of Holes Needed** | **Number of Days** | **Hole Diameter (mm)** | **Burden (ft)** | **Spacing (ft)** |
| Downhole Drill 600 cfm @250 psi | 16 | 1.166666667 | 13.71428571 | 2.6 | 0.1 | 0.36 | 1 | 4 | 21.77428571 | 0.7348117045 | 50 | 36.74058523 | 18.37029261 | 2985.167355 | 162.4997172 | 72 | 9.4464 | 10.86336 |
| | | | | | | | | | | | | | | | | Length and Width | 47.05735518 | 63.43678567 |
| | | | | | | | | | | | | | | | | | Number of Holes | 2985.167355 |

# Appendix I: Hydraulic Calculations

| Point | Diameter of Pipe (ft) | Length of Pipe Section (ft) | Area (ft^2) | Velocity (ft/sec) | Flow | | | | | | Material | Equivalent Roughness (E) (ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Start | | | | | | | Gallons/day | Gallons/sec | ft^3/sec | | Brick | 0.001 |
| Brick Inlet (7') | 7.00 | 111.00 | 38.48 | 6.03 | 232.09 | | 150000000.00 | 1736.11 | 232.0961 | | Cast Iron | 0.00085 |
| 48" Cast Iron Pipe | 4.00 | 91.00 | 12.57 | 18.47 | 232.09 | | | | | | Commercial Steel | 0.00015 |
| 48" Cast Iron Pipe (First Valve + Aqueduct) | 4.00 | - | 12.57 | 9.23 | 116.04 | | Gravitational force (ft/sec^2) | 32.17 | | | Concrete | 0.001 |
| 48" Cast Iron Pipe (After valve and aqueduct) | 4.00 | 7.00 | 12.57 | 9.23 | 116.04 | | | | | | | |
| 48" to 60" Increaser | 5.00 | 12.00 | 19.63 | 5.91 | 116.04 | | Density of Water (60F) (lbs/ft^3) | 62.42 | | | | |
| Tee Line | 5.00 | 0.00 | 19.63 | 5.91 | 116.04 | | | | | | | |
| Tee Branch | - | - | - | - | - | | | | | | | |
| 60" to 48" Reducer (After Branch) | 4.00 | 12.00 | 12.57 | 9.23 | 116.04 | | | | | | | |
| End 48" Reducer to End of 48" Hyd. Valve | 4.00 | 16.00 | 12.57 | 9.23 | 116.04 | | | | | | | |
| 48" Hyd. Valve to beginning of steel increaser (54") | 4.50 | 6.50 | 15.90 | 7.30 | 116.04 | | | | | | | |
| Steel Increaser (54" to 96") | 8.00 | 48.00 | 50.27 | 2.31 | 116.04 | | | | | | | |
| Concrete Conduit | 10.00 | 145.00 | 78.54 | 1.48 | 116.04 | | | | | | | |
| **Conduits Under Pool** | | | | | | | | | | | | |
| **Conduit No. 2 & 3** | | | | | | | | | | | | |
| Section g | 10.00 | 10.00 | 78.54 | 1.00 | 38.33 | 77.98 | 25.79 | | | | | |
| Section h | 8.59 | 10.00 | 57.95 | 0.79 | 32.22 | 45.77 | | | | | | |
| Section k | 8.35 | 10.00 | 54.67 | 0.00 | 8.64 | | | | | | | |
| Section m | 7.00 | 8.00 | 38.48 | 0.00 | -18.34 | | | | | | | |
| Section n | | | 0.00 | | -42.55 | | | | | | | |
| | | | 0.00 | | | | | | | | | |
| **Conduit No. 1 & 4** | | | | | | | | | | | | |
| Conduit No. 4 | 9.00 | | 63.62 | | 0.00 | | | | | | | |
| | | | 0.00 | | 0.00 | | | | | | | |
| End (pool) | - | - | - | - | - | | | | | | | |

Bernoulli's Equation

| Description | Pressure 1 (lbs/ft^2) | Density (lbs/ft^3) | Velocity 1 (ft/sec) | Gravitational Force (ft/sec^2) | Height 1 (ft) | Pressure 2 (lbs/ft^2) | Velocity 2 (ft/sec) | Height 2 (ft) | Major Head Loss (lbs*ft/sec^2) | Reynold's Number | Friction Factor f | Minor Head Loss (ft) | Relative Roughness (ft) | Length (ft) | Dynamic Viscosity (μ) (60F) | E/D | Loss Coeff. for Pipe Components (K) | Change in Pressure (lbs/ft^2) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1st Drop from Upstream | 0.00 | 62.42 | 0.00 | 32.17 | 285.00 | 219858.42 | 6.03 | 284.00 | 0.1165 | 82035881.25 | 0.013 | 0.84150877 | 0.001 | 111.00 | 0.000032 | 0.00014 | 1.5 | 1936.171331 |
| 48" Cast Iron Pipe | 219858.42 | 62.42 | 6.03 | 32.17 | 284.00 | 207321.76 | 18.47 | 284.00 | 1.0828 | 144101917.7 | 0.014 | 0 | 0.00085 | 91.00 | 0.000032 | 0.00021 | 0 | 3017.898942 |
| 48" Cast Iron Pipe (@ Valve & Aqueduct) | 207321.76 | 62.42 | 9.23 | 32.17 | 284.00 | 206822.55 | 9.23 | 284.00 | 0.0000 | 72050958.87 | 0.0135 | -0.1981770379 | 0.00085 | 0 | 0.000032 | 0.00021 | 0.15 | 399.2058473 |
| 48" Cast Iron Pipe (After valve and aqueduct) | 206922.55 | 62.42 | 9.23 | 32.17 | 284.00 | 206858.74 | 9.23 | 284.00 | 0.0313 | 72017375 | 0.0135 | 0 | 0.00085 | 7.00 | 0.000032 | 0.00021 | 0 | 62.81581341 |
| 48" to 60" Increaser | 206858.74 | 62.42 | 9.23 | 32.17 | 284.00 | 206394.24 | 5.91 | 284.00 | 0.0171 | 57640767.89 | 0.0131 | 0 | 0.00085 | 12.00 | 0.000032 | 0.00017 | 0 | 34.27268286 |
| Tee Line | 206394.24 | 62.42 | 5.91 | 32.17 | 284.00 | 207413.18 | 5.91 | 284.00 | 0.0000 | 57639736.57 | 0.0131 | -0.4884891525 | 0 | 0.00 | 0.000032 | 0.00017 | 0.9 | 981.0535558 |
| 60" to 48" Reducer | 207413.18 | 62.42 | 5.91 | 32.17 | 284.00 | 205734.18 | 9.23 | 284.00 | 0.0537 | 72049470.71 | 0.0135 | 0 | 0.00085 | 12 | 0.000032 | 0.00021 | 0 | 107.7817517 |
| End 48" Reducer to End of 48" Hyd. Valve | 205734.18 | 62.42 | 9.23 | 32.17 | 284.00 | 205191.28 | 9.23 | 284.00 | 0.0716 | 72049470.71 | 0.0135 | -0.1981708303 | 0.00085 | 16.00 | 0.000032 | 0.00021 | 0.15 | 542.9806754 |
| 48" Hyd. Valve to beginning of steel increaser (54") | 205191.28 | 62.42 | 9.23 | 32.17 | 284.00 | 205159.22 | 7.30 | 284.00 | 0.0159 | 68044151.74 | 0.0133 | 0 | 0.00085 | 6.50 | 0.000032 | 0.00019 | 0 | 31.91777498 |
| Steel Increaser (54" to 96") | 205159.22 | 62.42 | 7.30 | 32.17 | 284.00 | 219892.98 | 2.31 | 276.50 | 0.0035 | 38024835.35 | 0.0085 | 0 | 0.00015 | 48.00 | 0.000032 | 0.00002 | 0 | 7.369016211 |
| Concrete Conduit | 219682.80 | 62.42 | 2.31 | 32.17 | 276.50 | 232795.32 | 1.48 | 276.50 | 0.0059 | 28914380.74 | 0.012 | 0 | 0.001 | 145.00 | 0.000032 | 0.00010 | 0 | 11.83228275 |
| **Conduits Under Pool** | | | | | | | | | | | | | | | | | | |
| Section g to h | 219682.80 | 62.42 | 2.31 | 32.17 | 276.50 | 232795.32 | 1.48 | 276.50 | 0.0059 | 28914380.74 | 0.012 | 0 | 0.001 | 10 | 0.000032 | 0.00010 | 0 | 11.83228275 |