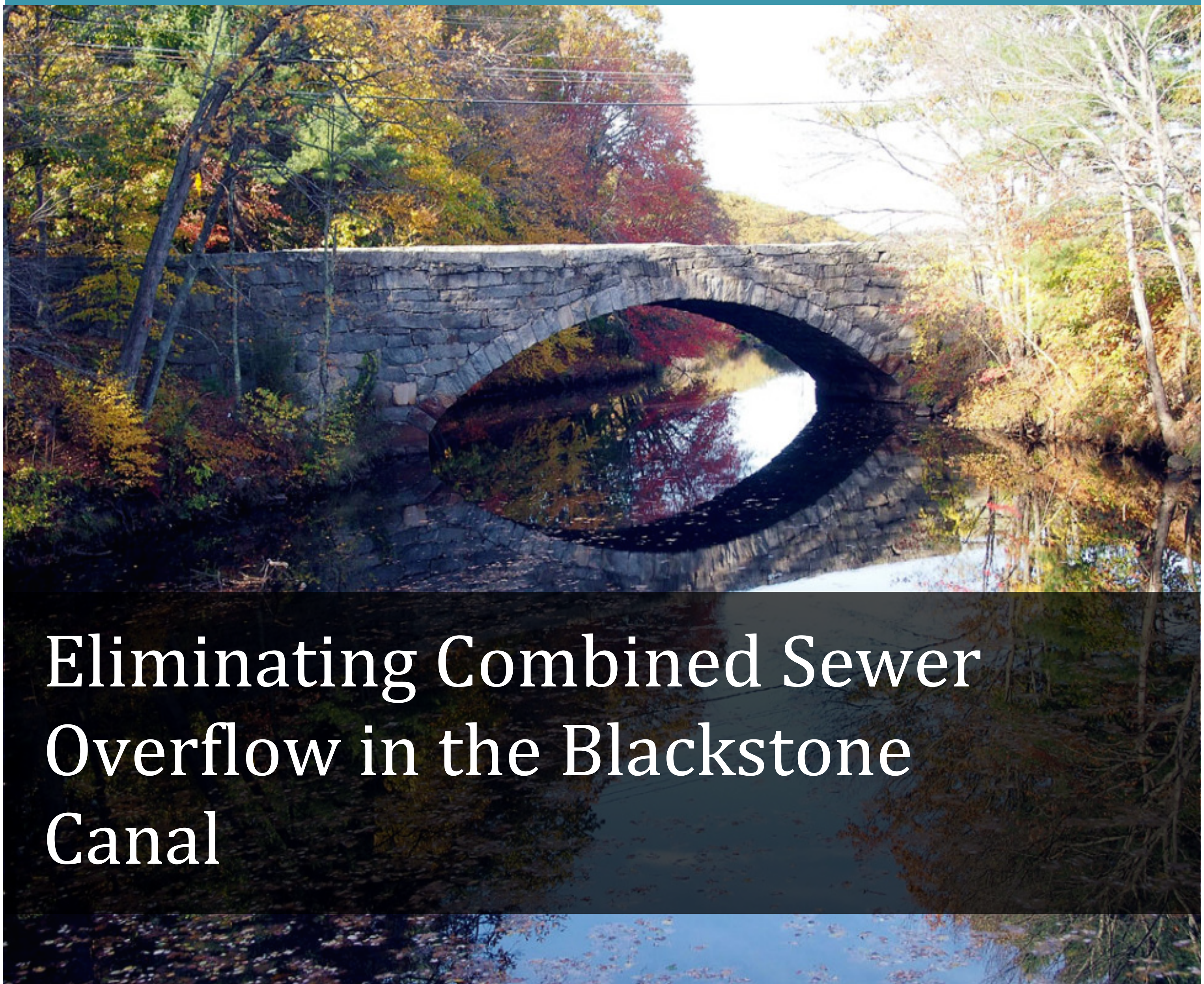


Eliminating Combined Sewer Overflow in the Blackstone Canal

By Chelsea Costa, Paula Miller, Dante Pace, and Victoria Scott

Sponsor:
Blackstone Canal District Alliance

Advisors:
Professors Ángel Rivera and Robert Traver
Worcester Polytechnic Institute

Eliminating Combined Sewer Overflow in the Blackstone Canal

An Interactive Qualifying Project Report
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in Partial Fulfillment of the Requirements for the
Degree of Bachelor of Science

March 5, 2015

Written by:
Chelsea Costa
Paula Miller
Dante Pace
Victoria Scott

Project Advisors:
Angel Rivera
Robert Traver

Sponsored By:
The Blackstone Canal District Alliance

Abstract

The Blackstone Canal District Alliance seeks to replicate or restore the Blackstone Canal. The project explored canal conditions and its role in the combined sewer system. Analysis of public works documents and interviews generated four scenarios to separate the canal from the sewer system: 1) separate the segment and add retention basin: \$5 million; 2) separate the segment and add treatment shaft: \$15 million; 3) separate the entire canal: \$17.5 million; 4) a complete separation of CSS: \$208 million.

Acknowledgements

This project could not have been completed without help from many people. We would like to thank Matthew Labovites and David Harris of the Department of Public Works and Parks for supplying us with invaluable information, and for answering our numerous questions. David Kubiak of the Massachusetts Water Resource Authority provided us with previous projects similar to ours and offered a new perspective on how to solve our problem. We would also like to acknowledge Professors Jeanine Plummer and Paul Mathisen for helping us interpret our collected data. Finally, we want to thank our advisors, Angel Rivera and Robert Traver. They have been a vital resource when we needed to take a step back and look at the bigger picture.

Table of Contents

Table of Figures

Executive Summary

The Blackstone Canal District Alliance is planning to construct, or reconstruct, the Blackstone Canal and use it as a water feature that will run through the Canal District. To move along with their proposals, the Alliance needs to know whether or not unearthing and restoring the canal is feasible. A restoration might be more costly than a replication, but it will preserve a historic landmark and serve as a tourist attraction.

The Blackstone Canal was constructed in the 1820's to connect Worcester to the Blackstone River and Providence, Rhode Island. For twenty years, the canal served as a source of power and transportation, and transformed Worcester into the birthplace of the American Industrial Revolution (Canal District Alliance). After years of innovation, the canal was decommissioned, and its concealment commenced in 1848. The canal had become an open sewer, due to industrial runoff and sewage entering it from several sources. The introduction of the Providence-Worcester Railroad also caused the canal to become an obsolete mode of transportation of goods and services.

The Blackstone Canal District Alliance, a group of local leaders devoted to the development of the Canal District, have considered utilizing the Blackstone Canal as a water feature to bring new businesses into the Canal District. The Alliance completed a feasibility study in 2003 on the replication of the canal, but they also want to determine feasibility of restoring the canal.

In order to unearth and restore the canal, it needs to be separated from the combined sewer system. The goal of this project was to determine the feasibility of separating the canal from the combined sewer system and eliminating combined sewer overflow, or CSO. In order to achieve this goal, three objectives were formulated. The first objective sought comprehensive understanding of the current combined sewer system and the physical conditions of the canal. Second, regulations regarding CSO and several case studies were researched. The final objective was to develop a simple feasibility study outlining the costs and benefits of removing the canal from the combined sewer system.

Through research, a broad understanding of the current combined sewer system and of how the canal functions as a combined sewage collector was obtained. Not only does it serve as a conduit for combined sewage during wet weather conditions, but there are also live sewage lines connecting directly to the canal, creating flow during dry weather. On a normal day, approximately 200,000 gallons of combined sewage flows through the canal. The flow is directed to the Quinsigamond Avenue Combined Sewer Overflow Treatment Facility (QACSOTF), and ultimately treated at the Upper Blackstone Wastewater Treatment Facility (UBWWTF). During severe weather conditions, the QACSOTF enters a preliminary treatment mode, disinfecting the water with chlorine before discharging into the Blackstone

River (Harris, 2015). Underneath Grabowski Square, the Mill Brook Conduit, which is a stormwater drainage conduit, passes by the canal, also known as Old Mill Brook. These conduits are connected by a weir wall, which is a half wall that allows one conduit to overflow into the other. After the weir wall, the conduits trade designation, with the canal turning into the Mill Brook Conduit, and the Mill Brook Conduit turning into the Old Mill Brook. Only in the most severe cases does the combined sewage of the canal overflow at the weir (Labovites, 2015).

The QACSOTF currently has a permit from the National Pollutant Discharge Elimination System (NPDES) that allows them to occasionally discharge into the Blackstone Canal, but only under certain conditions. The QACSOTF and the UBWWTF have to document their discharges, and all of this data is archived by the Environmental Protection Agency (EPA). The QACSOTF has been able to meet its requirements recently, but it has not always been able to in the past. Since 1990, the EPA, along with the Worcester Department of Public Works (DPW) and the Massachusetts Department of Environmental Protection (MassDEP), have been implementing the EPA Phase I and II plans for eliminating combined sewer discharge (United States Environmental Protection Agency & City of Worcester, 2005). While this has reduced the frequency of discharges that violate regulation, the violations still occur, meaning that there is still an issue. Any effects on this system need to be taken into consideration when researching ways to separate the canal from the current combined sewer system.

After compiling data from case studies and city documents regarding combined sewer separation and applying the best methods to Worcester, we created a set of four scenarios ranging from separating a small section of the canal to separating the entire system. The first scenario involves only separating the section of the canal from Union Station to Kelley Square. Two new conduits will be constructed along either side of the segment, diverting upstream flow around the segment, and rerouting the sewer lines entering the canal. The conduits will reconvene with the canal underneath Kelley Square. To prevent the canal from back flowing, a retention basin is utilized to store Combined Sewer Overflow (CSO), ultimately slowing the flow entering the CSO treatment facility. The cost for separating a mile of combined sewage is between $3.7-4.4 million (Kloss, Calarusse, & Stoner, 2006). Based on this estimate, the separation of the 0.6-mile long segment from the sewer system will cost between $2-3 million. The retention basin costs about $1.5 million, bringing the total cost to approximately $5 million (United States Environmental Protection Agency, 1999a).

The second scenario also involves separating the designated section between Union Station and Kelley Square. The water flowing into the segment from upstream would be treated using a treatment shaft then it will flow down the rest of the canal. The cost of separating the canal will be between $2-3 million, and the treatment shaft would cost between $12-13 million. The total estimated cost for this project is $15 million. The cost of unearthing and restoring the canal is not included in this cost estimation.

The third scenario involves separating the entire canal from the combined sewer system. At a cost of approximately $16 million, this would ensure that no sewage will flow through the canal. In this scenario, water from the Mill Brook Conduit will be used as a source of flow and have to be diverted to the reconstructed canal. A retention basin, costing approximately $1.5 million, will also need to be constructed to store any overflow from the newly constructed interceptors along either side of the canal. The total cost would be approximately $17.5 million, but the cost of redirecting the water is not included in this estimation, nor is the cost of unearthing and restoring the canal.

The final scenario involves a complete separation of Worcester's combined sewer system. This is by far the most extensive solution for removing the canal from the sewer system. There is approximately 4.03 square miles of combined sewers in Worcester. It would cost between $194-208 million to separate the entire system. The UBWWTF will continue to serve Worcester as a sewage treatment facility, while the QACSOTF could be reconfigured to store and treat stormwater.

In summary, the information gathered in this paper, as well as the cost estimations for different solutions, will prove critical in any decision the Alliance makes in regards to restoring or replicating the Blackstone Canal. These scenarios should be used as guidelines to tailor a specific solution that is appropriate for Worcester.

Chapter 1. Introduction

The Blackstone Canal, built in the 1820's, connected Worcester, Massachusetts, to Providence, Rhode Island. For twenty years, the canal was in operation and functioned as a source of power and transportation. Worcester consequently developed into a major inland port, becoming known as the birthplace of the American Industrial Revolution(Canal District Alliance). Immigrants who built the canal settled in the surrounding area, and established the neighborhood that is now known as the Canal District (Telegram & Gazette, 2002). With the advent of the Worcester-Providence Railroad, the need for the canal as a major mode of transportation was eliminated. Instead of taking a ferry or cargo ship down the canal and Blackstone River, people could now travel and transport goods between Worcester and Providence within a day by train. Worcester continued its booming urbanization and developed a need to drain runoff and manage sewage. The transportation value of the canal was gone, and the city incorporated it into its growing combined sewer system. In 1848, the Canal was decommissioned, and its concealment commenced.

The Blackstone Canal is now mostly underground. It was covered because sewage and storm runoff entering the canal led to unsanitary conditions. These conditions resulted from an inadequate combined sewer system, or CSS. In a CSS, the sewer and storm water runoff are channeled into the same pipe to be transported to a treatment facility. Since this single pipe lacks the capacity to carry an excess flow of stormwater, an overflow of untreated wastewater into the canal can occur, leading to increased levels of contaminants. This concept is known as Combined Sewer Overflow (CSO). There are many regulations limiting the amount of allowable CSO in order to reduce the risk of negative health impact. For that reason, the city of Worcester has set up a system for treating this overflow. However, some contaminants may still discharge into the Blackstone River. Alleviating the CSO will not only benefit the river, but it will also be a large step towards the ultimate goal of unearthing the canal.

The Blackstone Canal District Alliance proposed unearthing the section of the Blackstone Canal that runs from Union Station to Kelley Square, two important landmarks within the Canal District. The main goal of the Blackstone Canal District Alliance is to revitalize the Canal District. They have an image in mind of a redeveloped Canal District, with the Blackstone Canal as the main water feature. The canal would attract tourism, allow for commercial expansion, and promote urban development. The district could reap great benefits if the canal were to be reopened.

Considering that a feasible solution to the CSO could lead to the unearthing of the canal, the task presented to our team was to analyze and determine the feasibility of ameliorating the Combined Sewer Overflow affecting the Blackstone Canal. In order to achieve this goal, our team formulated a set of three objectives. The first was to evaluate the baseline condition of the canal; the second, to analyze the best practices of CSO management; the final, to complete a feasibility plan for the separation of the designated section of the canal from the sewer system.

Chapter 2. Literature Review

In addition to the focus on Combined Sewer Overflow (CSO), this report also considers the social dimensions that are part of the greater dynamic, including stakeholders that are affected and the site in which the project will be carried out. The scope of our research extended to the neighborhoods that would be affected by such a revitalization project, as well as how the community leaders who are sponsoring the project would benefit. We thoroughly examined the technical aspects of CSO and the effects poor sewer management can have on the environment. Previous case studies that involve similar CSO systems and identify solutions that have been used in other locations were analyzed. The following section will summarize the research that we have completed in order to expand our knowledge on this project.

2.1 Site Description

To understand the significance surrounding the revitalization project, it is important to understand the historical significance of the Blackstone Canal District. The Blackstone Canal District formed as immigrant workers settled in the area surrounding the canal while it was being built in the early to mid 1800s. The ease of transportation for people and goods, which resulted from the canal, contributed to the vibrant community within the Canal District. However, the arrival of the Providence-Worcester Railroad reduced the demand for the canal. Eventually, the pollution and smell from contaminants in the canal led to the decision to conceal it (Sinha, 2010).

In recent years there have been streetscape improvements in the Blackstone Canal District along Millbury Street, Water Street, and Green Street, as well as part of Harding Street (Worcester Business Journal, 2013). Figure 1 shows a map of the canal and the Canal District, including the identified streets. Community leaders, including John Giangregorio, the president of the Canal District Alliance, have already secured millions of dollars in federal money in order to fund upgrades and streetscapes, with the ultimate goal of improving the quality of life in the area and creating more jobs (Worcester Business Journal, 2013). A majority of these community leaders are a part of the Blackstone Canal District Alliance.

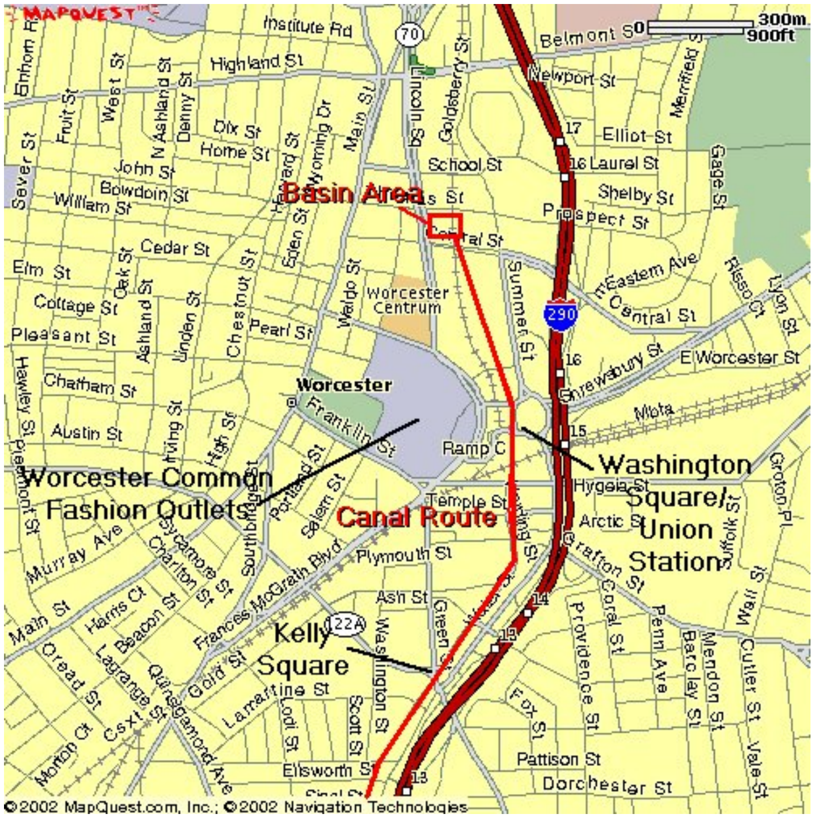


Figure 1: Map of the Blackstone Canal

The Blackstone Canal District Alliance started as a city task force focused on reviving the Blackstone Canal and the Canal District. After the completion of a feasibility study in 2003, some members of the original task force branched off to form the Alliance. The Alliance is now a non-profit organization whose main goals are to educate the general public about the history of the Blackstone Canal, to promote the Blackstone Canal project, and to revitalize the Blackstone Canal District.

2.2 Stakeholders

The communities that live near the Blackstone Canal have much to gain from improving the combined sewer system that is currently in place, but improvement requires a large capital outlay. The costs of achieving the complete separation of the Blackstone Canal from the combined sewer system may range from a few million to hundreds of millions of dollars (Bennett, 2002; Glod, 2006). If federal grants are not provided to Worcester to assist the restructuring, then the city will be required to fund the entirety of the project. An undesirable result of this would be an increase in taxes for the residents of Worcester (Bennett, 2002). The required construction for this project would likely include the closure of numerous streets throughout the city for extended periods of time. Serious economic and social effects may occur due to traffic conditions and travel limitations throughout the city. Businesses located on these closed streets may experience a reduction of customers due to inaccessible parking and poor street conditions. The community also faces the risk of the project becoming bigger than expected, similar to the situation that Bostonians endured throughout the “Big Dig” project that took place from 1982-2007. The “Big Dig” experienced rising costs, poor management, and inadequate infrastructure.

Redevelopment of the surrounding communities could bring positive outcomes to stakeholders as well. A previous study conducted by a group of WPI students concluded that reopening the canal would result in an immense economic return on the city's investment (Crimmins, Messier, Ouellette, & Spunar, 2014). The study stated that the “projected increase in visitors would sustain 270 to 349 new jobs” and city property tax revenue would increase by approximately $8 million (Corcoran, 2015). The Big Dig not only increased property tax revenue, but it also shortened the daily commute on Interstate 93, greatly improving intercity travel. The construction also created hundreds of temporary constructions and maintenance jobs.

Permanently fixing the CSO issue could potentially involve updating the entire sewage system. This project would take large amounts of time and money to complete. Currently, the Environmental Protection Agency (EPA) fines Worcester for the level of contaminants flowing into the Blackstone River. Currently, the EPA has strict regulations on how much sewage can be discharged into the Blackstone River. There are occasional violations of these regulations, but they happen infrequently and unpredictably. The cost of preventing this issue overall varies, and it is easier to permit these rare discharges than to prevent the issue overall. The treatment plants would benefit greatly from a solution to control the CSO. If the wastewater treatment facilities were upgraded, they would be able to treat at higher rate, and they would have more control over flow into and out of the plant.

2.3 Combined Sewer Overflow: A Technical Overview

A major aspect of our project is Combined Sewer Overflow, one of the main concerns for reviving the Blackstone Canal. Combined Sewer Overflow (CSO) occurs when cities have a combined sewer system (CSS). Figure 2 (below) illustrates how storm water can force overflow of sewage and urban runoff into rivers.

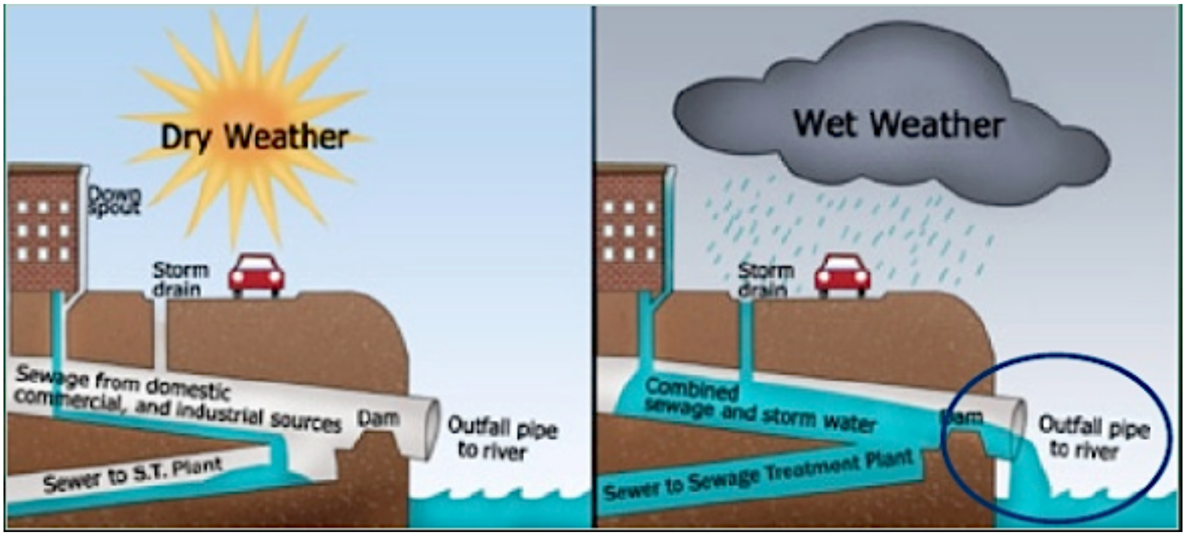


Figure 2: Combined Sewer System in Wet Weather and Dry Weather Conditions (Brown, 2012)

This system consists of drains, frequently called 'collectors', and the main trunk line, often called an 'interceptor.' Collectors are the receivers of sewage from individual users and of surface runoff in a particular area. The interceptor then carries the input from the collectors to the treatment facility. The issue occurs in the design of the system. Usually, the collectors are designed with the ability to carry a peak flow in storm conditions, but the interceptors are only designed to have the capacity to convey a peak flow during dry weather condition. In order to prevent the interceptors from being overloaded by the input, either regulators or outfall pipes can be put in place (Béron, Brière, Rousselle, & Riley, 1988). Regulators are devices, such as valves, installed to control the amount of flow moving downstream and to provide an outlet for flows that exceed the sewer capacity (United States Environmental Protection Agency, 1999b). This excess inflow is then discharged to a receiving stream. Outfall pipes connect to the interceptors. When the water flow reaches a level that could potentially overload the interceptor, it spills over the dam located at the connection between the interceptor and the outfall pipe. The overflowing water then travels down the outfall pipe and is discharged into a nearby water body, or receiving stream (Brown, 2012). In the case of our project, this receiving stream for the overflow is the Blackstone Canal.

Since the combined sewer overflow can discharge a combination of both sewage and stormwater, it can carry a number of contaminants into the receiving stream (Massachusetts Water Resources Authority, 2014). These contaminants may have an effect on flow rate, indicator bacteria, total suspended solids (TSS), biochemical oxygen demand (BOD) and dissolved oxygen (DO), pH, settleable solids, nutrients, and any "toxic pollutants reasonably expected to be present in the CSO based on an industrial survey or tributary land use, including metals typically present in stormwater, such as zinc, lead, copper, and arsenic" (United States Environmental Protection Agency, 1999c). Certain contaminants, including bacteria, volatile organic compounds, oil and grease, and dissolved metals, require special techniques for their removal. The EPA has sought to reduce the potential for negative effects by creating policies limiting the amount of allowable sewer overflow, including the nine minimum controls, described as "technology-based actions or measures designed to reduce CSOs and their effects on receiving water quality" (United States Environmental Protection Agency, 1999c). The nine minimum controls are as follows:

1. Proper operation and regular maintenance programs for the sewer system
2. Maximum use of the collection system for storage
3. Review and modification of pretreatment requirements to assure CSO impacts are minimized
4. Maximization of flow to the publicly owned treatment works (POTW) for treatment
5. Prohibition of CSOs during dry weather
6. Control of solid and floatable materials in CSOs
7. Pollution prevention
8. Public notification to ensure that the public receives adequate notification of CSO occurrences and CSO impacts
9. Monitoring to effectively characterize CSO impacts and the efficacy of CSO controls (United States Environmental Protection Agency, 1999c).

These policies, along with water quality standards and other regulations, are designed to ensure that CSO only occurs as a result of wet weather, to "bring all wet weather CSO discharge points into compliance with the technology-based and water quality-based requirements of the CWA [Clean Water Act]," and to minimize water quality impacts, biota impacts, and health impacts (United States Environmental Protection Agency, 1999c).

2.4 Blackstone Canal Feasibility Study of 2003

In 2003, a feasibility study measured the costs and benefits of recreating the Blackstone Canal and revitalizing the Canal District. It focused on replicating a section of the canal, as well as commercially developing the surrounding area.

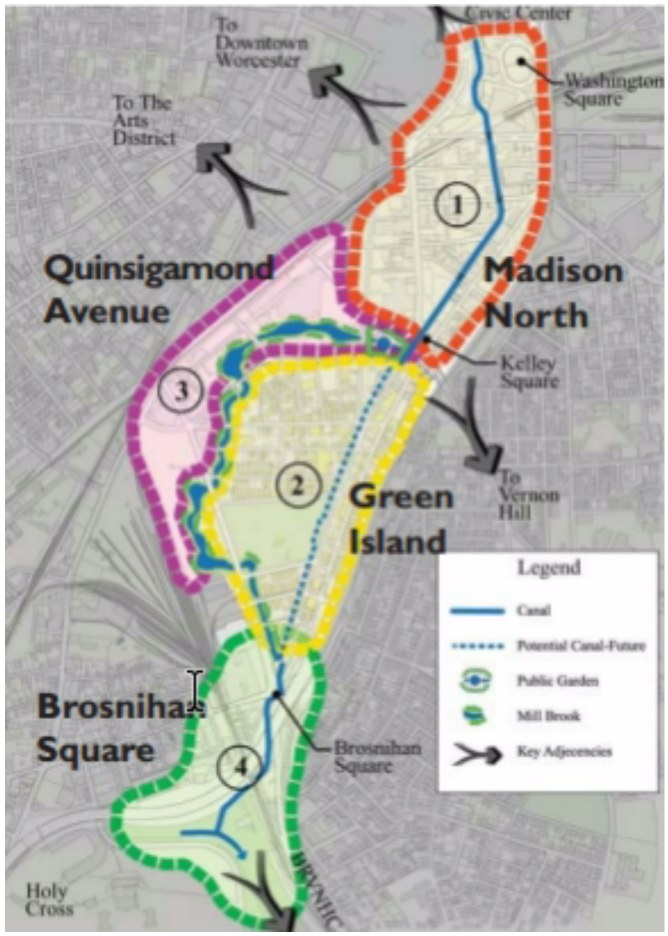


Figure 3: Map of the Canal District (Rizzo, 2003)

The most extensive part of the proposal began with Sector 1: Madison North, shown in Figure 3 (above). Sector 1 stretched from Washington Square to Kelley Square. This area was the proposed sector that would include a replica of the canal. The other sectors involved streetscape improvements and historical landmarks to designate where the canal used to run. The proposed project would have taken place over the course of twenty years with a total estimated cost of $74.5 million. A replica of the canal would be less expensive than unearthing and restoring the original canal. The study suggests that a replica should be built above the original Blackstone Canal because re-routing the infrastructure of the original canal was estimated to have been too costly (Rizzo Associates, 2003). Much of this cost is due to the current state of the canal, which will be discussed in further detail in Chapter 4.

2.5 Case Studies: Solutions for Combined Sewer Overflow

Case studies are invaluable sources of information regarding the application of systems that eliminate or manage CSO. The following case studies help lay out the possible effects on the community and the environment. They show the costs of implementing and managing these solutions, the technological aspects of the different methods of handling CSO, and the public opinion towards these systems.

Case 1: "Mayor backs combined sewer fix in Atlanta, GA"

The first relevant case study is a system put in place in Atlanta, Georgia. In 1998, a plan was approved to remedy their CSO infrastructure. In October of 2002, a report from a panel headed by Georgia Tech President Wayne Clough, which contained several alternative plans, urged Mayor Shirley Franklin to take "the cheapest option and the one that closely follows the city's current plan" (Bennett, 2002). The city separated 27 percent of their 330-mile network of sewer pipes, as well as constructed two deep tunnels to store the combined sewage. This reduced the number of treatment plants to four; these plants only release overflow on average four times a year. This plan cost the city $834 million dollars, which is $155 million less than the city's current plan. This combined sewer fix is only one part of a $3 billion plan to fix the city's aging sewer systems. Without federal or state funding, the water bills in Atlanta are expected to triple by the end of 2014 (Bennett, 2002).

The biggest issue Atlanta faced was community opposition towards a temporary fix. Many neighborhood residential activists have been pushing the city for "the complete division of sanitary and storm sewers" (Bennett, 2002). Residents accused the city government of spreading misinformation to favor the tunnels and ignoring their requests. One plan with which the critics debated involved the formation of a network of ponds and parks to control and filter storm water. Clough and his panel responded to the community's criticism by stating that the full separation would be too costly and that water quality would be much better with the current plan. In this plan, overflow collects in the tunnels and is piped to new treatment plants before being released. Jackie Echols, a resident of Atlanta who opposed the tunnels, stated "I'm afraid we'll be here again in eight to ten years with the same problem" (Bennett, 2002). Her opinion resonated throughout the community of Atlanta.

Case 2: Treatment Shaft for Combined Sewer Overflow Detention

A second case study features a solution for the CSO, and it involves the development and testing of a treatment shaft. The treatment shaft described throughout the study is currently being implemented in Dearborn, Michigan, and functions as a storage unit for overflow as well as an on-site treatment center. The CSO system that functioned in Dearborn prior to the installation of treatment shafts was similar to the system currently used in Worcester, Massachusetts (Aram, 2005). Similar to the effect that overflow has upon the Blackstone Canal, the overflow for the city of Dearborn contaminated a local body of water, in this case the Rouge River, prior to the treatment shaft integration.

The treatment shaft allows for adequate storage and treatment of the CSO wastewater discharge. The shaft provides services such as settling, screening, skimming, and disinfection before releasing the overflow into a body of water or into interceptor pipes that lead to a wastewater treatment plant. This process also leaves a smaller environmental footprint because the treatment shaft itself lies below the infrastructure of the city (Wright, Ghalib, & Eloubaidy, 2010). The treatment shafts are only used during wet-weather conditions. During dry conditions the water is carried through the interceptors directly to the wastewater treatment plant. There are many benefits to integrating the shafts into the CSO system, including eliminating undesirable surges, minimizing head losses and short-circuiting, and serving as functional storage and treatment for about 6.8 million gallons of wastewater (Glod, 2006; Wright et al., 2010). This treatment shaft has a diameter of 29 meters and a maximum depth of 51 meters (Wright et al., 2010).

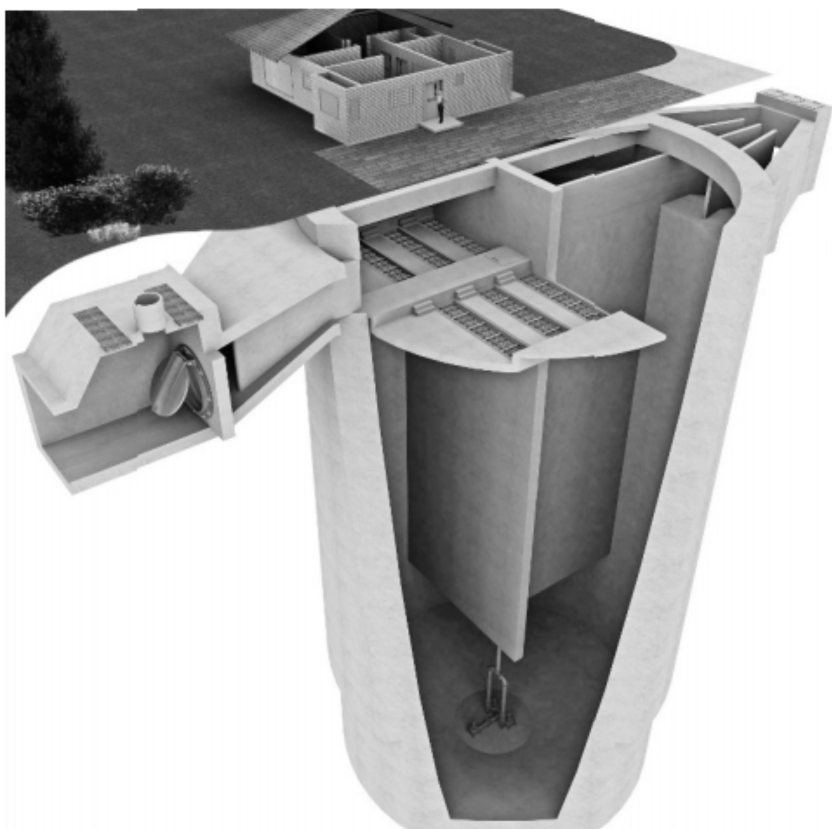
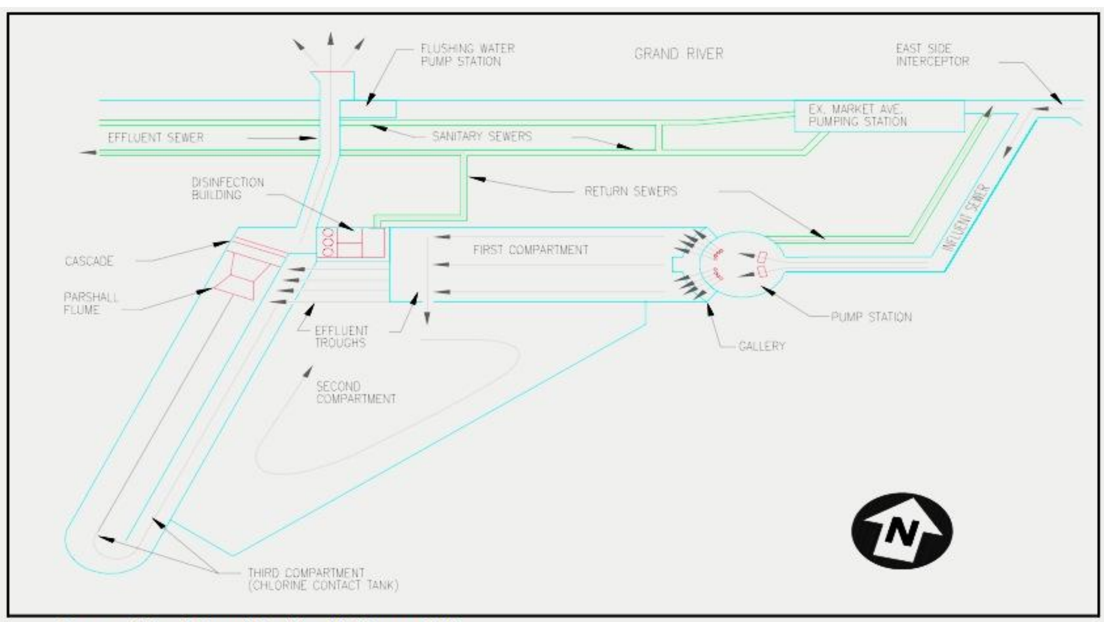


Figure 4: Rendition of Treatment Shaft (Wright, 2010)

Due to the size, the total cost for this project in Dearborn was an estimated capital cost of $172.9 million, with operation and maintenance cost of about $2.14 million annually (Glod, 2006). The application of these systems in Dearborn resulted in capital cost savings of over $60 million, and operating costs were lowered by more than $500,000 per year (Glod, 2006). A treatment shaft installed in Worcester would be much smaller and cost less than the one in Dearborn due to the smaller required flow capacity. Overall, the treatment shaft could be a very useful method in resolving the issue of the Blackstone Canal's involvement in the city's CSO system.

Case 3: Sewer Separation and Green Infrastructure in Grand Rapids, MI

The third case study looked at a series of improvements to the sewer system in the City of Grand Rapids, Michigan, a city with a similar population density to Worcester (United States Census Bureau, 2010). Because of this similarity, it can be inferred that both cities would experience similar effects, such as disruptions to business and traffic, etc. The combined sewer system for Grand Rapids dated back to the early 1800s. In 1965, overflows into local rivers reached a peak yearly discharge volume of 12.6 billion gallons. Considering the large volume of low-quality effluent that was contaminating local water bodies, the City made a plan to eliminate all combined sewer overflows by 2019. This plan included two phases. Phase I, which took place from 1992 to 1999, worked on the west side of this city. This phase involved the construction of 35 miles of storm sewer pipes, two stormwater pumping stations, a river crossing, and the Market Avenue Retention Basin (MARB). The MARB is a 30.4 million gallon facility that is used for temporary storage (see Figure 5). The entirety of Phase I, an area of over 3.1 square miles, cost $160 million (Gausewitz, 2014).



Source: City of Grand Rapids, Michigan, 1992.

Figure 5: Market Avenue CSO Retention Basin (EPA, 1999a)

Phase II began on the east side of the city in 1999 and is still in progress. It will cover an area of about 3.4 square miles, and it is expected to bring the cost of the entire project to approximately $305 million upon its completion.

This project, though costly, has had many benefits. In 2011, the city discharged 49.266 million gallons of combined sewage, a significant reduction from 12.6 billion gallons (over 99.8 percent) (Grand Rapids Environmental Services, 2011). The 59 overflow points in the city's sewer system in 1991 have now been reduced to 5 overflow points. In addition, the region's water quality index has shown improvement since 2007 (See Figure 6), an important benefit for the environment.

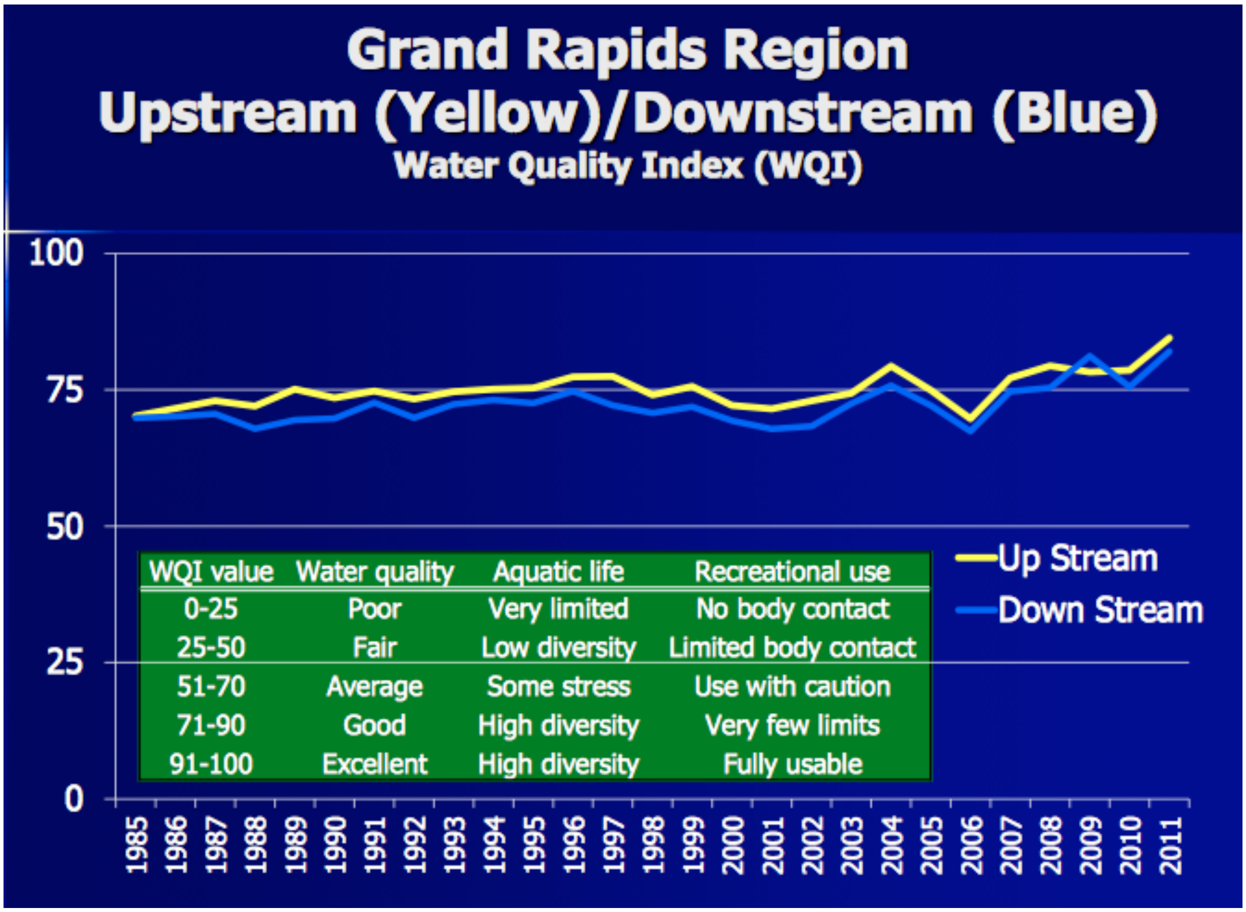


Figure 6: Grand Rapids Region Water Quality Index (Delong, 2011)

Case Study 4: South Dorchester Bay Sewer Separation

Our final case study involved the sewer separation of South Dorchester Bay in Boston, MA. Though Dorchester is a more densely populated area, the city's combined sewer system is comparable to Worcester. This project, completed in 2007, allowed the MWRA to decommission the Commercial Point and Fox Point CSO treatment facilities by eliminating all CSO flows entering the systems (Massachusetts Water Resource Authority, 2004). During this separation project, 135,700 linear feet of new storm drains were installed over a 1,750-acre area, removing storm runoff from local sewers. Upon the projects conclusion, the annual discharge volume of 30 million gallons to Savin Hill, Malibu, and Tenean beaches was completely eliminated. The total cost of the project came to $118,394,583 (Massachusetts Water Resources Authority, 2014).

2.6 Summary

After reviewing literature and examining several relevant case studies, we noted three key findings. First, we noticed that combined sewer overflow can cause significant pollution in local water bodies. This means that CSO could be a costly issue for the city of Worcester to fix if it is negatively affecting the Blackstone River. Secondly, we found that different overflow problems require different solutions. Larger, more infrequent overflow discharges will require a large and expensive solution. Our third finding showed us that without state or federal funding to control or eliminate CSO, the city will have to fund the entire project, and the citizens can expect major tax increases.

Chapter 3. Methodology

3.1 Evaluating the Baseline Condition of the Canal

The first step in completing the overall goal was to evaluate the current condition of the Blackstone Canal. The site assessment included mapping and conducting interviews. This helped provide a full picture of the site and its parameters. We interviewed experts from the Department of Public Works (DPW) with the goal of learning the design and function of the sewer system.

We evaluated the condition of the canal water and researched the potential effects of the discovered contaminants on public health and the environment. Much of this data was recorded in a database maintained by the Environmental Protection Agency (EPA). The level of each contaminant was then compared to the limits required by government regulations. Many of these regulations are set by government organizations, such as the EPA and the Massachusetts Department of Environmental Protection (MassDEP).

3.2 Best Practices for CSO Management

In order to determine the best methods for alleviating combined sewer overflow (CSO), we reviewed case studies and obtained government documents for information regarding current methods of CSO storage applied in locations similar to Worcester. We evaluated case studies that describe effective methods of controlling CSO to aid in the creation of a list of possible solutions for the Worcester site. With the information from these case studies, we identified criteria to be used in a deciding the most practical solutions for Worcester and the Canal District. These criteria include the amount of overflow that is discharged into the canal and the cost effectiveness of proposed solutions to eliminate CSO from the canal.

We also analyzed government documents pertaining to any CSO regulations or effective design modifications in different locations. Construction and restoration documentation aided in our understanding of what is occurring underneath Harding Street, while technical documents and permits showed us the current practices in Worcester. Local practices were compared to EPA standards and regulations to confirm whether or not Worcester is in violation of the set parameters.

These case studies and government documents were also used to estimate the cost of this project for Worcester. The regulations for CSO management in locations with effective CSO systems were compared to those of Worcester. Comparing different scenarios and CSO projects aided in determining potential benefits and disadvantages of completing similar projects within the city.

3.3 Feasibility Plan

To begin the feasibility study, ideal methods of controlling or preventing CSO in similar systems were applied to the Blackstone Canal. Our team performed in depth research on similar projects to accurately estimate the costs of separating the canal from Worcester's sewer system. We analyzed various project costs, including the costs of construction and materials.

As part of our feasibility plan, we identified social, environmental, and economic impacts of CSO mitigation scenarios. Our previous analysis of case studies gave us some insight towards possible complications and benefits of the project on the Blackstone Canal and the local community. Research on the layout of the pipes assisted in studying the effect of each possible solution on whole the sewer system. Maps helped identify important points of intersection between streets, the canal, and sewer lines, indicating which areas are most affected by large construction projects.

We also considered the possible effects of this project on nearby bodies of water to determine if the quality of water will improve or degrade. To gain information on nearby water sources, we contacted officials in local government organizations, such as the Department of Public Works and Park (DPWP) and the Massachusetts Water Resource Authority (MWRA). Using this information, along with data from the EPA, we were able to infer the different effects that the project would have on these water sources. The data from the EPA contained a log of discharge information and water quality in the Blackstone Canal, where the discharge leaves the sewer system. Using this information, we compared the quality of the water being discharged and the quality of the receiving waters to determine if the receiving waters were being degraded.

The final part of the feasibility study is the economic impact of separating the canal from the combined sewer system. We analyzed case studies in order to gauge the economic benefits of areas similar to Worcester that underwent similar sewer separation projects. We also had to consider the costs of the project. We used information from previous MRWA CSO mitigation projects to estimate the cost of separating combined sewers. The costs of the treatment shaft and retention basin installations were also estimated from case studies and data from the EPA. Combinations of different alternatives to complete sewer separation, such as partial separation or redirection, were also analyzed in terms of cost.

3.4 Data Management

In the process of collecting data, we conducted a series of interviews to gather information. The participants of these interviews included city officials as well as experts on CSO and the canal. Participants were asked for their consent before they were identified in our report. All data collected over the course of the project was stored in a password-protected laptop to protect the identity of those who were interviewed.

3.5 Estimated Timeline

We created a timeline in order to give a visual summary of the strategies by which we collected our data and the time frame in which we completed those activities (see Figure 7).

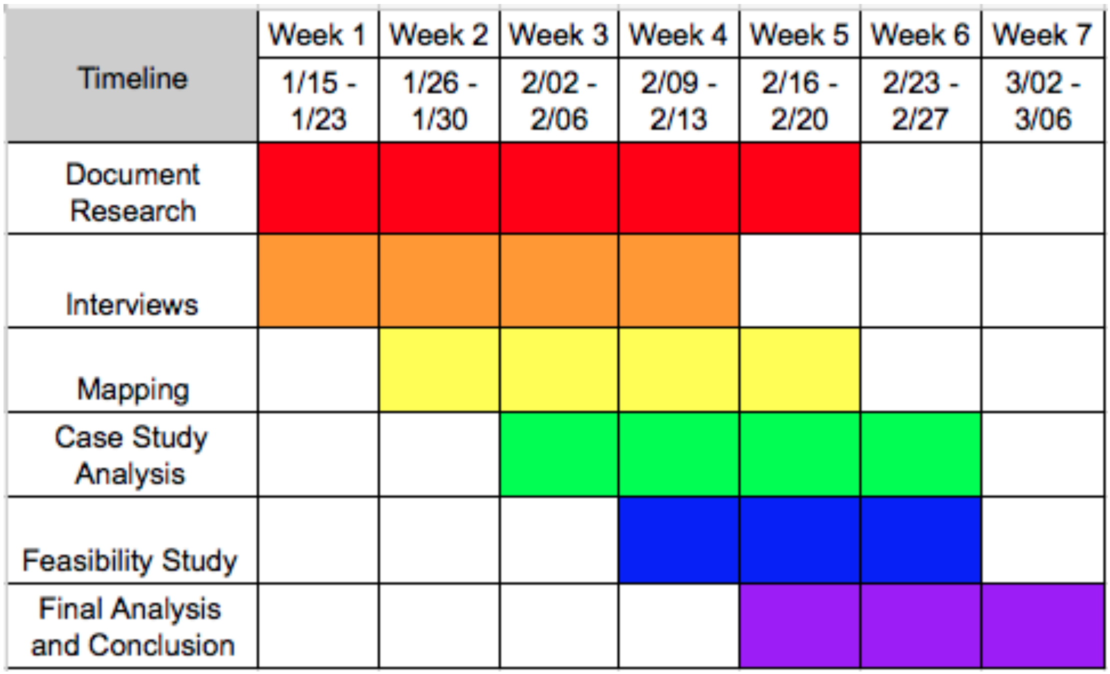


Figure 7: Methodology Timeline

In summary, we started with researching structure and function of the canal. This was done through research and interviews. Case studies allowed us to identify best practices and to find potential solutions for the CSO. We used these solutions to conduct a feasibility study, which included conducting interviews to help determine possible impacts of each solution. Upon the completion of our project, a final analysis was made, concluding with a feasibility study.

Chapter 4. Findings

The data collected from the Worcester Department of Public Works (DPW), the Massachusetts Water Resource Authority (MWRA), the Blackstone Canal District Alliance, and other interested parties, enabled us to understand and evaluate the current condition of the canal. By researching case studies, we were able to determine the best management practices for CSO around the country, as well as current regulations. This information allowed us to analyze how different solutions could be implemented in Worcester. This section will describe how these solutions work and how they could fit into separating the combined sewer system and the canal.

4.1 Baseline Conditions of Canal

The Blackstone Canal starts at Lincoln Square, runs through Worcester, and leads to the Blackstone River. The section that the Canal District Alliance is focused on is a 0.6-mile long segment that runs underneath Harding Street. This section begins near Union Station and ends at Kelley Square. A number of documents were acquired from the Worcester DPW in order to determine the canals current condition (See Appendix). A map obtained from a Sanitary Engineer within the Sewer Department shows a large section of the combined sewer system in the Canal District, as well as what streets the canal runs underneath (Figure 8). According to the DPW, the canal is a CSO collector known as Old Mill Brook. There is also a large twin box conduit that carries only stormwater. The conduit is known as the Mill Brook Drainage Conduit, or the Mill Brook Conduit. This clarification was crucial for understanding the sewer layout since multiple agencies were using different names for the same structures. There are stars on the map given to us by the DPW that show where regulators allow overflow into the canal (Figure 8). Digital copies of restoration plans from 1986 were also obtained from the DPW. These plans show live sewer lines directly connected to the canal (Figure 9).

Figure 8: DPW Map of Canal from Kelley Square to Union Station

The canal is not just a combined sewer collector, which our initial research led us to believe, but it is actually an integral part of Worcester's sewer system. In dry weather, the canal handles approximately 200,000 gallons of wastewater per day, originating from live sewage lines and other interceptors (Labovites, 2015). Figure 9 shows a number of sewage lines connecting to the Old Mill Brook every 10 to 15 feet. The specific activity of each line is unknown, but there are live sewage lines entering the canal every 15 to 20 feet (Labovites, 2015). In the section from Union Station to Kelley Square alone, there are potentially 12 of these live sewage lines, 3 of which are confirmed (See Figure 10).

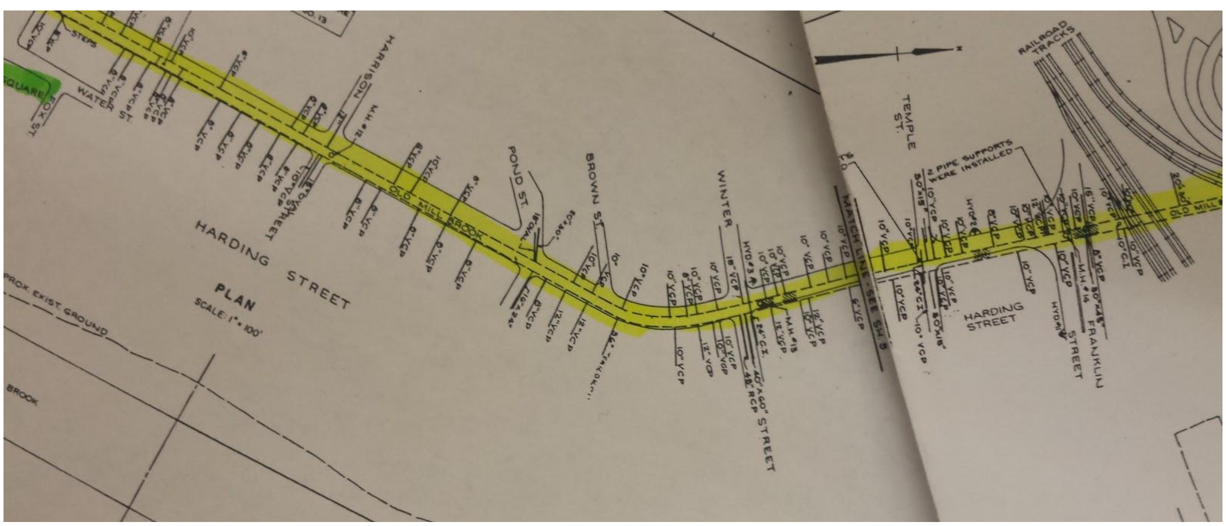


Figure 9: Inlets into the Canal

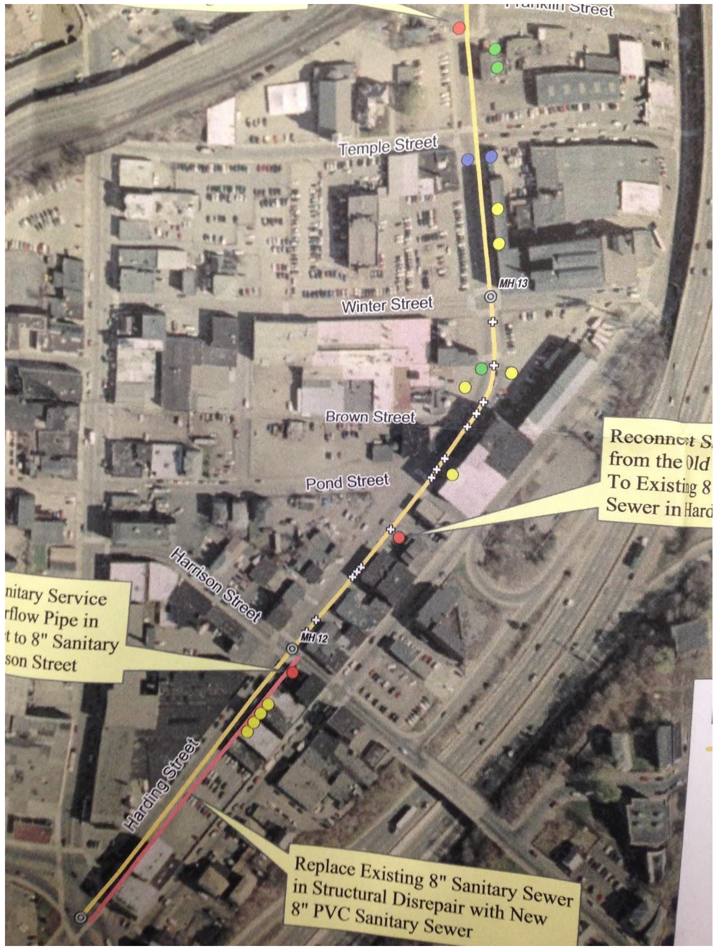


Figure 10: Live Inlets (Red) and Unknown Inlets (Yellow)

Overflow occurs when excess stormwater discharges into the canal. Sewage and stormwater flows enter the system through collectors that empty into interceptors. Interceptors then carry the flow to treatment facilities. Regulators are the valves that allow any overflow to enter the canal. Overflow also occurs when the Mill Brook Conduit and Old Mill Brook temporarily run side-by-side, connected by a weir wall (shown in Figure 11). The weir wall allows either conduit to occasionally overflow into the other. When the Old Mill Brook reaches a certain capacity of flow, in the event of a 100-year storm, the water would flow over the weir and mix with the clean water from the Mill Brook Conduit that flows into the Blackstone River. After the weir wall, these conduits exchange designations, with the Mill Brook Conduit turning into the Old Mill Brook and the Old Mill Brook turning into the Mill Brook Conduit. The latter leads to a treatment facility (see Figure 11).

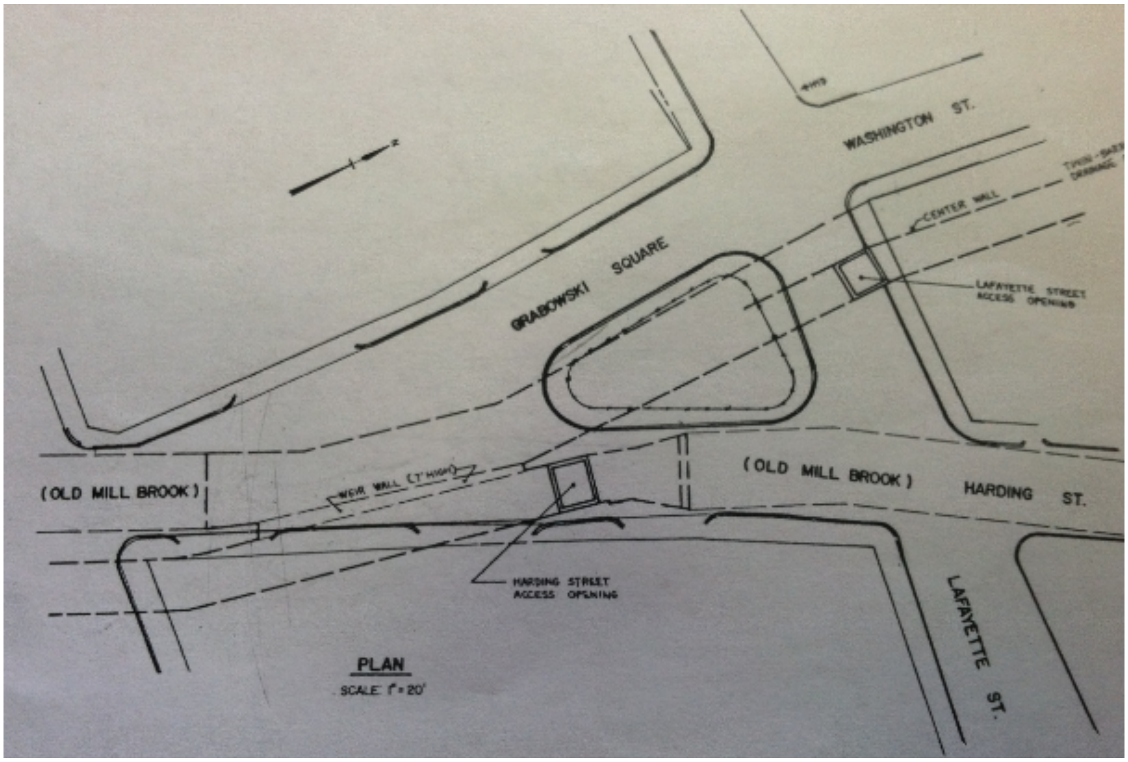


Figure 11: Weir Wall Underneath Grabowski Square

The sewage and stormwater in the canal are carried to the Quinsigamond Avenue Combined Sewer Overflow Treatment Facility (QACSOTF). It acts as a pumping station to the Upper Blackstone Regional Wastewater Treatment Facility during dry and slightly rainy periods. The QACSOTF only switches to treatment mode in times of heavy rain, as it has a pumping max of 54 million gallons per day (Eliadi, 2014; Labovites, 2015). After treating the water, the QACSOTF discharges into the Old Mill Brook, which eventually leads to the Blackstone River.

4.2 Current Management Practices for CSO

Many of the regulations regarding CSO are described in Title 40 of the Code of Federal Regulations (CFR) within the National Pollutant Discharge Elimination System (NPDES). Assessing the concentration of fecal coliform, or bacteria that indicate that sewage is present in water, is one method the EPA uses to measure water quality. The limit for treated water is 200 colonies of fecal coliform per 100 mL of water. In 2004, the median level of fecal coliform in CSO nationwide was between 3 to 40 million per 100 mL (United States Environmental Protection Agency, 2004). The city of Worcester has undergone plans from 1990 to 2011 to lower the instances of discharge of effluent exceeding the limit to around twice a year (United States Environmental Protection Agency & City of Worcester, 2005). These plans included the construction of the QACSOTF and turning the section of the canal north of Kelley Square into combined sewer storage. In addition to having the ability to pump a maximum of 54 million gallons per day, the QACSOTF also has two 1.2 million gallon tanks that can be used for either storage or treatment of CSO. The facility can handle a total of 350 million gallons per day, maximum. In heavy rainfall, this facility will give a basic treatment involving the removal of solids via box screens, settling of solids in one of the facility's two tanks, chlorination with a 15 to 18 minute detention time, and de-chlorination, likely using sodium hypochlorite. After treatment, the QACSOTF discharges to Old Mill Brook, eventually leading to the Blackstone River. In reality, there are between 3 and 5 discharge events a year (Harris, 2015). This becomes a greater issue as such severe storms occur more frequently due to climate change.

Currently, the QACSOTF has a NPDES permit to discharge to the Blackstone River, which flows into the Narragansett Bay. There are very stringent limits on the fecal coliform, chlorine, and pH levels of the effluent discharged from the QACSOTF. From the EPA database, we concluded that the amount of sewage that the facility discharges is within acceptable levels, but chlorine and pH levels in the effluent vary. In terms of nutrient levels, the regulations are not as strict. The Quinsigamond Ave Treatment Facility is required to report the concentration of all nutrient discharges, but there is no set limit on these nutrient concentrations (United States Environmental Protection Agency & City of Worcester, 2005). Violation of regulations is a unique problem to deal with when considering that the QACSOTF rarely discharges, typically serving solely as a pumping station. This infrequency makes it difficult for the EPA to identify issues with the treatment processes and impose fines for continuous violations.

4.3 Applicable Solutions to the Canal District

Sewer Separation

To rid the section of the canal between Kelley Square and Union Station of sewage, this section would have to be separated from the combined sewer system. Achieving this separation would include redirecting many of the live sewage lines connected into the canal into two new interceptors. These interceptors would run parallel with the canal, carrying all the raw sewage to the treatment facilities. The canal can then be used as a storm drain conduit, similar to the Mill Brook Conduit. This is the most costly option, and preliminary costs, such as the cost of separation per mile of combined sewer, will be examined in the feasibility analysis.

Retention Basin

A retention basin is a large container designed to collect combined sewage during wet weather conditions. They are rarely operational except during severe weather events. Retention basins can also be converted into structures that treat wastewater if necessary. In 1988, the Shockhoe Retention Basin and Diversion System, a 41 million gallon hydraulic retention system, was built in Richmond, VA for only $1,077,900 (United States Environmental Protection Agency, 1999a).

The reason a retention basin needs to be considered is due to the fact that the canal is currently used in a similar fashion during severe wet weather. The gates at the Kelley Square Control Station are normally open during dry weather conditions, allowing the canal to act as a large sewage conduit. When excess stormwater begins to overwhelm the treatment facilities, the gates partially or fully close. The amount of combined sewage flowing into the QACSOTF can then be controlled, and the canal will store most of this excess stormwater (CDM, 2006). On rare occasions, the volume of water will be greater than the canal's capacity, resulting in a backflow of water all the way to Washington Square.

Treatment Shaft

A treatment shaft is an alternative solution to removing the combined sewer from the canal. These treatment shafts act as both a retention basin and as an onsite treatment facility. Large amounts of water can be stored by utilizing the vertical shape and the small footprint of the shaft. Treatment shafts can also perform primary treatment processes, handling "primary settling, skimming, fine screening, and disinfecting" (Tetra Tech, 2013). This treatment is comparable to the QACSOTF and can supplement it in treating combined sewage. This would further lower the potential for CSO directly discharging into the Blackstone River.

A case study on the treatment shaft in Dearborn, MI, summarized in the Literature Review, showed just how effective this solution could be for eliminating CSO. The Dearborn treatment shaft eliminated all CSO discharge into the Rouge River and lowered operating and maintenance costs by $500,000 a year (Glod, 2006). The total cost of the treatment shaft in Dearborn, MI was approximately $173 million (Glod, 2006). This treatment shaft was designed to hold 6.8 million gallons of combined sewage. A much smaller treatment shaft would be required in Worcester. It would act as a complement for the QACSOTF. Being on a smaller scale (just under one tenth the size of the Dearborn shaft), a treatment shaft in Worcester should cost much less to construct. According to our linear estimate, a treatment shaft would cost around $12.5 million. In the next section, we will describe our cost estimation methods. The benefits of such a project, along with the benefits of a separated sewer, will also be discussed in the next section.

4.4 Cost Analysis

Cost of Sewer Separation

Complete separation of combined sewer systems is the most effective way of eliminating combined sewer overflow, but it is also the most expensive. It is estimated that for every mile of combined sewers, the cost of separation is between $3.5 and $4.4 million (Kloss et al., 2006). This number was derived using an inflation calculator to find PPP (purchase power parity) between 2000 and 2014. The EPA mentions that a capital investment of $76 billion would be required to solve all issues of combined sewer overflow across the nation (Tian, 2011). When calculating the South Dorchester Bay Sewer Separation, a $118 million project that involved 25.7 miles of new storm drains, the per mile separation cost was approximately $4.6 million. After considering the area serviced by South Dorchester Bay's combined sewer systems, we estimated that separating 1 square mile of combined sewer would cost $43.4 million (Massachusetts Water Resources Authority, 2014). Compared with the many projects listed on the MRWA website, our estimated per mile cost for separating combined sewer systems was fairly average. With this number in mind, the amount of the combined sewer system being separated must be taken into consideration. If only separation of the entire canal is considered, then all combined sewer lines above Kelley Square will have to be separated. This will eliminate all the sewage running through the section that the Canal District Alliance wants to uncover. For our purposes, we are also estimating the cost of a full combined sewer separation. Using all this data from previous combined sewer projects, separating all 4.03 square miles of the combined sewer system would cost between $194 and $208 million.

Cost of Retention Basin

The retention basin in Richmond, VA is much larger, almost 20 times larger, than will be required for Worcester's combined sewage system. The construction of a retention basin this large cost Richmond $1,077,900, which equates to nearly $0.03 per gallon (United States Environmental Protection Agency, 1999a). Our cost estimate for a 2.5 million gallon retention basin is $1.5 million. The Canal District is a fairly urbanized district of Worcester, so much of the cost of installation will involve redirection of current subterranean infrastructure. Finding an area to dig up and relocate more than 12,000 cubic yards of soil will also be a challenge. Worcester is a densely populated city; therefore, any construction project this extensive will be complicated.

Cost of Treatment Shaft

A treatment shaft is an alternative to separating the entire sewer system. Treatment shafts are large containment structures that take in untreated wastewater and treat it onsite. To handle the flows in wet weather conditions, a treatment shaft would need to be designed to handle 350 million gallons per day of flow (Harris, 2015). This size estimation is based on the maximum amount of daily flow that the QACSOTF can handle. The cost to build a treatment shaft that can hold 6.8 million gallons and can handle 1,205 million gallons per day costs $36.8 million (NIH Consultants, 2008). The size that Worcester would require is one-third this, therefore our estimations indicate that it will cost significantly less than the example given. According to the case studies that we analyzed, we can estimate that $12.5 million would be required to install a treatment shaft. This cost is equivalent to the cost of separating five to seven miles of combined sewer lines.

4.5 Implications of Canal Separation

Impact of Sewer Separation on Community

As in many major public works projects, the construction involved in separating a combined sewer system can have a very serious impact on the surrounding communities. Creating separated sewer systems will involve closing entire streets at a time, restricting access to certain businesses. In a place such as the Canal District, a business-oriented neighborhood, restricting access to local businesses can have serious economic impact. It will disrupt local traffic as well, which will affect not just the locals, but also anyone who commutes through the Canal District.

Impact of Treatment Shaft on Community

A treatment shaft is a low profile solution for cleaning up combined sewage. Construction would extend over a smaller area than a total sewer separation. It will require a large amount of excavation however, and over 12,000 cubic yards of soil will need to be relocated. The amount of traffic that is disrupted is dependent on the location selected for the treatment shaft.

Benefits of Clean Water in Canal for Community

The DPW has informed us that, on very rare occasions, combined sewage can back up all the way to Washington Square. Having a separate sewer system can make certain that no untreated sewage will overflow onto the streets by introducing additional lines solely for the transportation of sewage. Less exposure to raw sewage is beneficial to the health and environment of the Canal District. It is also be beneficial to all the businesses along Harding Street, since having no risk of sewage back up allows for the retainment of customers.

The canal can serve many purposes, as well as being the main attractor for tourists to the Canal District. An open canal with clean water can bring in more urban development to the neighborhood, including, but not limited to: streetscaping, green infrastructure development, and property development. For the locals, it would be providing an improvement to the appearance of the neighborhood, as well as giving a more tangible meaning to the district's name. The culmination of these factors can give a sense of pride to those who call the Canal District home.

Environmental Impact of Separated Sewer

Separating all combined sewer lines will help eliminate CSO discharges to the Blackstone River and alleviate stress on the treatment facilities. By transporting stormwater in a different conduit, the potential for sewage overflow is eliminated. Without the combined volume of sewage and stormwater, treatment facilities are less likely to be overwhelmed by flow. Additionally, separating stormwater and sewage and treating the two at different facilities can allow for a more specialized treatment, resulting in cleaner effluent.

If the sewer system were separated, the canal would need a water source during dry conditions. This water source could be the Mill Brook Conduit, which is supplied by Indian Lake and Salisbury Pond. During wet weather, however, the canal may be in danger of flooding. In the event of stormwater flooding, the effects of runoff is much less threatening to the health of the afflicted communities than the effects combined sewage. There is also a very real possibility that this will cause more nutrient pollution discharging into the Blackstone River. Such pollution is already a major issue affecting the Narragansett Bay (Thurston, Goddard, Szlag, & Lemberg, 2003). Excess stormwater runoff from separated sewer systems not only causes these problems, but it also contributes to "stream degradation, habitat alteration, low base flows, and increased toxic loadings from nonpoint sources" (Thurston et al., 2003).

Including a treatment shaft in these separation plans can help remedy the run-off solution by treating the water onsite. The main purpose of the shaft would be to treat the combined sewage above Washington Square during either dry or wet weather conditions. During dry weather, additional water from the Mill Brook Conduit can be run through the treatment shaft, treated, and discharged to the canal. A treatment shaft could ensure that no extra pollution will be discharged into the Blackstone Canal, and it could also potentially lower the amount during dry weather.

Chapter 5. Recommendations

From our findings, we have been able to determine that the canal is used as a sewer, collecting both combined sewer overflow and flow from live sewer lines. The cost of separating the canal from this combined sewer system could be between $5 million and $208 million. These costs do not include any potential start-up costs or work on the unearthing and restoration of the canal. We have provided a set of scenarios to serve as our recommendations (see below).

Scenario 1: Separating the Segment from the Sewer System by Redirecting Upstream Interceptor

The segment of the canal that our team focused on stretches from Union Station to Kelly Square, a distance of 0.6 miles. This segment could be separated from the sewer system by redirecting the upstream flow around the segment and reconnecting it past Kelley Square. There would be two new interceptors constructed along either side of the segment to which live sewer lines and storm drains would be rerouted. The flow from upstream would also be redirected along either side of the canal through these interceptors. The new conduits would reconvene with the canal under Kelley Square, where the Kelley Square Control Station is currently located. Separating the segment would cost about $5.28 million, but this does not include the cost of replacing/reconstructing the Kelley Square Control Station. A retention basin could be constructed to replace the control station in order to prevent combined sewage from back flowing up the canal. The basin would cost approximately $1.5 million, bringing the total to about $6.8 million (United States Environmental Protection Agency, 1999a). The now separated segment could be supplied with water from the Mill Brook Conduit. These estimates do not include the cost of supplying the canal with water, unearthing the canal, or restoring the canal.

Scenario 2: Separating the Segment from the Sewer System and Installing a Treatment Shaft

Similar to the first, this scenario would also separate just the 0.6-mile long segment. According to our cost estimations, separating this small segment from the combined sewer system would cost about $5.28 million. However in this scenario, the new interceptors along either side of the canal would be used to redirect the flow of sewage lines directly entering the canal away from the segment of focus. Since this scenario would allow contaminants enter the canal from upstream, the water entering this segment would have to be treated. We suggest the addition of a treatment shaft, with the capability of storing 2.26 million gallons, at the head of the segment. The treatment processes in this shaft would improve the quality of the water flowing downstream into the Quinsigamond Avenue CSO Treatment Facility and the Upper Blackstone Treatment Facility. A cleaner influent would require less treatment to meet EPA standards, easing the stress on these treatment facilities. The installation of this shaft would cost approximately $12.5 million, bringing the total to about $17.8 million. This cost does not include the cost of unearthing or restoring the canal.

Scenario 3: Separating the Entire Canal from the Sewer System

The canal stretches over a length of about 1.75 miles. Considering this, our cost estimations indicate that separating the entire canal from the sewer system would cost about $16 million. This would include the addition of two new conduits, one on each side of the canal, to handle all of the sewage. In order to prevent these conduits or the Quinsigamond Avenue Treatment Facility from being overloaded in storm conditions, a retention basin would need to be installed to store excess wastewater, slowing the flow to the treatment facility. This basin would cost approximately $1.5 million, making the total project cost approximately $17.5 million. In order to provide flow in the newly separated canal, water could be redirected from the Twin Box Conduit/Mill Brook Conduit to supply the canal with flowing water. However, neither the cost of redirecting this water nor the costs of unearthing and restoring the canal were considered in our estimate.

Scenario 4: Separating the Entire Combined Sewer System

The most extensive and expensive solution would be to separate the entire combined sewer system in Worcester. The system covers approximately 4.03 square miles, and it would cost about $194 million to $208 million to separate (Gausewitz, 2014; Massachusetts Water Resources Authority, 2014). This solution would ensure that combined sewage no longer enters the Blackstone River.

The sewer separation could also lead to another project that would improve the overall water quality in the Blackstone River. The separated sewage lines could be directed to the Upper Blackstone Waste Water Treatment Facility, while the stormwater would be directed to the Quinsigamond Avenue Treatment Facility. The Quinsigamond Avenue facility will have to be repurposed for storing and treating stormwater, as opposed to combined sewer overflow. By specializing these two plants, more specific treatment methods can be used for the different types of contaminants in sewage and storm runoff. This would result in a cleaner effluent overall. This project could potentially cost millions of dollars, but it is the next step in making sure that the water from Worcester doesn't degrade the water quality in the river.

Chapter 6. Conclusion

The costs and benefits of each plan, as outlined, indicate that there are many factors that need to be taken into consideration when choosing a plan of action to implement. For that reason, the Canal District Alliance needs to find a balance of costs and benefits that make this project worthwhile for them. A previous study conducted by students at Worcester Polytechnic Institute estimated that the replication of the canal would cost about $25 million. This cost would be comparable to what the cost of unearthing and restoring the canal would be if the Combined Sewer System were not part of the problem (Crimmins et al., 2014). Either project would bring hundreds of temporary and permanent jobs to the Canal District, as well as raise property tax revenues by an estimated $8 million (Corcoran, 2015).

The resolution of the combined sewer overflow and the unearthing of the original canal could potentially receive funding from the Environmental Protection Agency for compliance with the Clean Water Act and from the Blackstone Valley Heritage Corridor for the canal's historical significance. Worcester was recently included as part of a National Park because of its historic role in the Industrial Revolution. The canal could be a tourist hotspot, and that would bring in revenue for the city and the National Park system.

In conclusion, clean water must be flowing through the canal before it can be unearthed. There are multiple solutions to this problem, but they are all very costly. Depending on which solution is determined to be the most economically feasible by the Canal District Alliance and the City of Worcester, the return on this investment will make all the difference. It will breathe new life into the Canal District, bring in new development projects, turn Worcester into a must-visit destination for tourists, and improve the quality of life for those who live in the district. Worcester and Providence would complement each other as 'bookends' of the Blackstone Valley Heritage Corridor and the new National Park. Worcester deserves to be treated with distinction, and opening this canal would ensure that the city of Worcester would be put on the map once again.

References

Aram, K. (2005). Dearborn CSO Project Under Way (Vol. 99, pp. 4). Indianapolis: Associated Construction Publications, LLC.

Bennett, D. L. (2002). Franklin backs combined sewer fix: Home Edition. *Metro News,* p. 1B. Retrieved from http://wpi.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwY2BQSLJITgY2BBINgI2HZGD2STU2T7RIA9Y9ppZJiQaphig3RCCV5m5CDEypeaIMsm6uIc4eurCiMT4lJyfeCHQdlgGw8jIWY-BNBC3-zisBbxJLkWBQAB0ibpmWnGgIutM6xSw5MRFYSaWlgs7mMrBMMbWQZBDDbhgAWrcsfA

Béron, P., Brière, F., Rousselle, J., & Riley, J. (1988). Strategies to Control Combined Sewer Overflows. *Journal of Environmental Engineering, 114*(2), 454–459.

Brown, T. (2012). How Is the Water? 2012: Sewage Contamination in the Hudson River Estuary 2006 - 2011. New York.

Canal District Alliance. The Blackstone Canal in Worcester: Blackstone Canal District Alliance.

CDM. (2006). *Technical Memoranda of the Kelley Square Controls and Old Mill Brook Conduit Improvements Project*: City of Worcester, Massachusetts.

Corcoran, L. (2015). Study finds Blackstone Canal opening could deliver huge return on investment for Worcester. *MassLive*. Retrieved from http://www.masslive.com/news/worcester/index.ssf/2015/01/study_finds_blackstone_canal_o.html

Crimmins, R., Messier, J., Ouellette, D., & Spunar, N. (2014). Blackstone Canal District Alliance: Blackstone Canal Revitalization. from http://wp.wpi.edu/wcpc/projects/projects-by-term/fall-2014/blackstone-canal-district-alliance-blackstone-canal-revitalization/

Eliadi, K. (2014). Managing Worcester's Combined Sewer System. Retrieved November 14, 2014, from http://www.worcesterma.gov/dpw/water-sewer-operations/combined-sewer-system

Gausewitz, P. (2014). Grand Rapids' Combined Sewer Separation Project: Materials Testing Consultants.

Glod, R. (2006). CSO Project Could Save Money. *Pollution Engineering, 38*(3), M8. http://wpi.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwY2BQMEs2NQEmk6RUY2NLC9Mks7RE0-Q0I7MUY3NTc5MU8FYxxA0RSKW5mxADU2qeKIOcm2uIs4curGiMT8nJAR2tawqaMjM2NBZj4E0Erf7OKwHvEkuRYFBIM0s0N7cE9h7MjY1NzJJMk8wNzNKMjAxTjS2TTAwTUyUZxHGYBgA4bSwQ

Grand Rapids Environmental Services. (2011). What are Combined Sewers?

Harris, D. (2015). Sanitary Engineer - Department of Public Works.

Kloss, C., Calarusse, C., & Stoner, N. (2006). *Rooftops to rivers: Green strategies for controlling stormwater and combined sewer overflows*: Natural Resources Defense Council.

Labovites, M. (2015). Assistant Commissioner of Operation for Department of Public Works.

Massachusetts Water Resource Authority. (2004). Combined Sewer Overflow Control Plan: Quarterly Progress Report.

Massachusetts Water Resources Authority. (2014). Combined Sewer Overflows (CSOs). Retrieved November 18, 2014, from http://www.mwra.com/03sewer/html/sewcso.htm

NIH Consultants, L. (2008). Final Report on Interim Construction Progress: Ease Dearborn CSO Control Project Contract No. 6. Detriot, Michigan.

Rizzo Associates. (2003). Free the Blackstone! *Blackstone Canal Feasibility Study*.

Sinha, D. R. (2010). The Environmental Kuznets Curve Hypothesis and Legacy Pollution: A GeoHistorical Analysis of the Environmental Consequences of Industrialization in Worcester, Massachusetts (USA). *The Industrial Geographer, 7*(1), 1-18.

Telegram & Gazette. (2002, 05/02/2002). Blackstone Canal District designated. *Telegram & Gazette,* pp. 0-B4. Retrieved from http://ezproxy.wpi.edu/login?url=http://search.proquest.com/docview/268832759?accountid=29120

Tetra Tech, I. (2013). *Emerging Technologies for Wastewater Treatment and In-Plant Wet Weather Management*: United States Environmental Protection Agency.

Thurston, H. W., Goddard, H. C., Szlag, D., & Lemberg, B. (2003). Controlling storm-water runoff with tradable allowances for impervious surfaces. *Journal of Water Resources Planning and Management, 129*(5), 409-418.

Tian, S. (2011). Managing stormwater runoff with green infrastructure: Exploring practical strategies to overcome barriers in citywide implementation.

United States Census Bureau. (2010). *State and County QuickFacts*. Retrieved from: http://quickfacts.census.gov/qfd/states/26/2634000.html

United States Environmental Protection Agency. (1999a). Combined Sewer Overflow Technology Fact Sheet Retention Basins. Washington, D.C.

United States Environmental Protection Agency. (1999b). *Combined Sewer Overflow Technology Fact Sheet: Maximization of In-Line Storage*. Washington, D.C.: Retrieved from http://water.epa.gov/scitech/wastetech/upload/2002_06_28_mtb_maxstrg2.pdf.

United States Environmental Protection Agency (Writer). (1999c). Combined Sewer Overflows: Guidance for Modeling and Monitoring.

United States Environmental Protection Agency. (2004). 2004 Report to Congress.

United States Environmental Protection Agency, & City of Worcester. (2005). *Draft National Pollutant Discharge Elimination System Permit to Discharge to Waters of the United States*. Boston, MA: Retrieved from http://www.epa.gov/region1/npdes/permits/2005/finalma0102997fs.pdf.

Worcester Business Journal. (2013, April 1, 2013). New Life In An Old Setting: Worcester's Canal District Embarks On A New Era. *Worcester Business Journal*.

Wright, S. J., Ghalib, S., & Eloubaidy, A. (2010). Treatment Shaft for Combined Sewer Overflow Detention. *Water Environment Research, 82*(5), 434-439. doi: 10.2175/106143009X426086

Appendices

Appendix A: Maps from the Department of Public Works

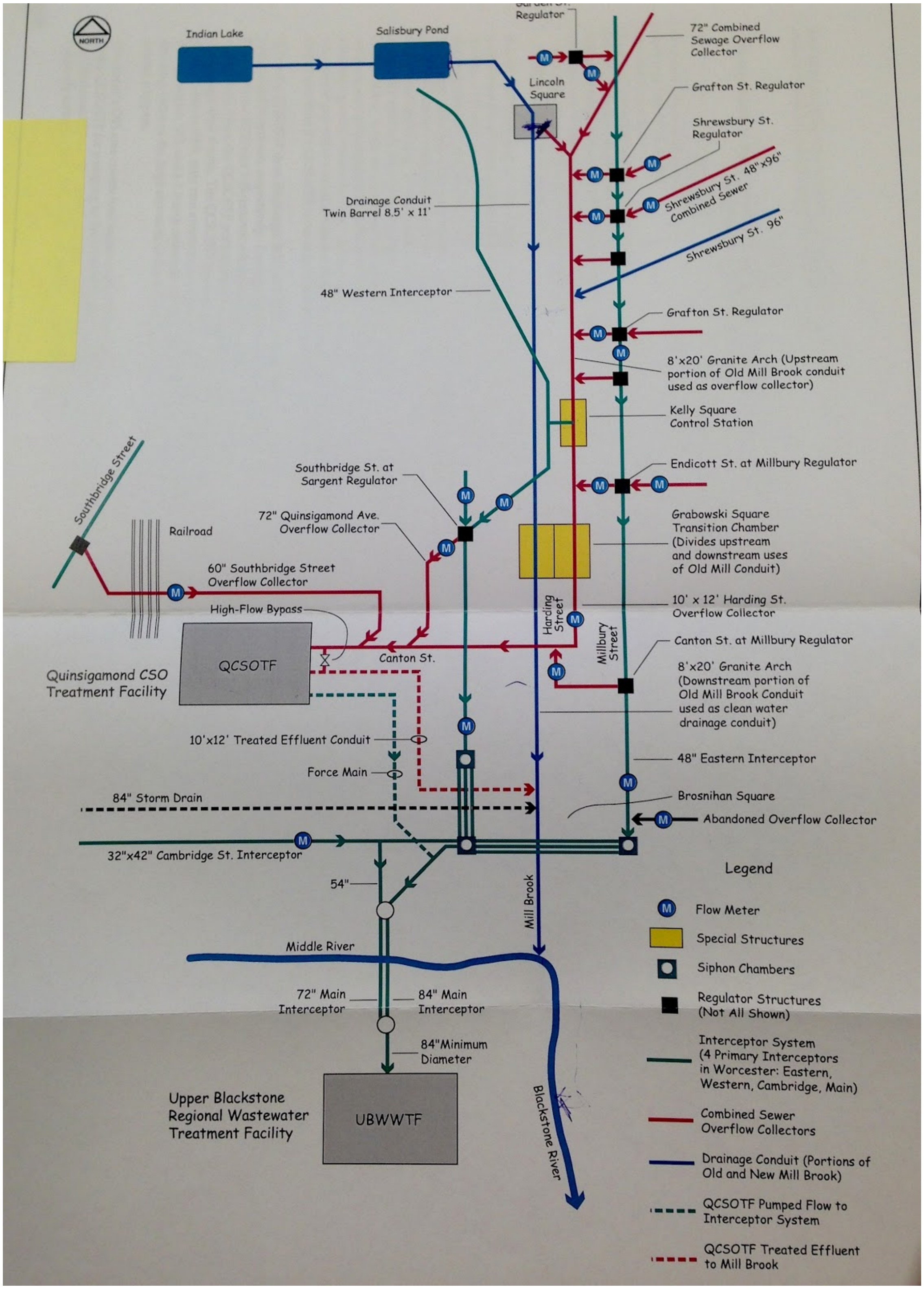


Figure A. 1 Schematic of Old Mill Brook

Figure A. 2: Sewer Line Activity in Old Mill Brook

Figure A. 3: Map of the Blackstone Canal (Highlighted) and Mill Brook Conduit (Blue)

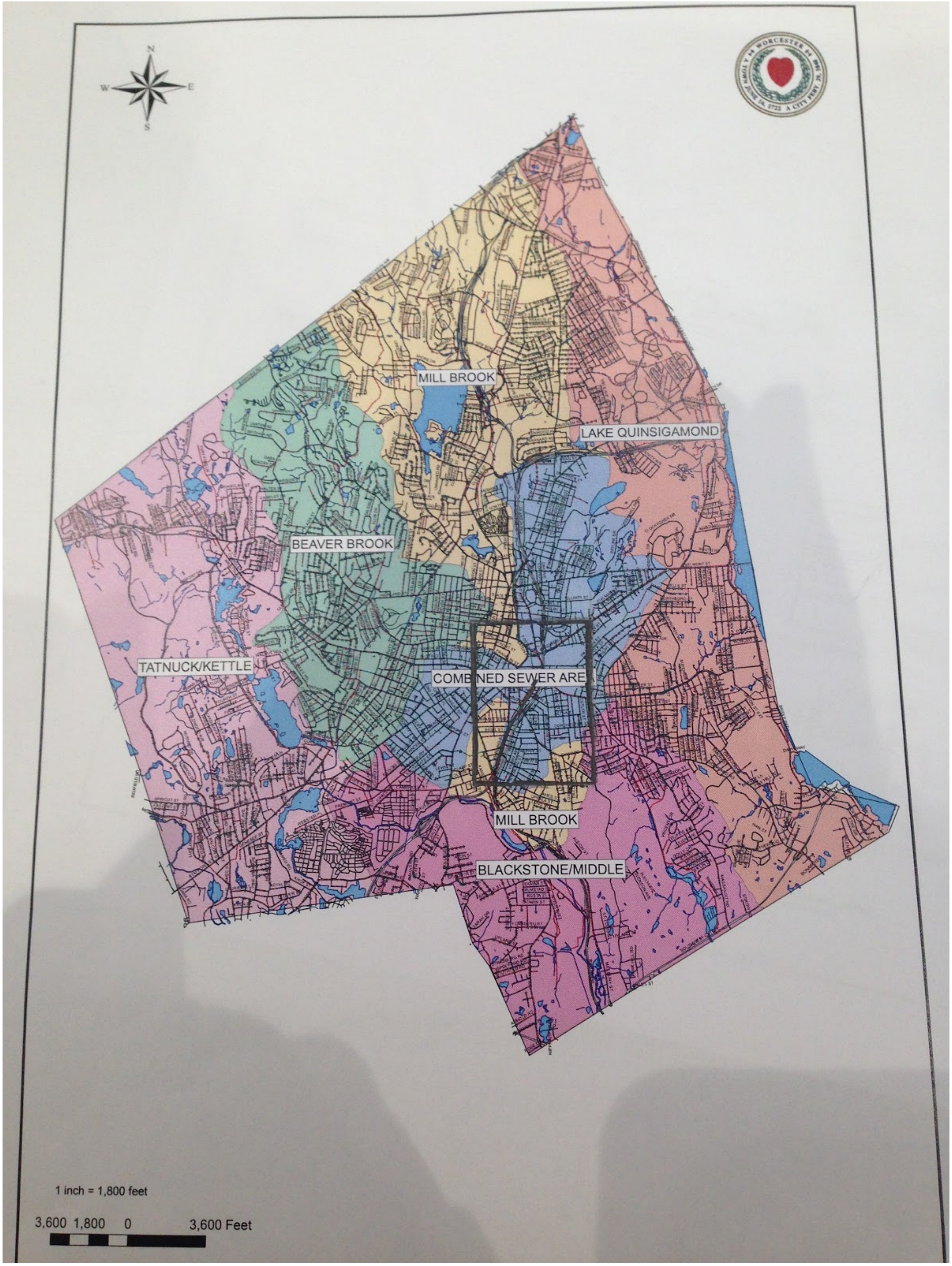


Figure A. 4: Sewer Systems in Worcester, MA

Appendix B: DPW Plans for Improvements to Combined Sewage System

Contract No. 3

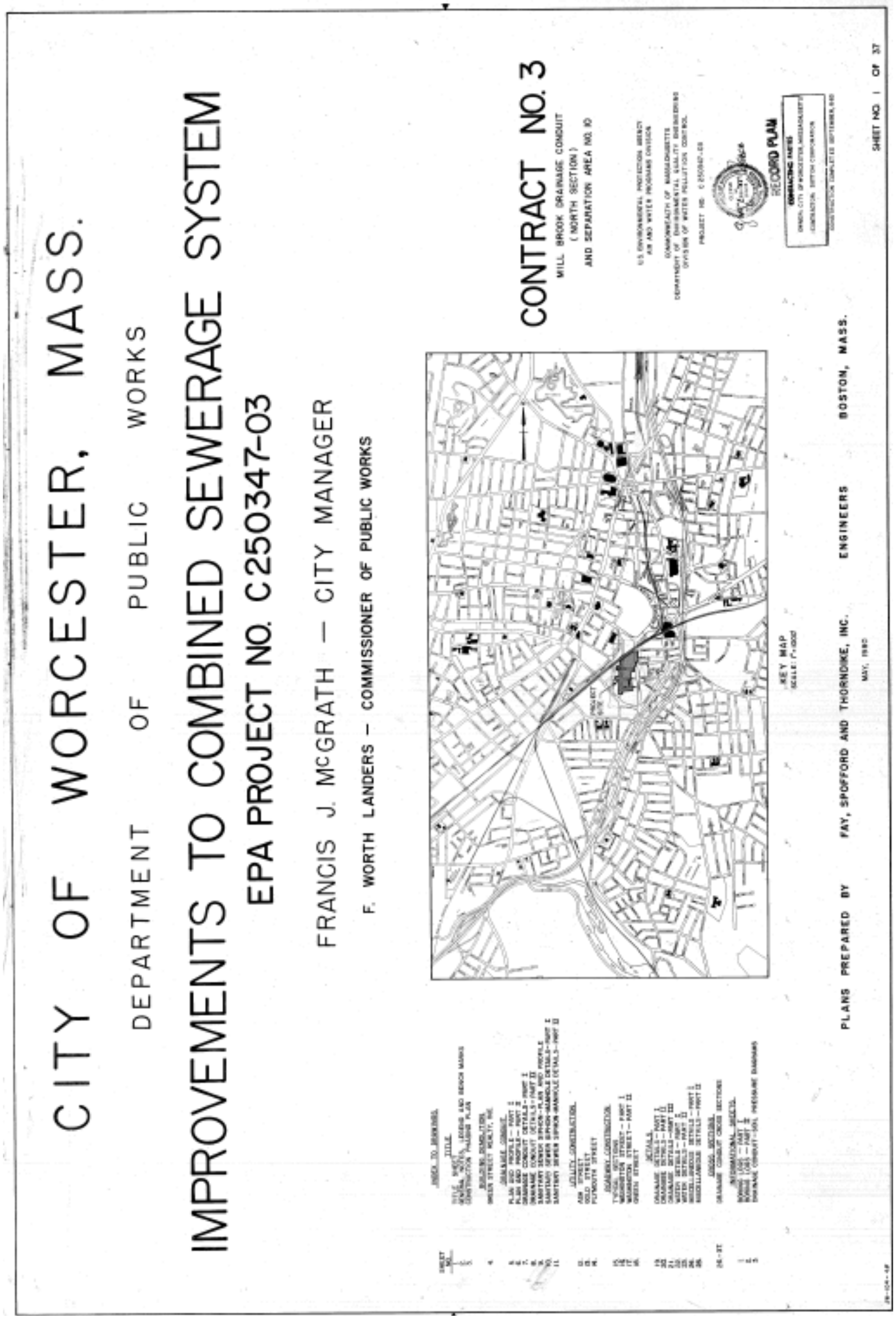


Figure B. 1: Cover Page for Improvements to Combined Sewerage System Contract No. 3

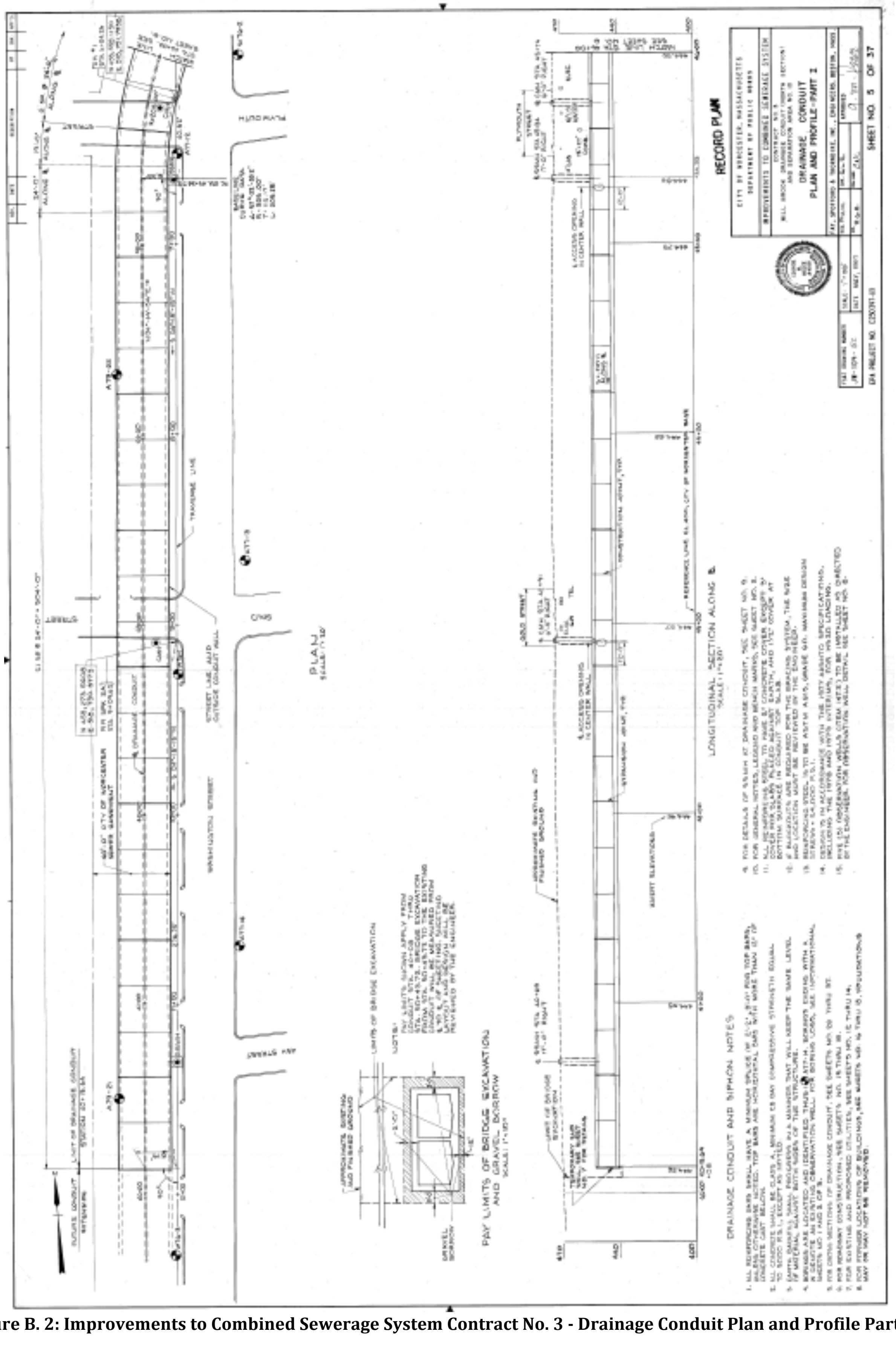


Figure B. 2: Improvements to Combined Sewerage System Contract No. 3 - Drainage Conduit Plan and Profile Part I

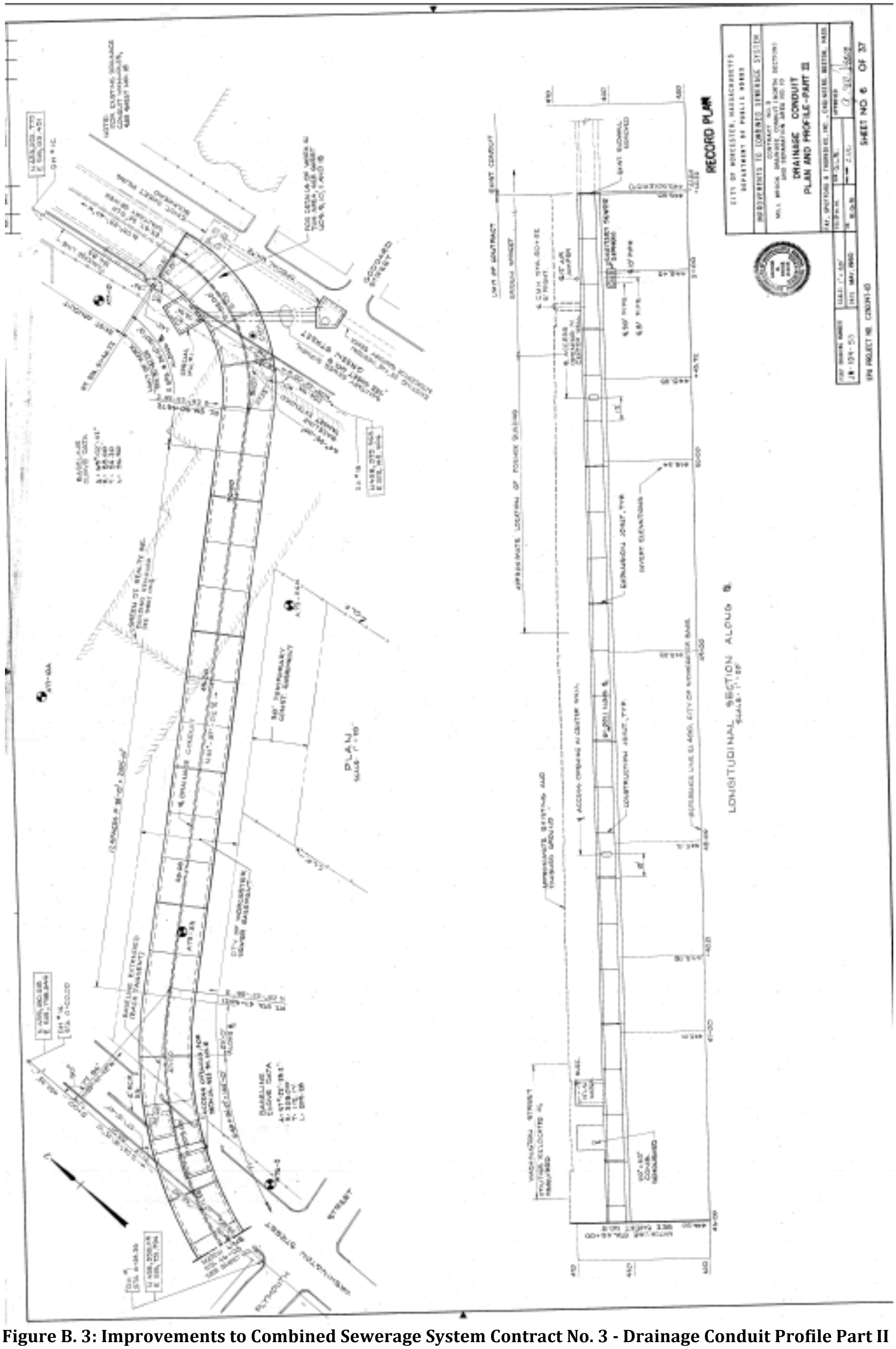


Figure B. 3: Improvements to Combined Sewerage System Contract No. 3 - Drainage Conduit Profile Part II

Contract No. 4-5

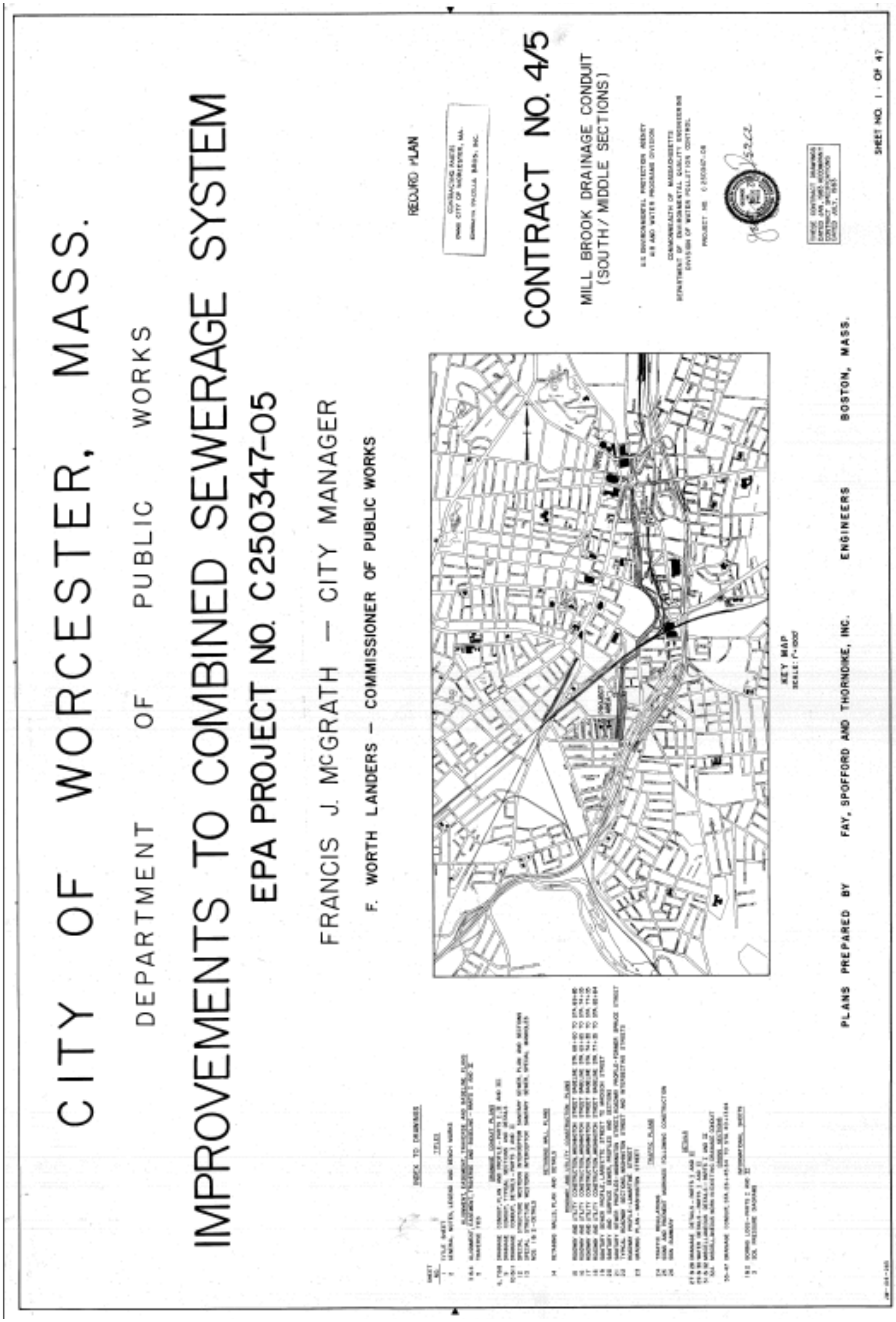


Figure B. 4: Cover Page for Improvements to Combined Sewerage System Contract No. 4-5

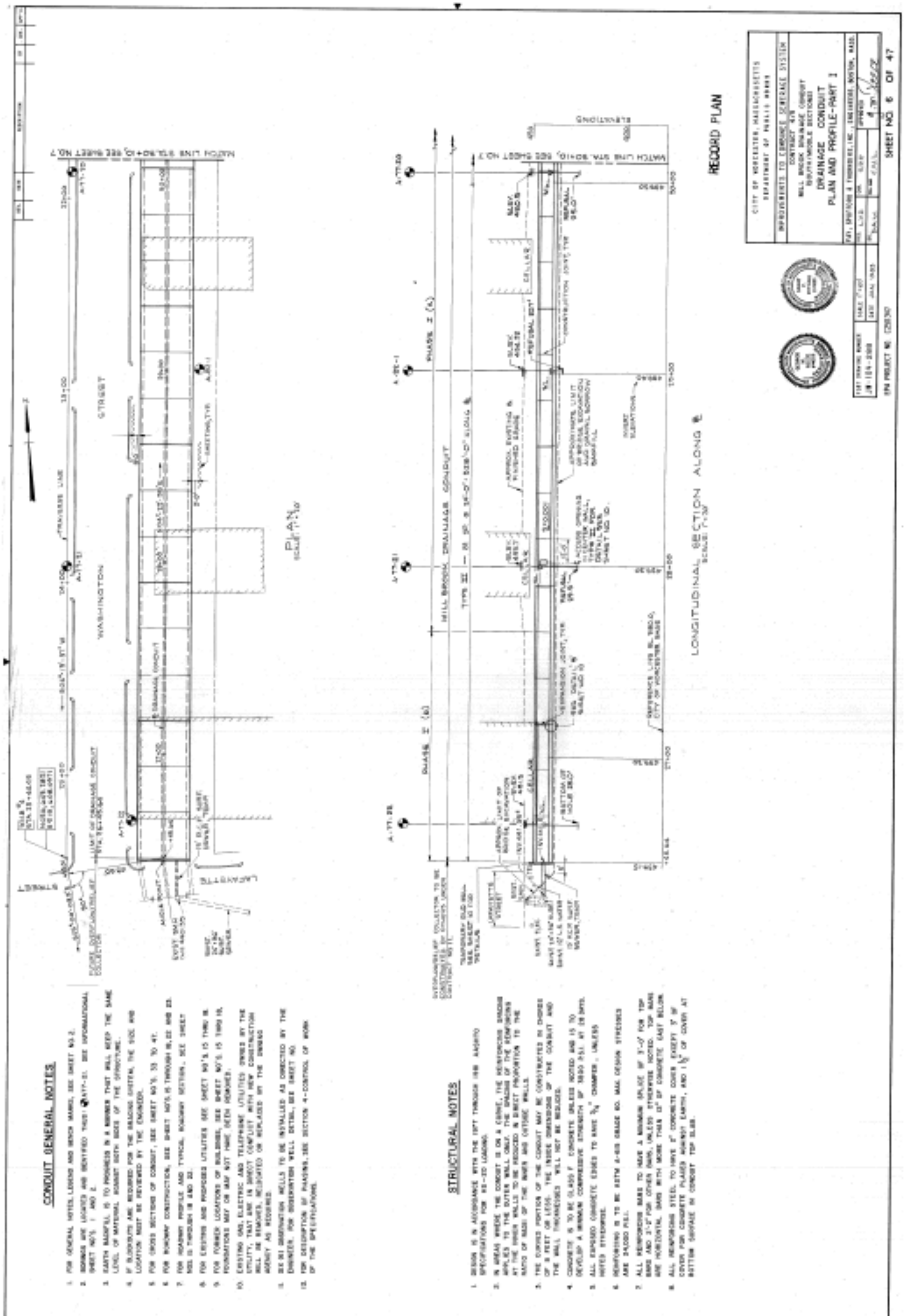


Figure B. 5: Improvements to Combined Sewerage System Contract No. 4-5 - Drainage Conduit Plan and Profile Part I

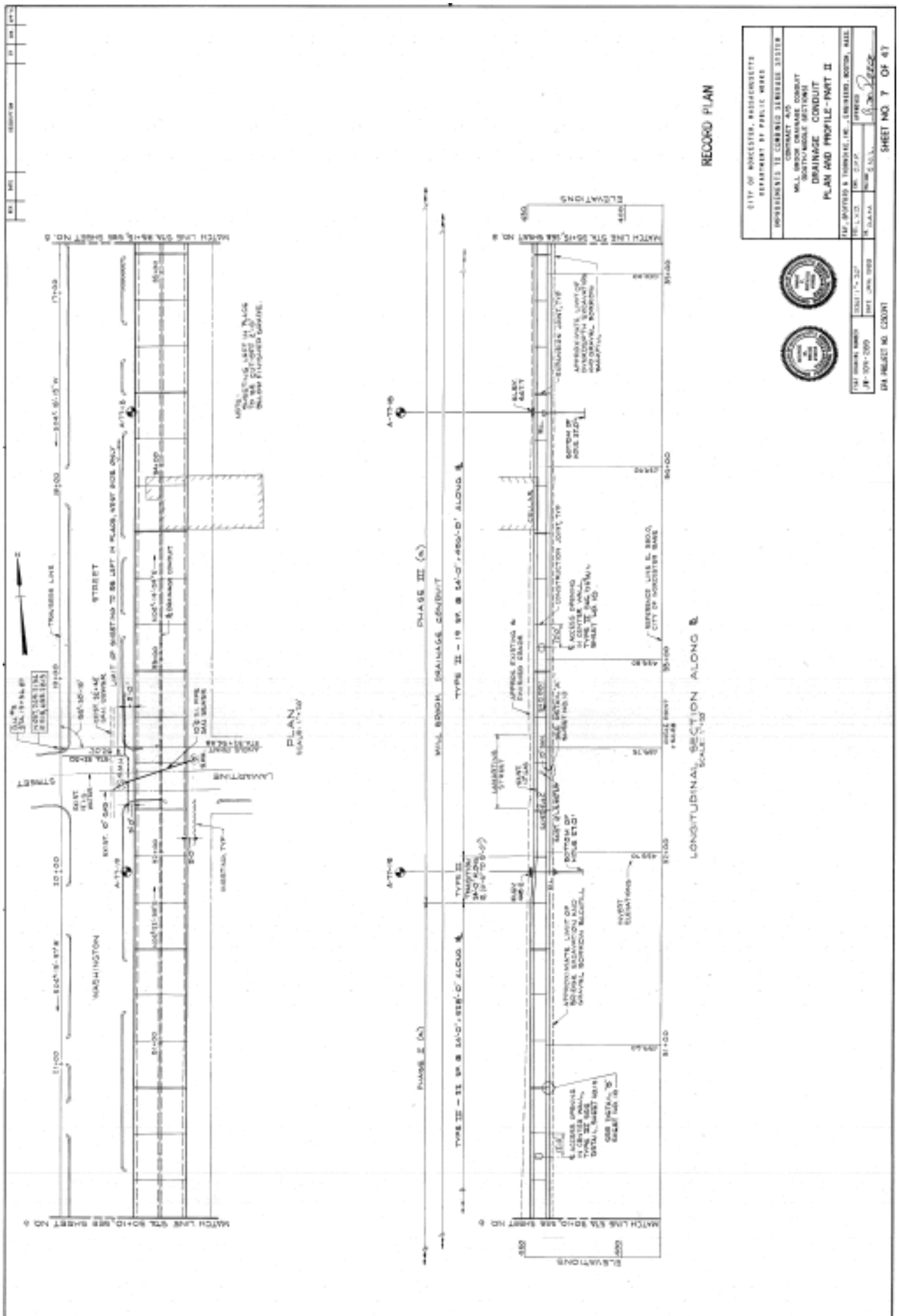


Figure B. 6: Improvements to Combined Sewerage System Contract No. 4-5 - Drainage Conduit Plan and Profile Part II

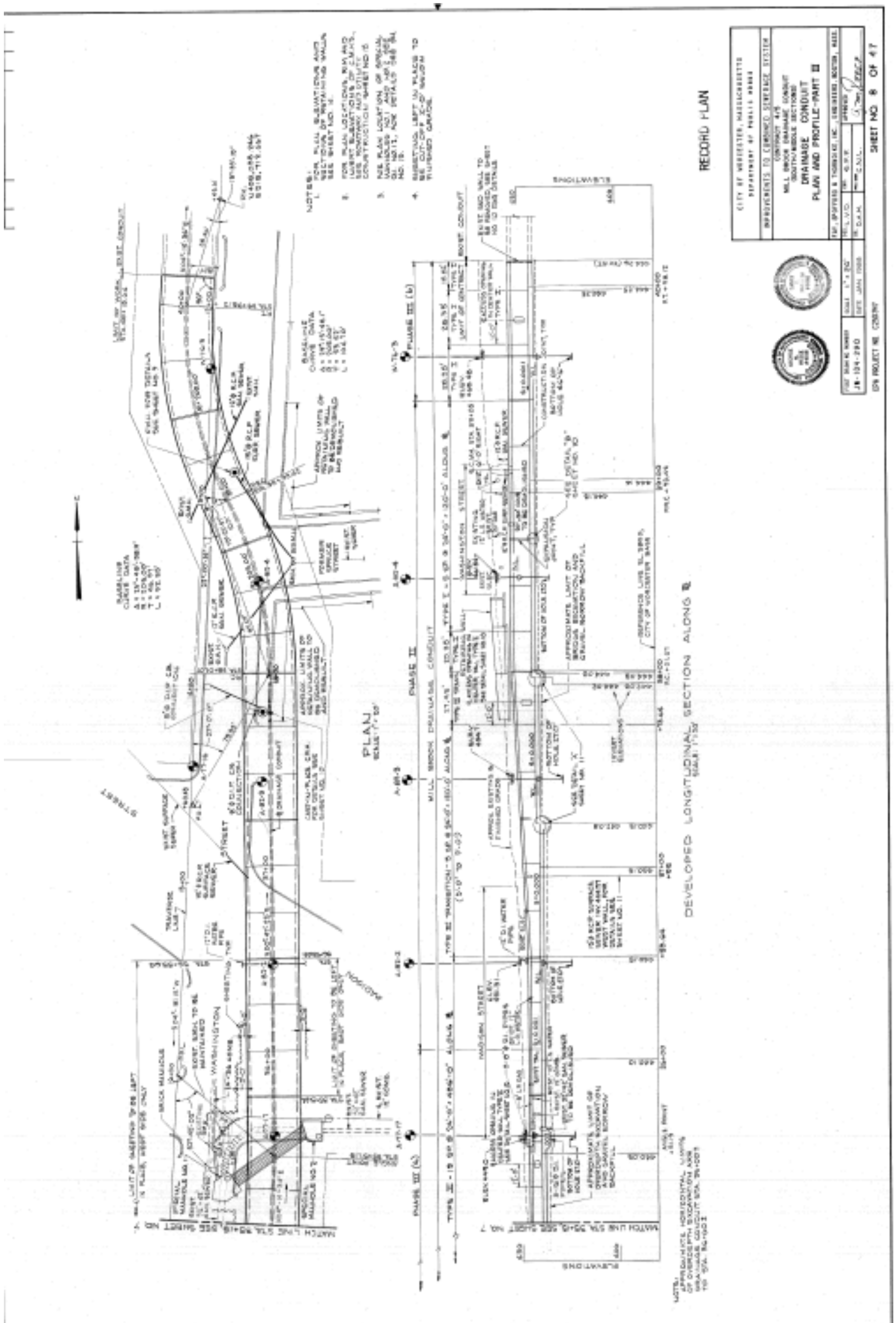


Figure B. 7: Improvements to Combined Sewerage System Contract No. 4-5 - Drainage Conduit Plan and Profile Part III

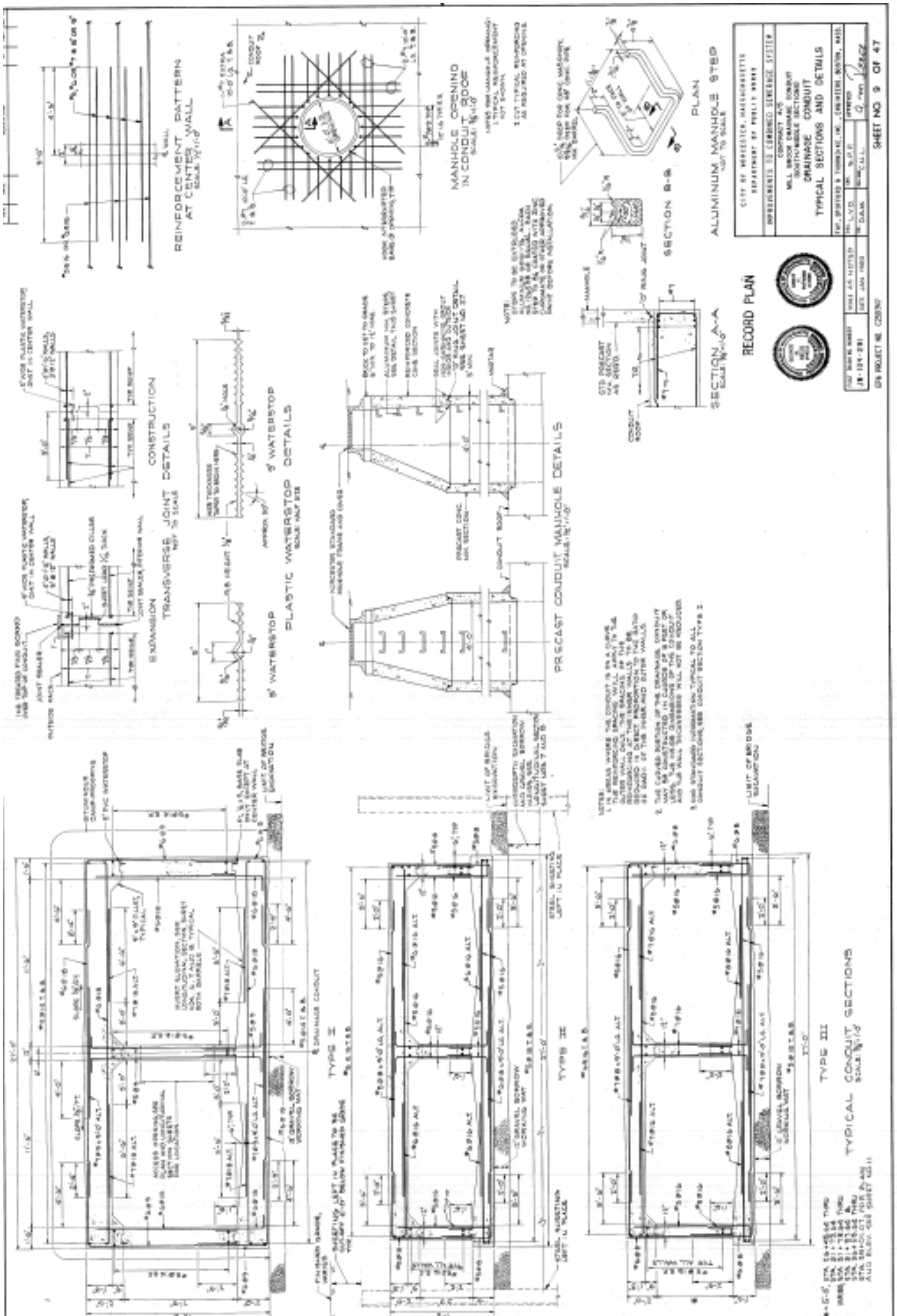


Figure B. 8: Improvements to Combined Sewerage System Contract No. 4-5 - Typical Sections and Details

Contract No. 12

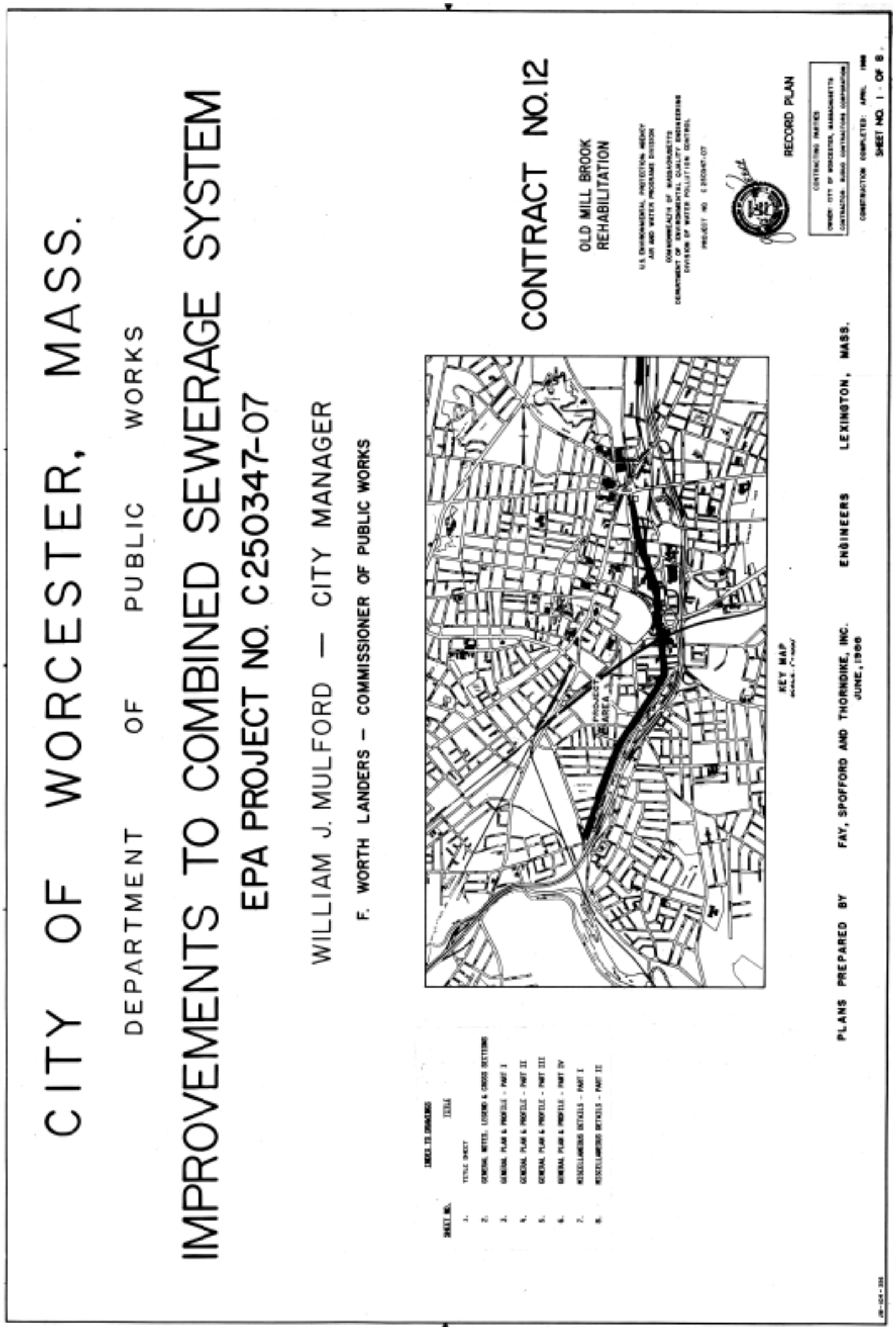


Figure B. 9: Cover Page for Improvements to Combined Sewerage System Contract No. 12

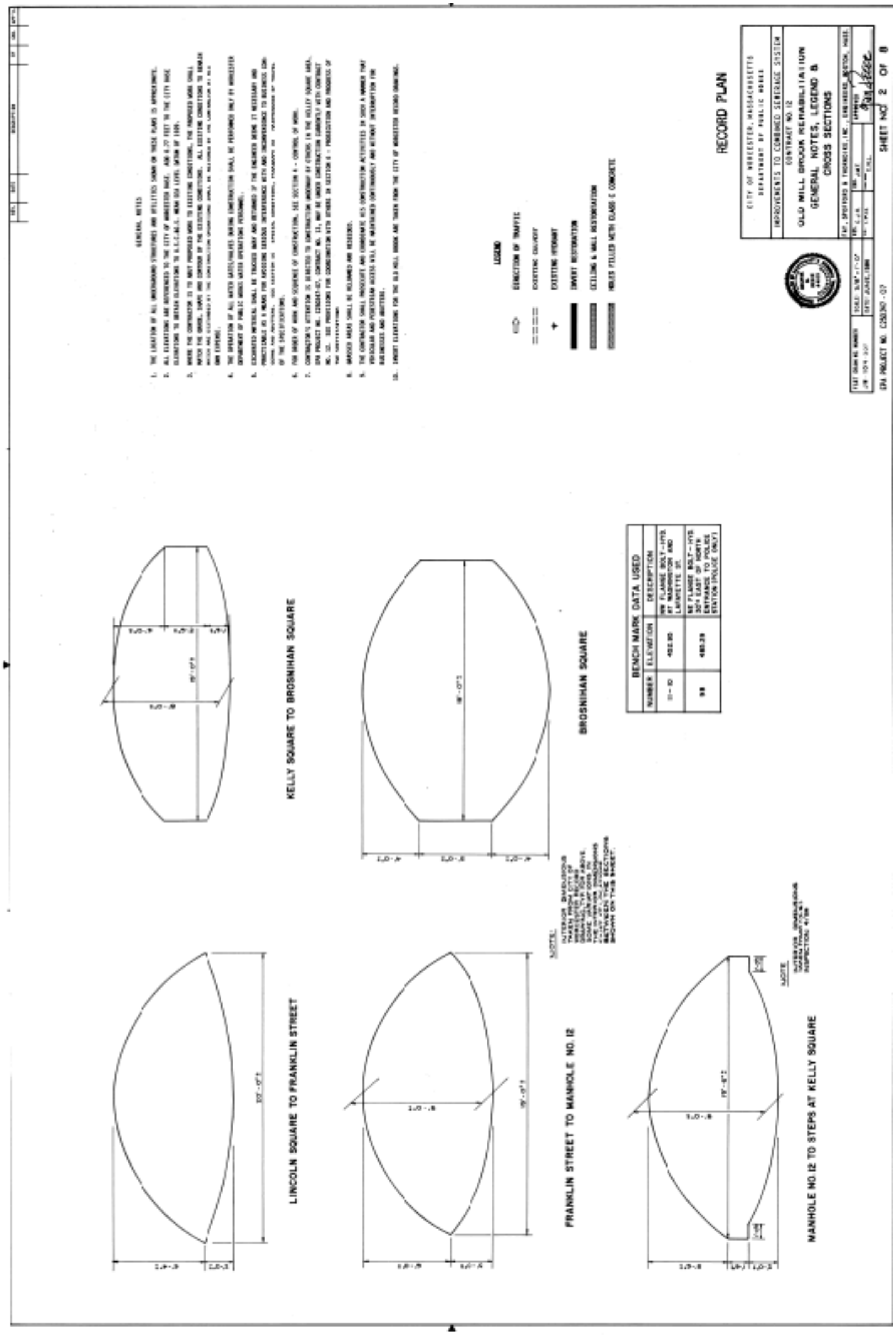


Figure B. 10: Improvements to Combined Sewerage System Contract No. 12 - General Notes, Legend, & Cross-Sections

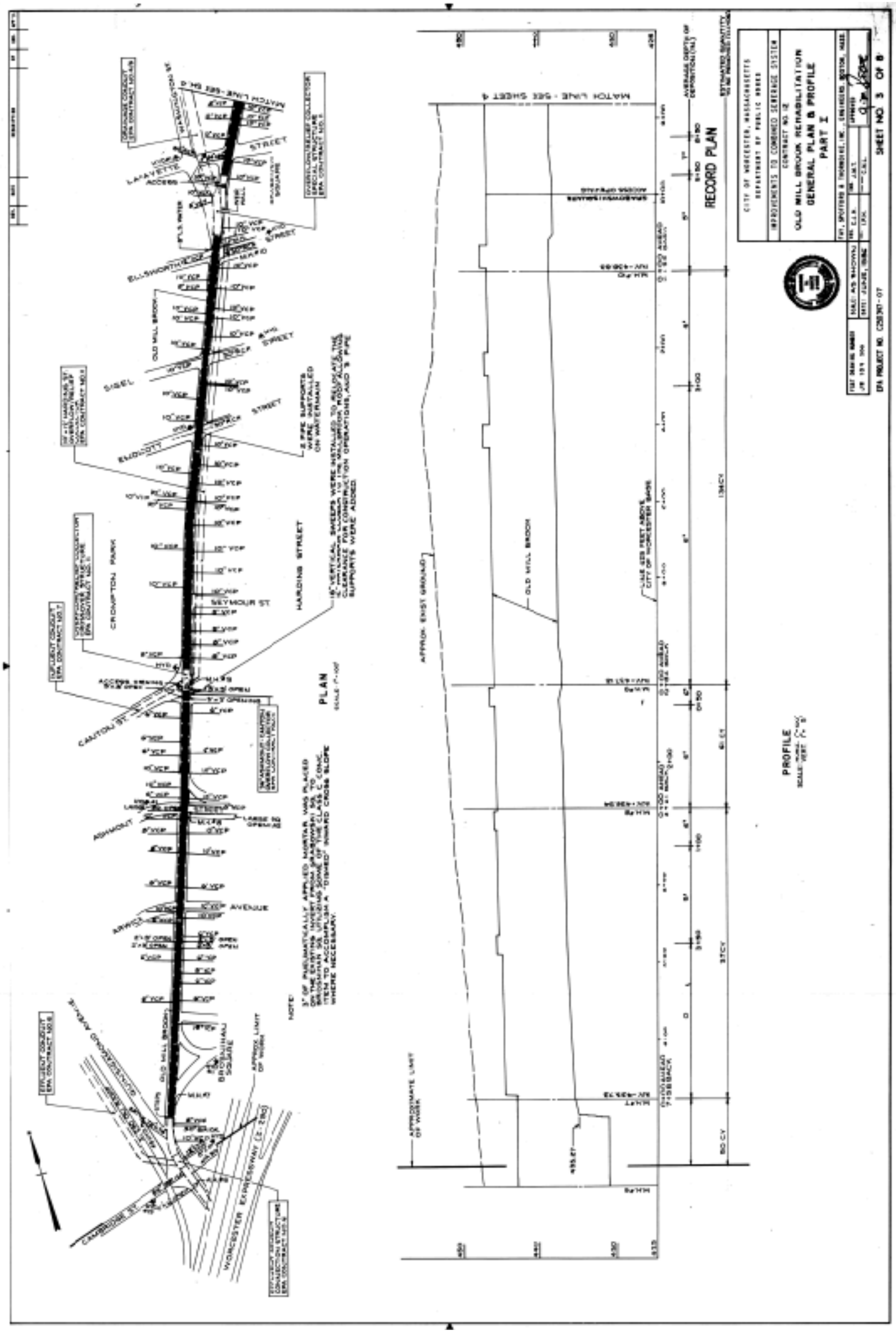


Figure B. 11: Improvements to Combined Sewerage System Contract No. 12 - General Plan & Profile Part I

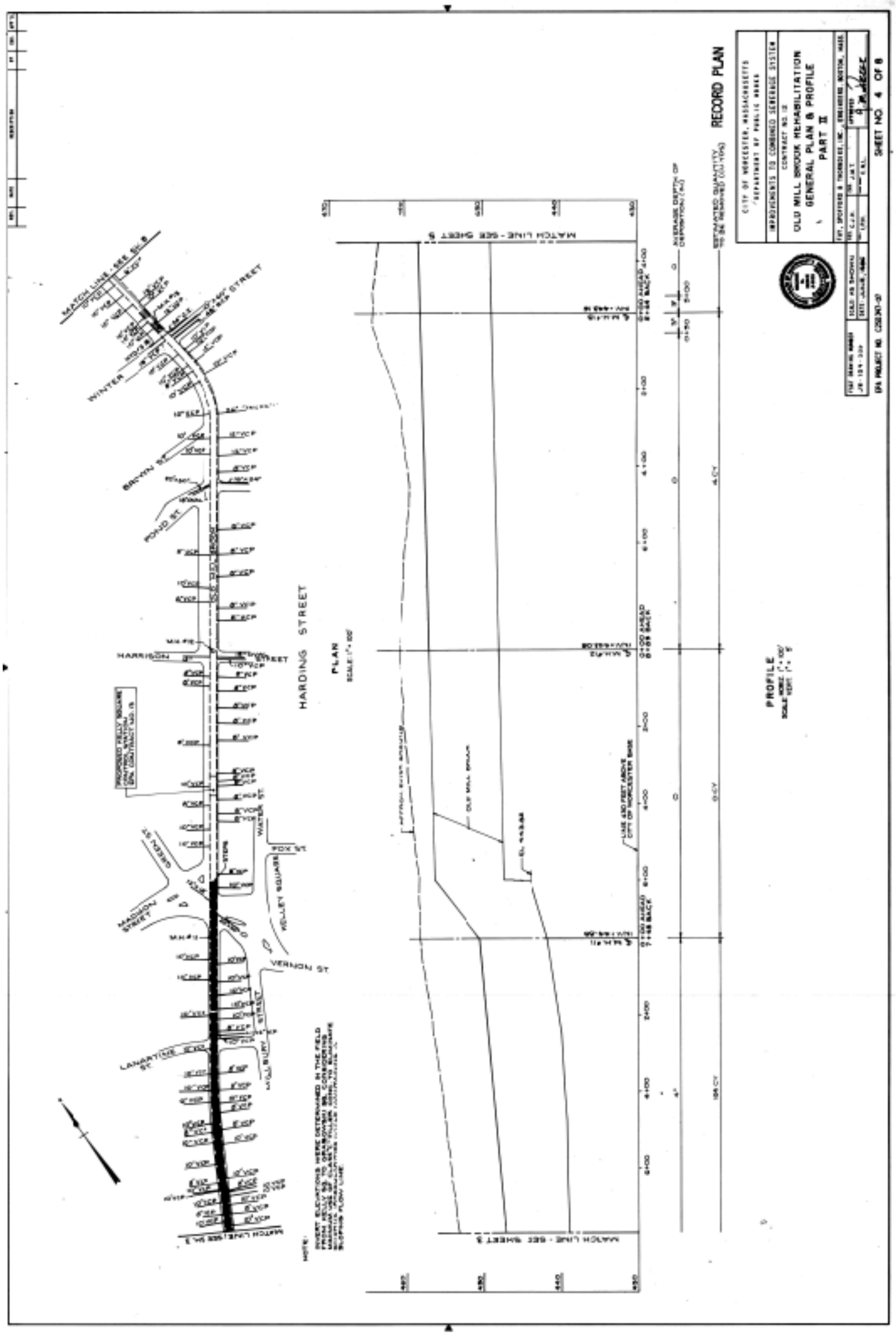


Figure B. 12: Improvements to Combined Sewerage System Contract No. 12 - General Plan & Profile Part II

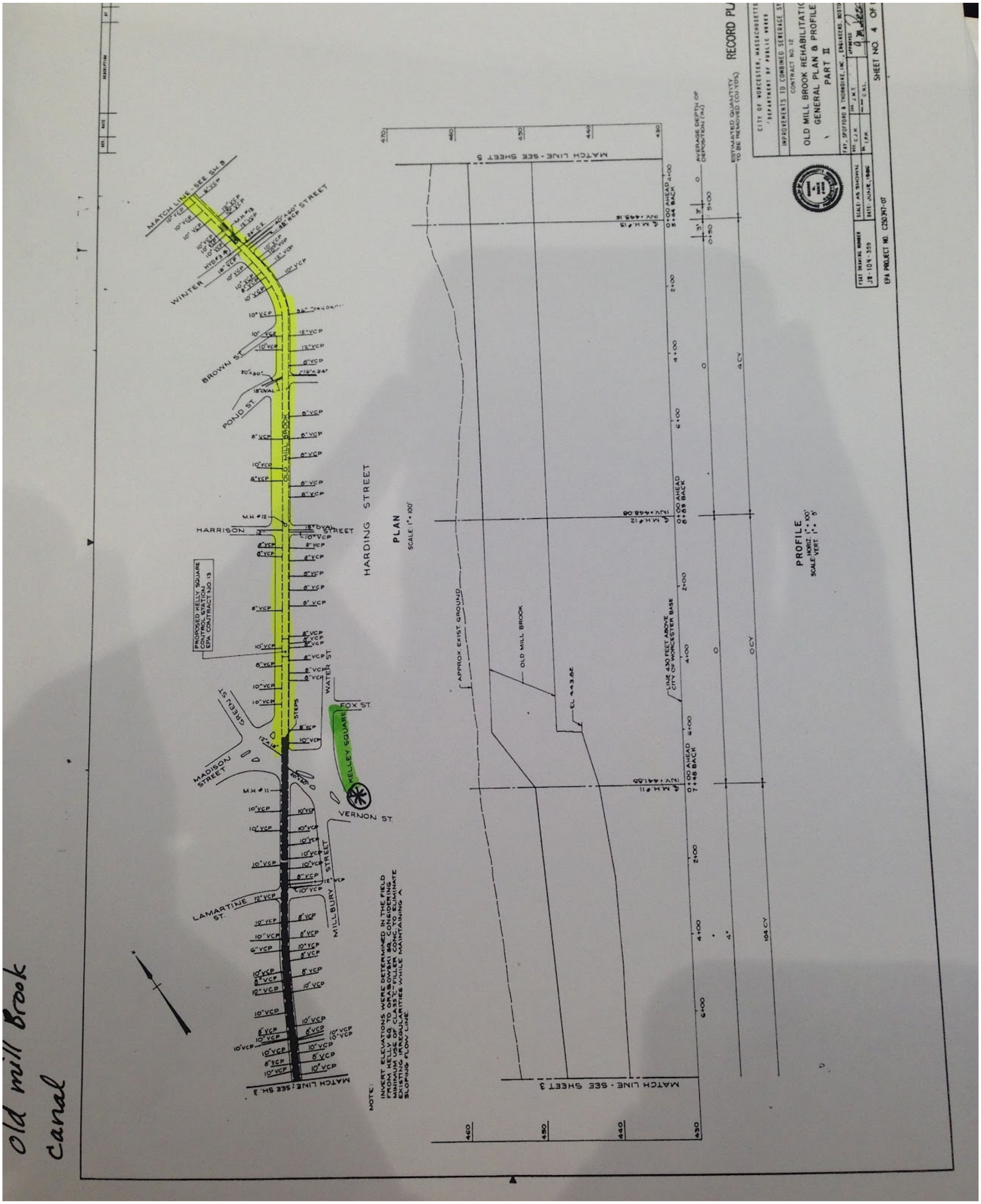


Figure B. 13: Improvements to Combined Sewerage System Contract No. 12 - General Plan and Profile Part II (Highlighted Canal Segment)

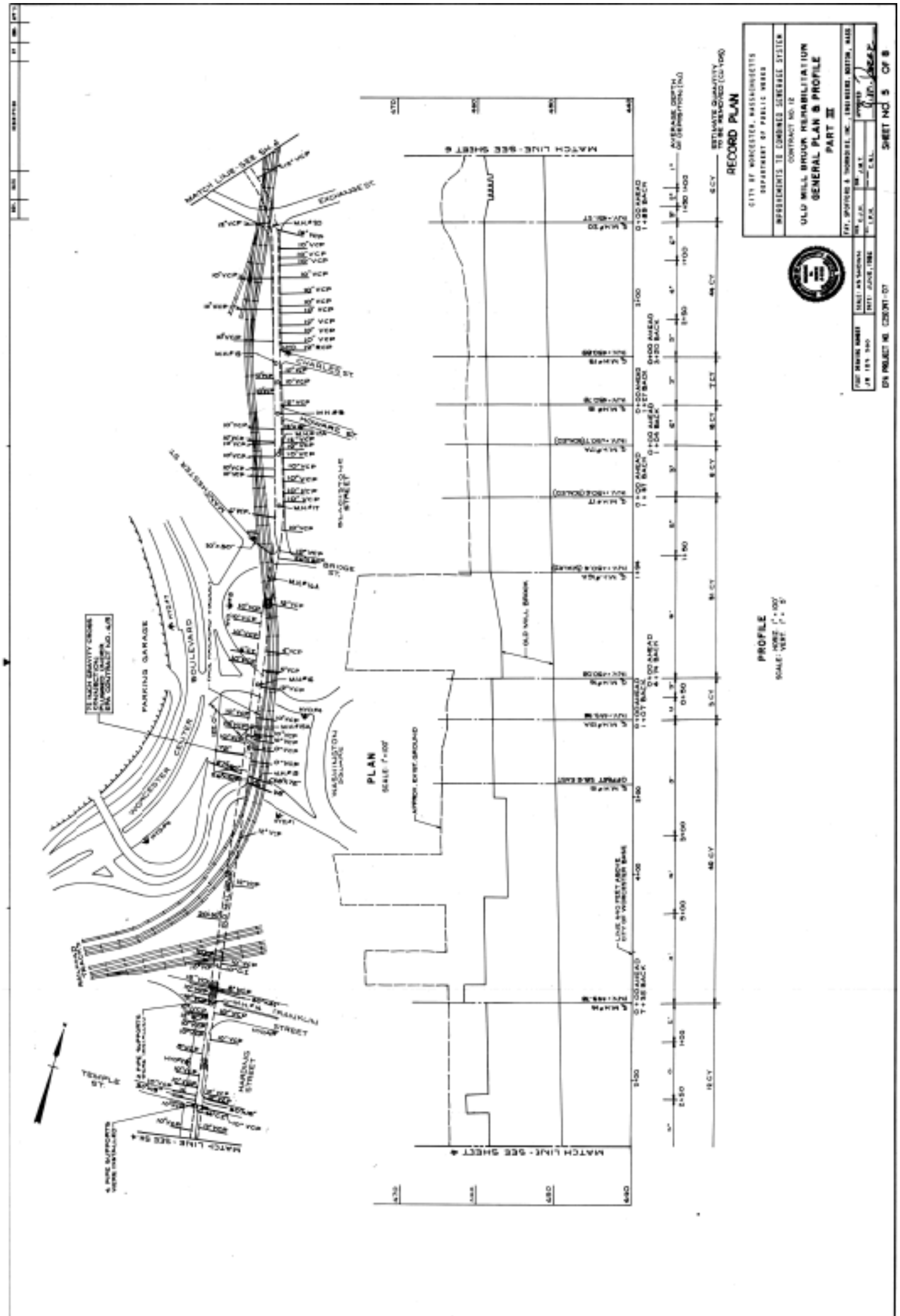


Figure B. 14: Improvements to Combined Sewerage System Contract No. 12 - General Plan & Profile Part III

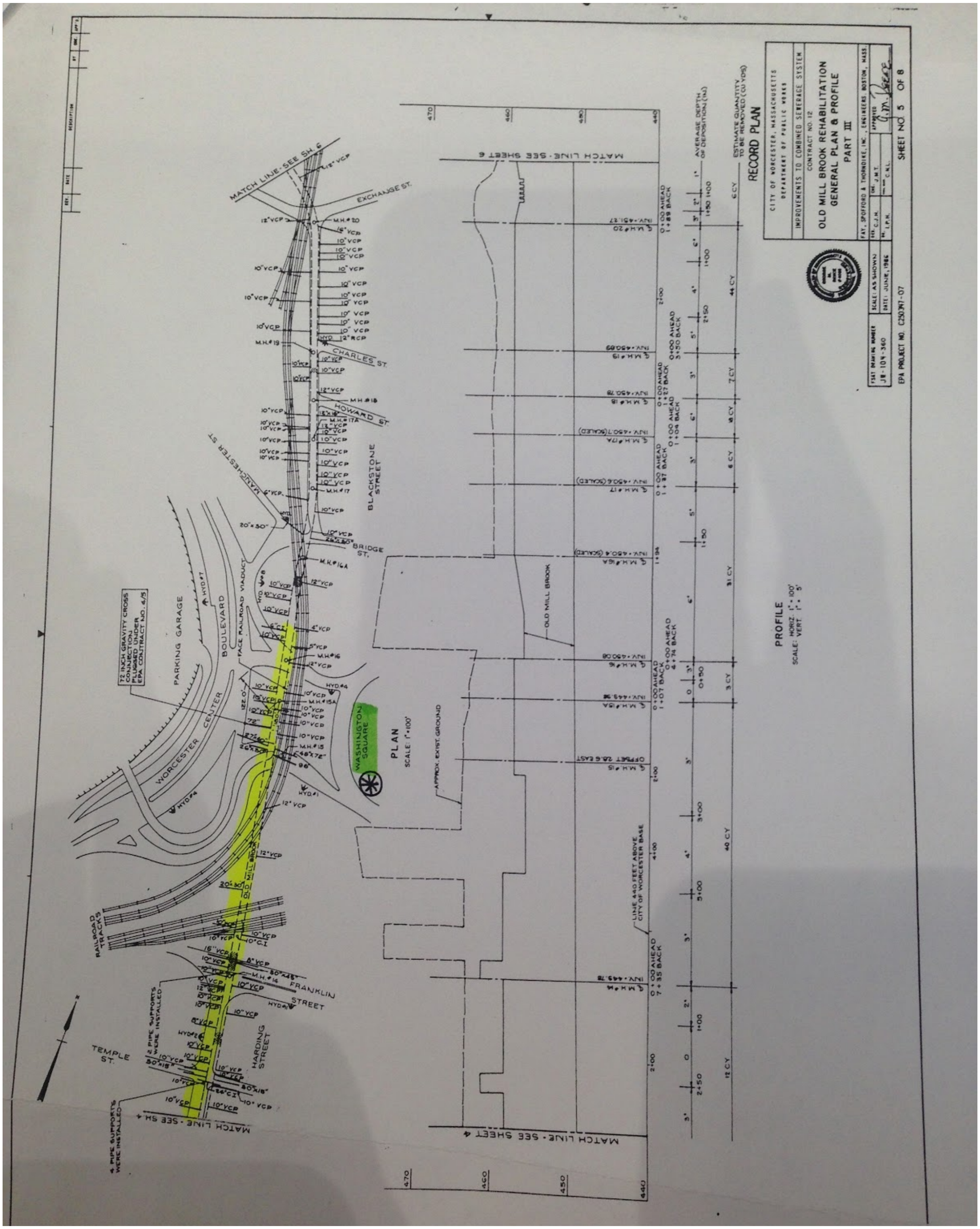


Figure B. 15: Improvements to Combined Sewerage System Contract No. 12 - General Plan & Profile Part III (Highlighted Canal Segment)

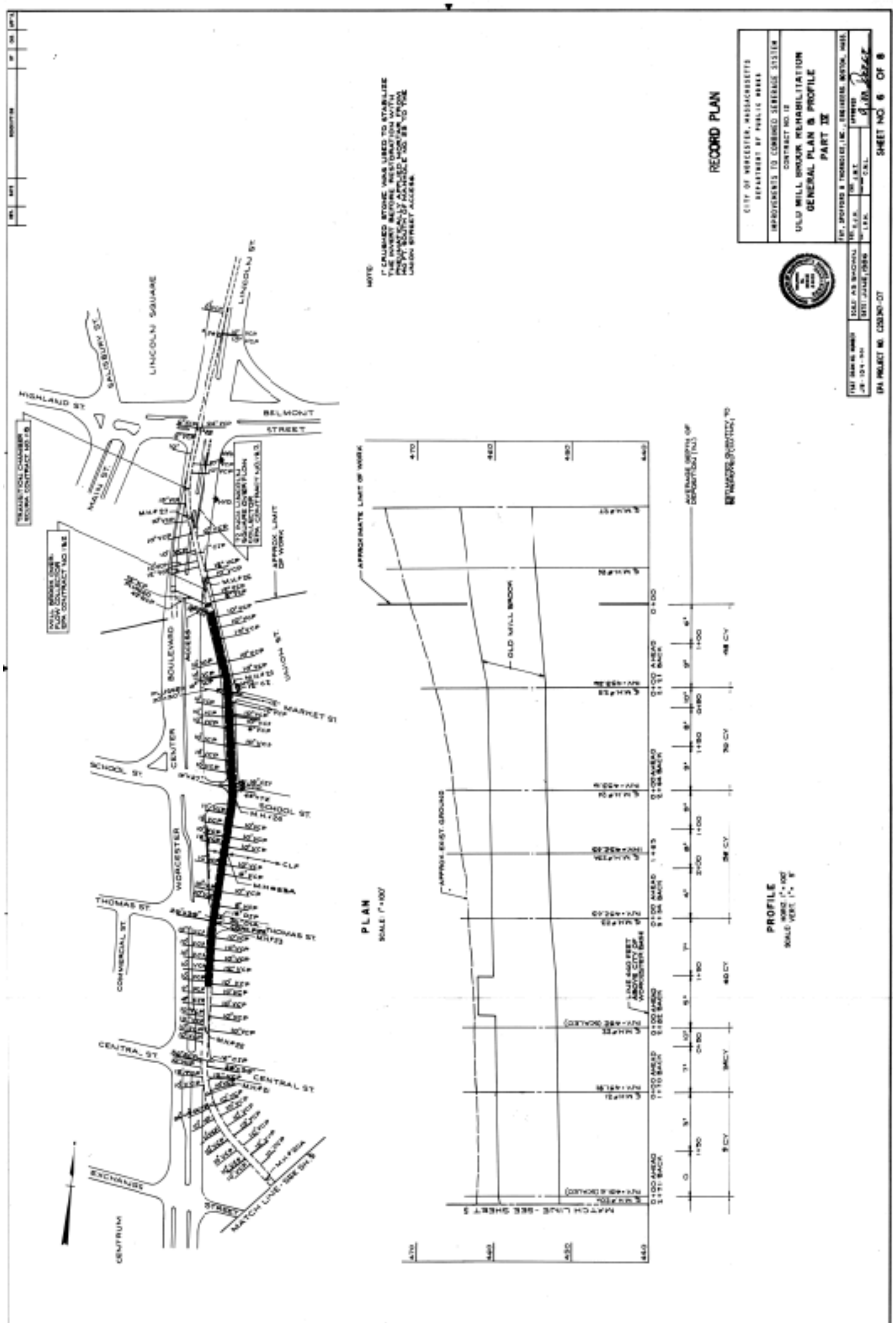


Figure B. 16: Improvements to Combined Sewerage System Contract No. 12 - General Plan & Profile Part IV

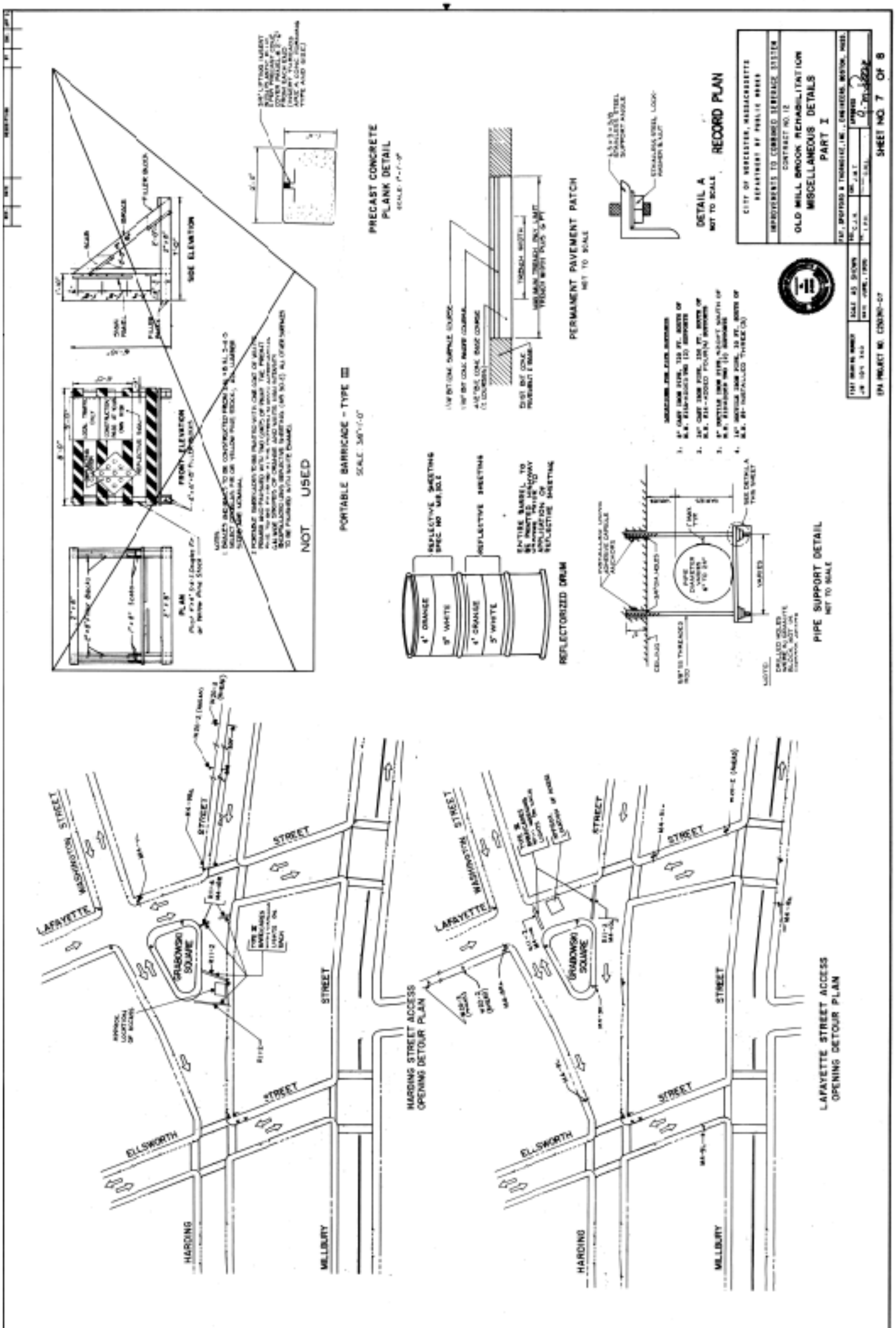


Figure B. 17: Improvements to Combined Sewerage System Contract No. 12 - Misc. Details Part I

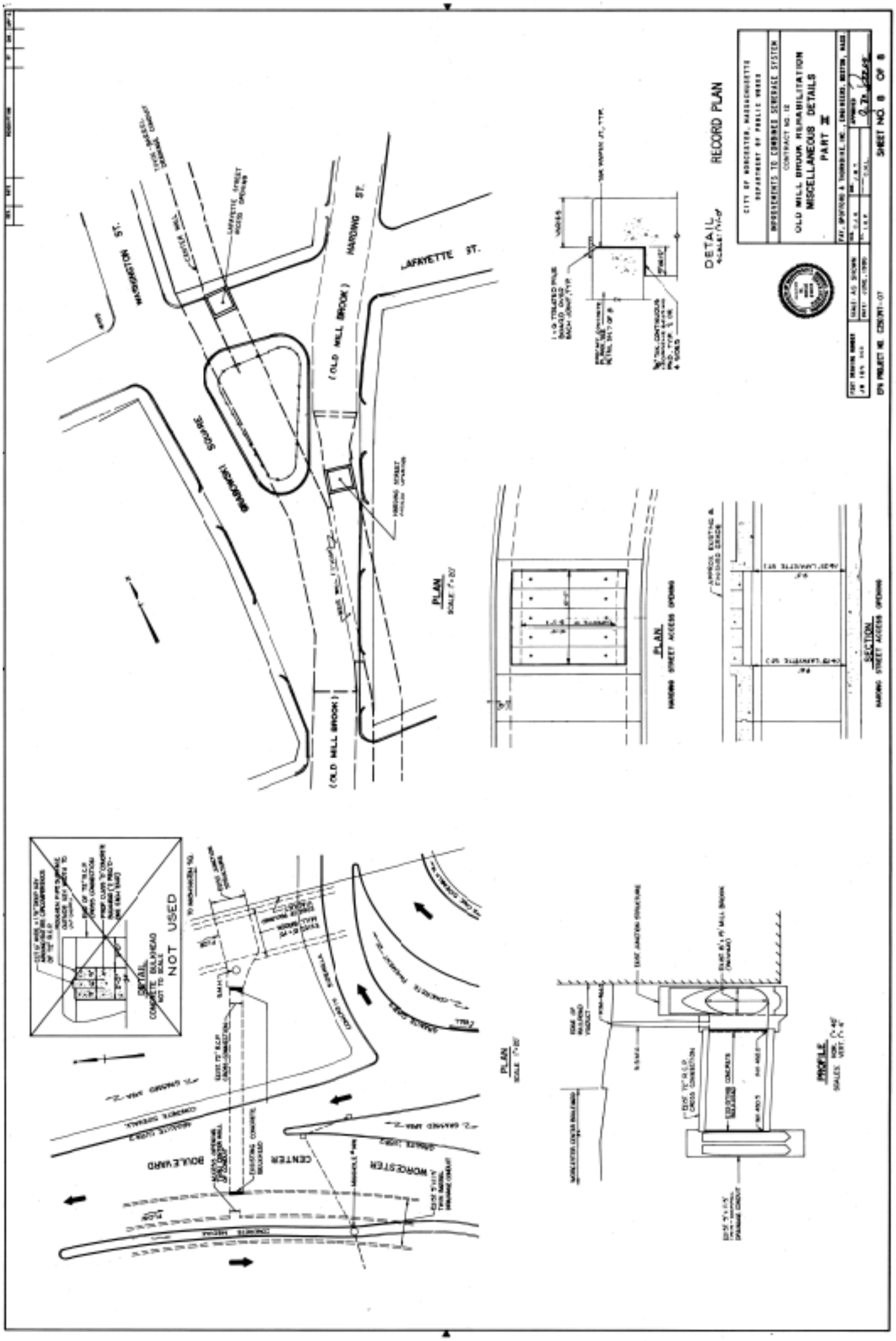


Figure B. 18: Improvements to Combined Sewerage System Contract No. 12 - Misc. Details Part II

Appendix C: DPW Plans for Sewer Overflow Regulators

Contract No. 5

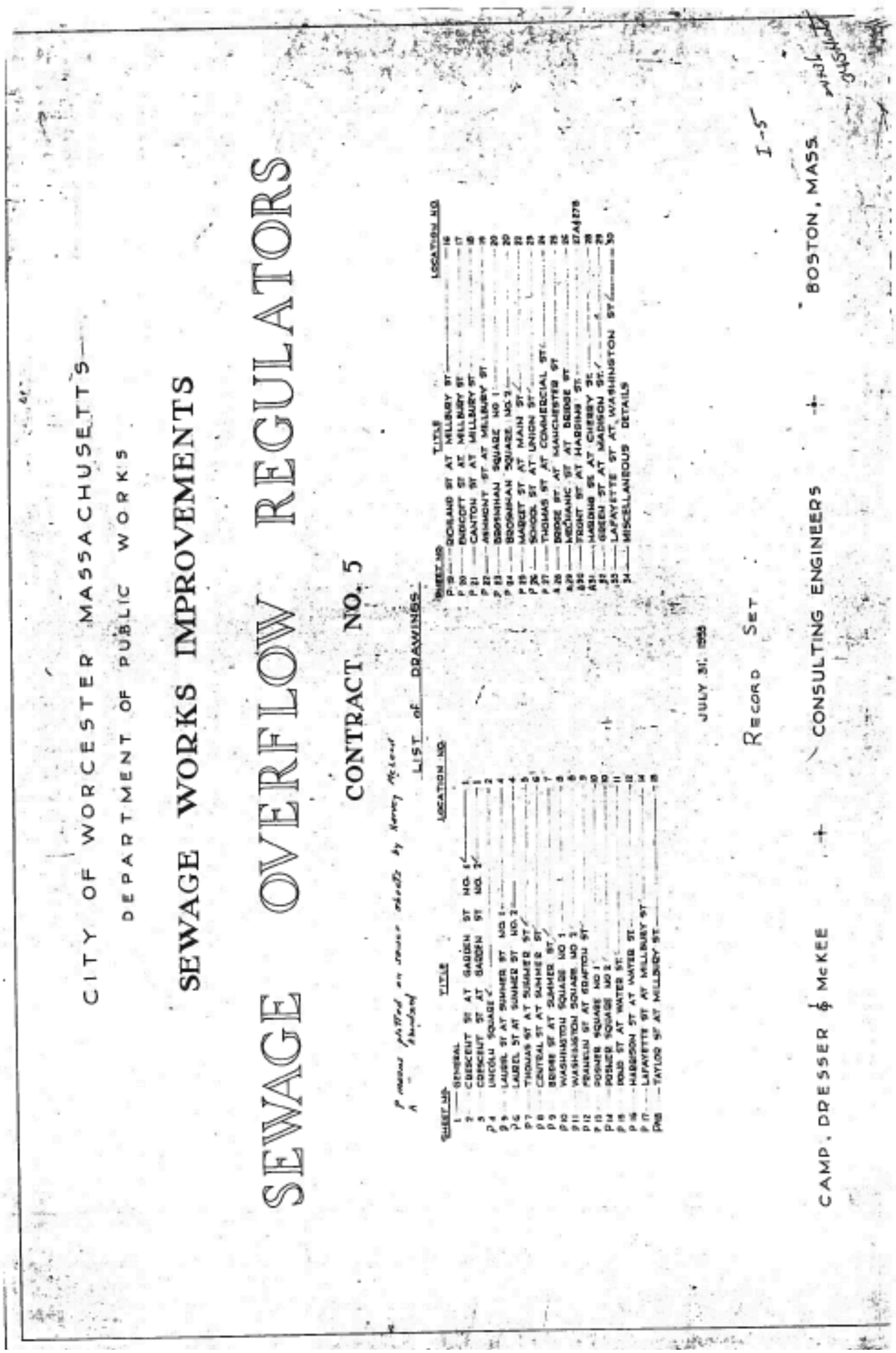


Figure C. 1: Cover Page for Sewer Overflow Regulators Contract No. 5

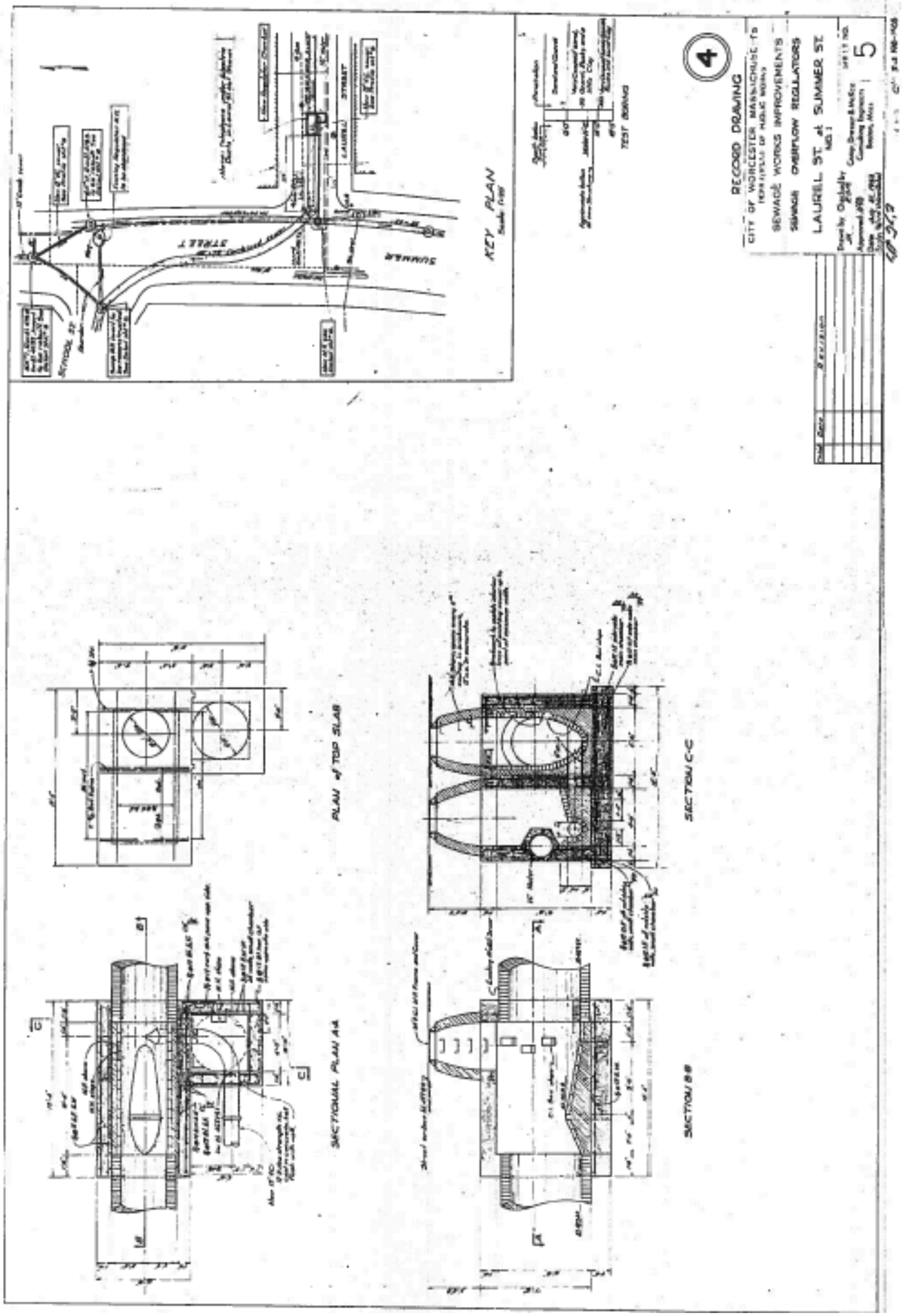


Figure C. 2: Sewer Overflow Regulators Contract No. 5 - Laurel St. at Summer St.

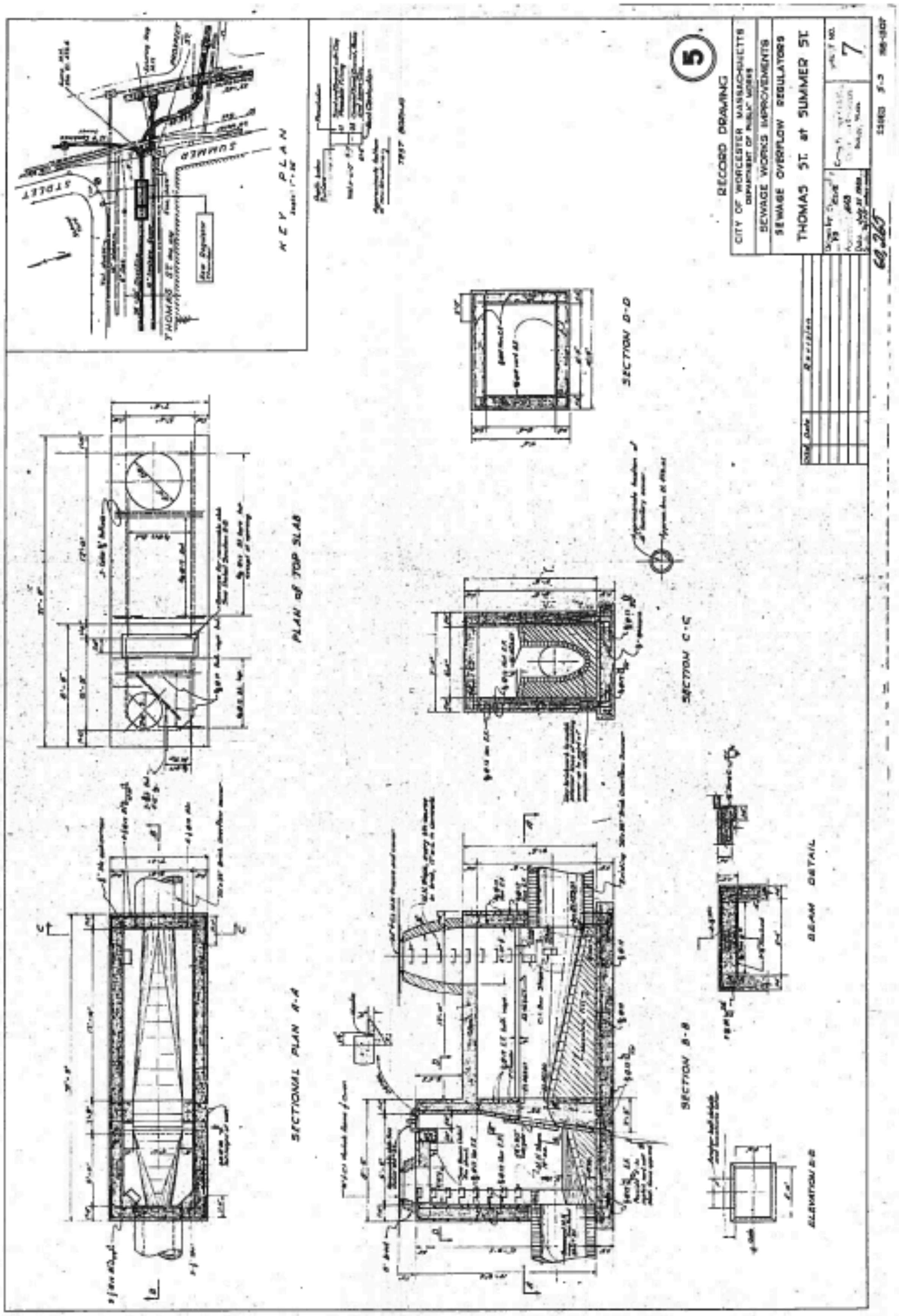


Figure C. 3: Sewer Overflow Regulators Contract No. 5 - Thomas St. at Summer St.

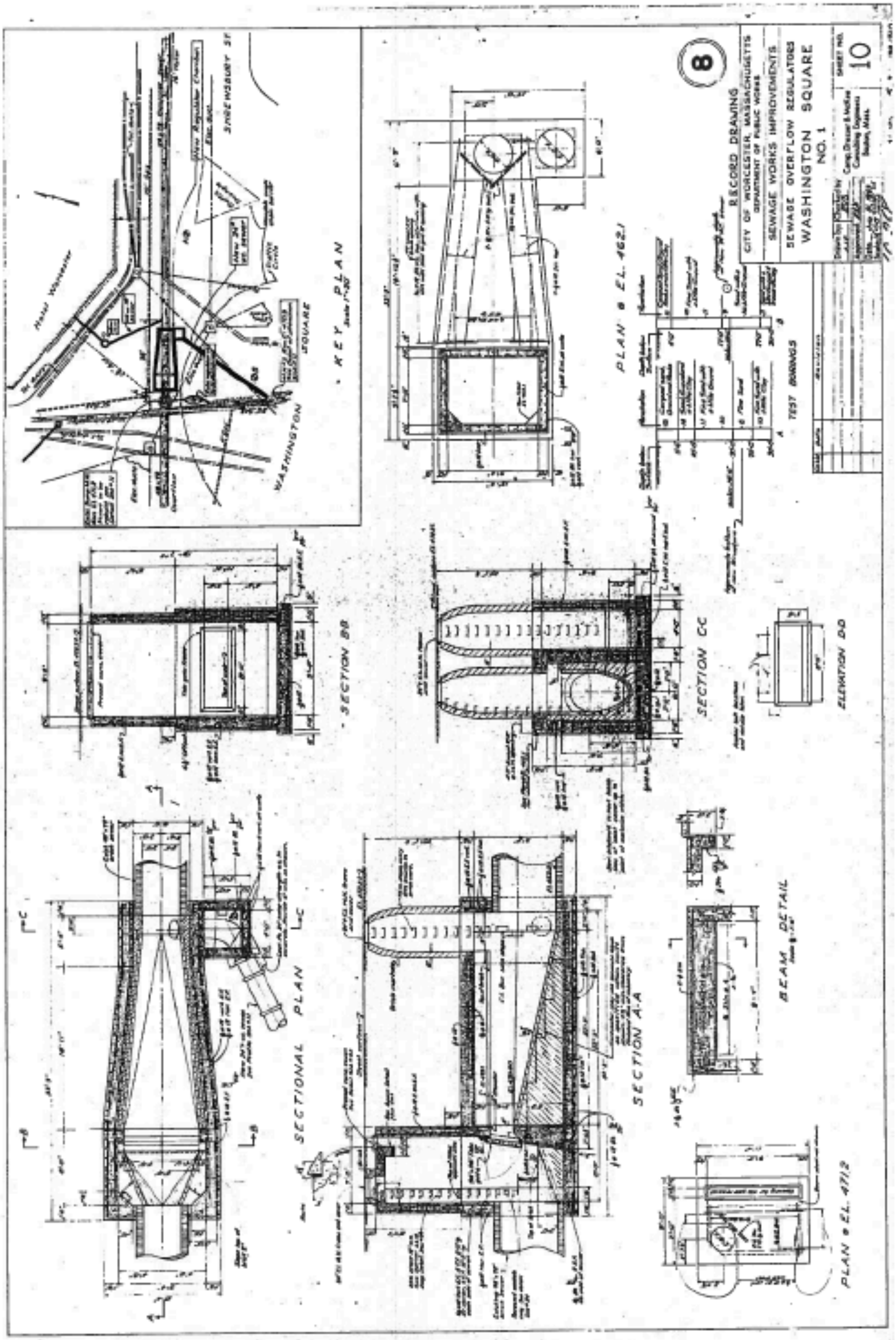


Figure C. 4: Sewer Overflow Regulators Contract No. 5 - Washington Sq. No.1

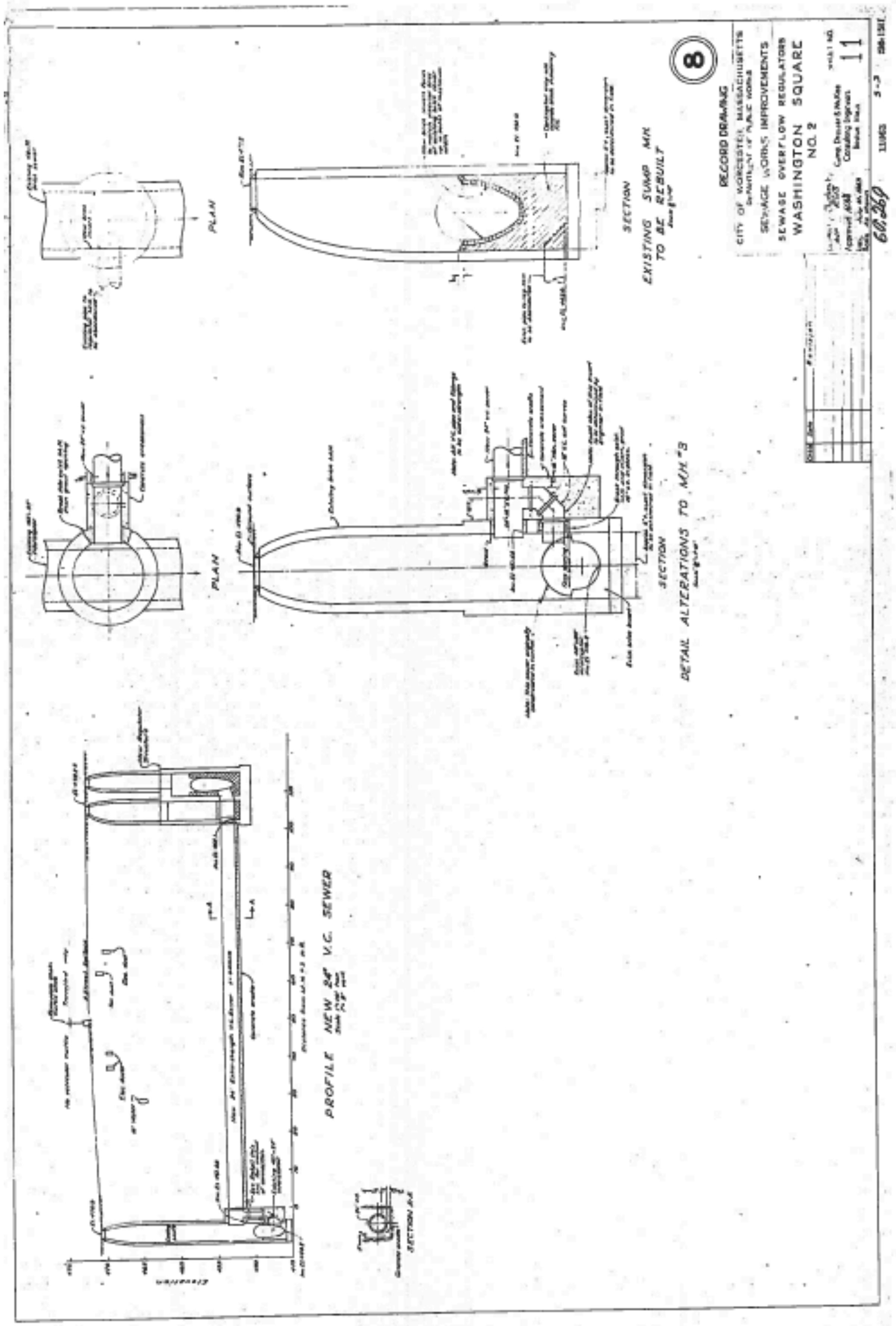


Figure C. 5: Sewer Overflow Regulators Contract No. 5 - Washington Sq. No. 2

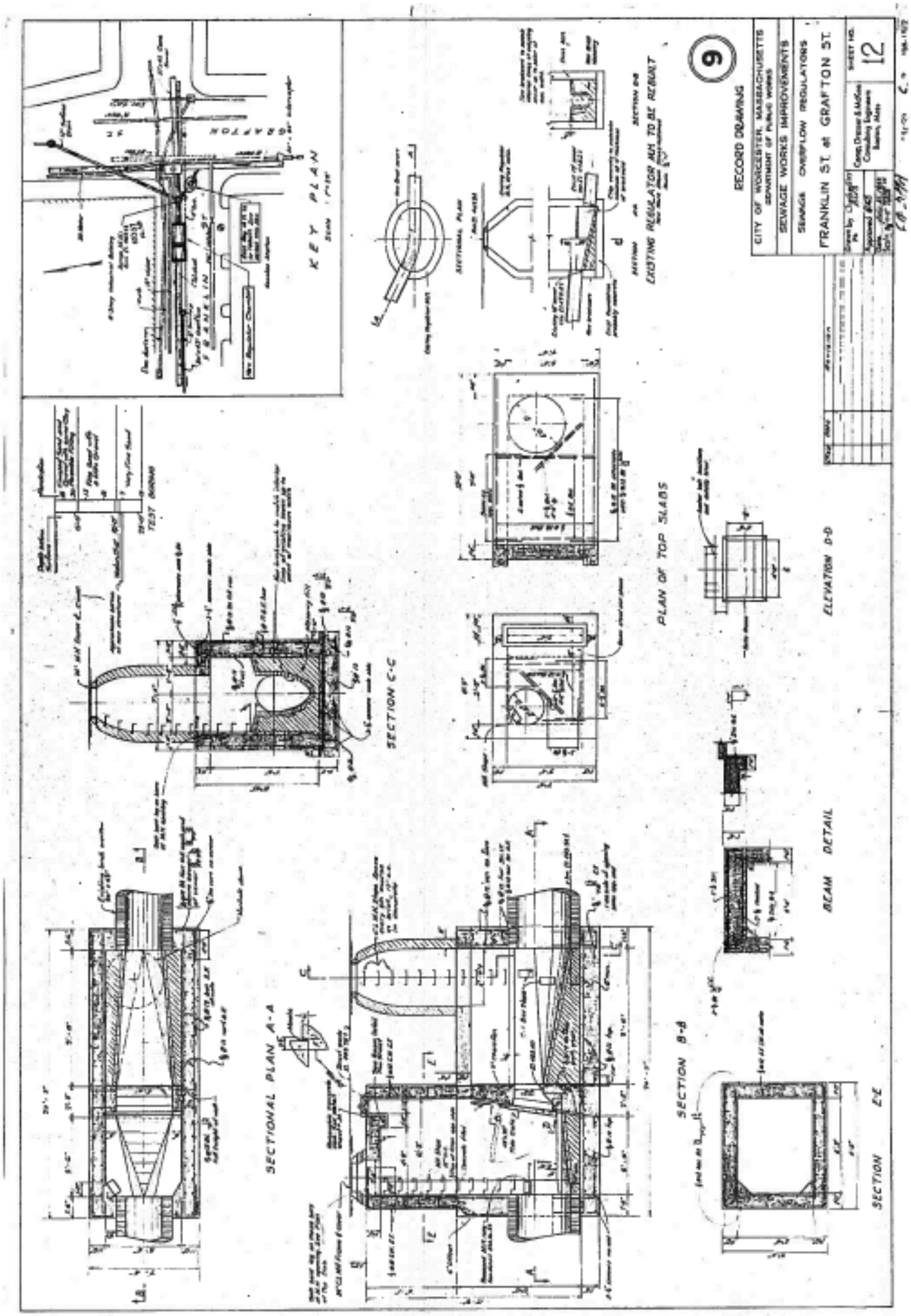


Figure C. 6: Sewer Overflow Regulators Contract No. 5 - Franklin St. at Grafton St.

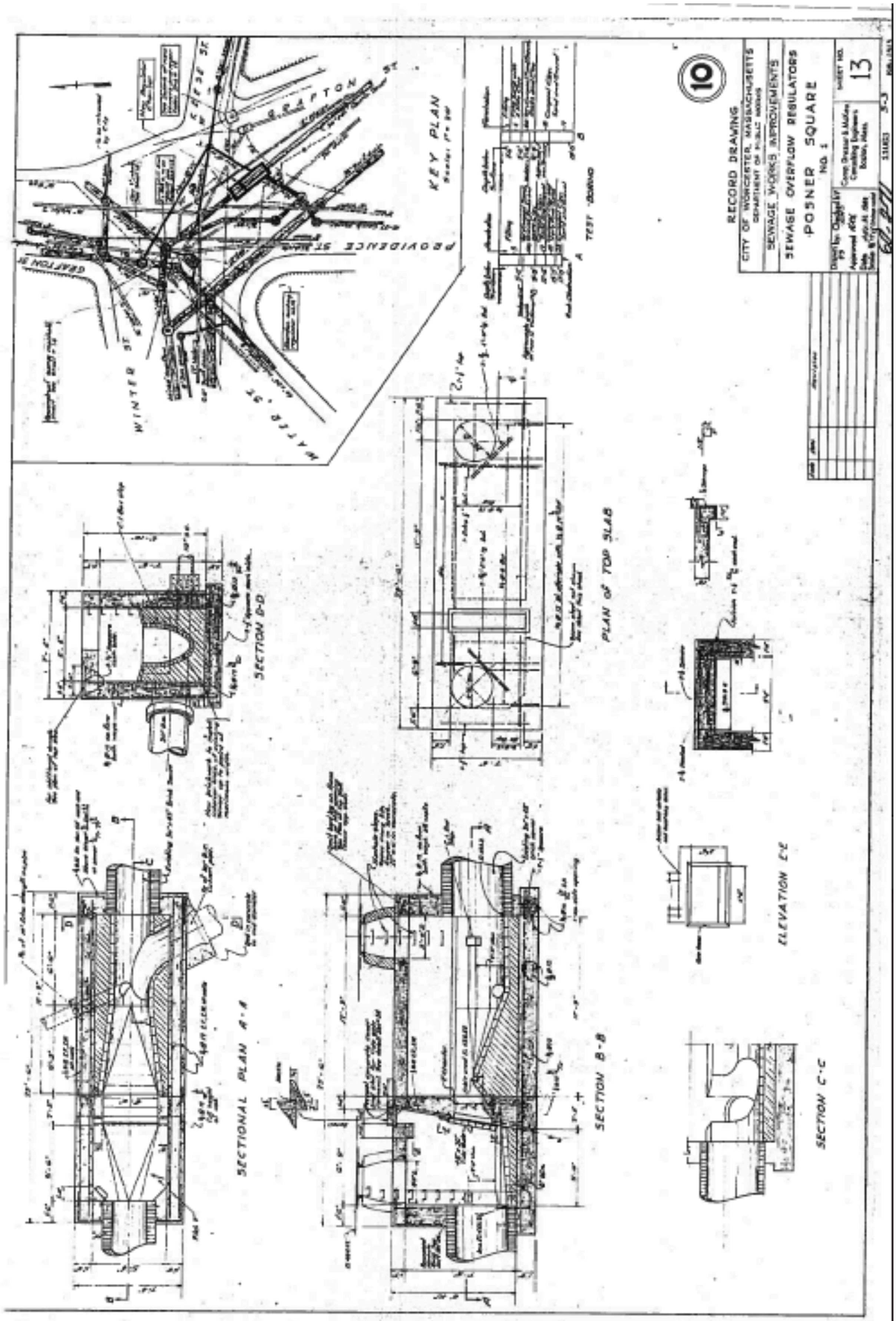


Figure C. 7: Sewer Overflow Regulators Contract No. 5 - Posner Sq. No 1

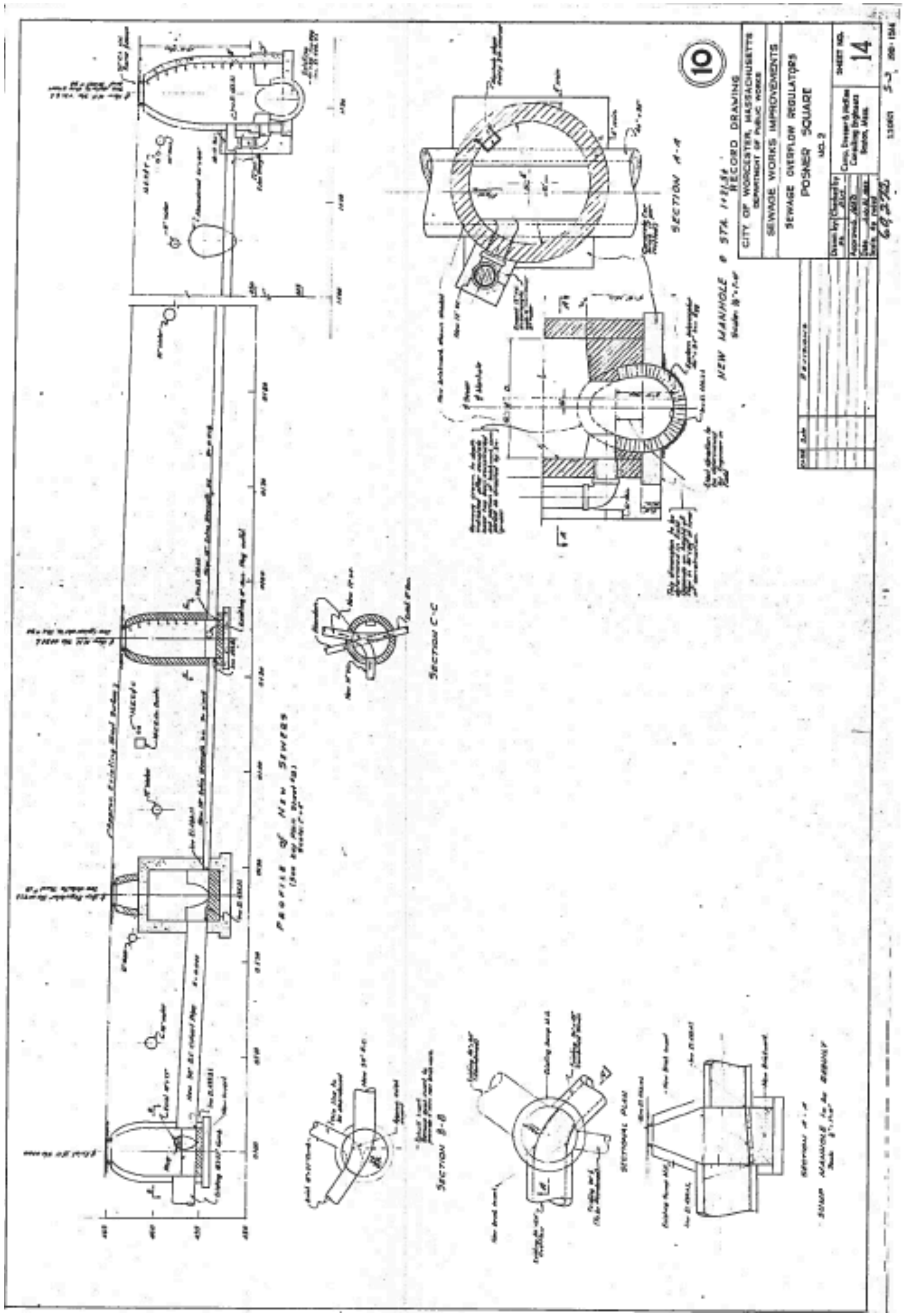


Figure C. 8: Sewer Overflow Regulators Contract No. 5 - Posner Square No. 2

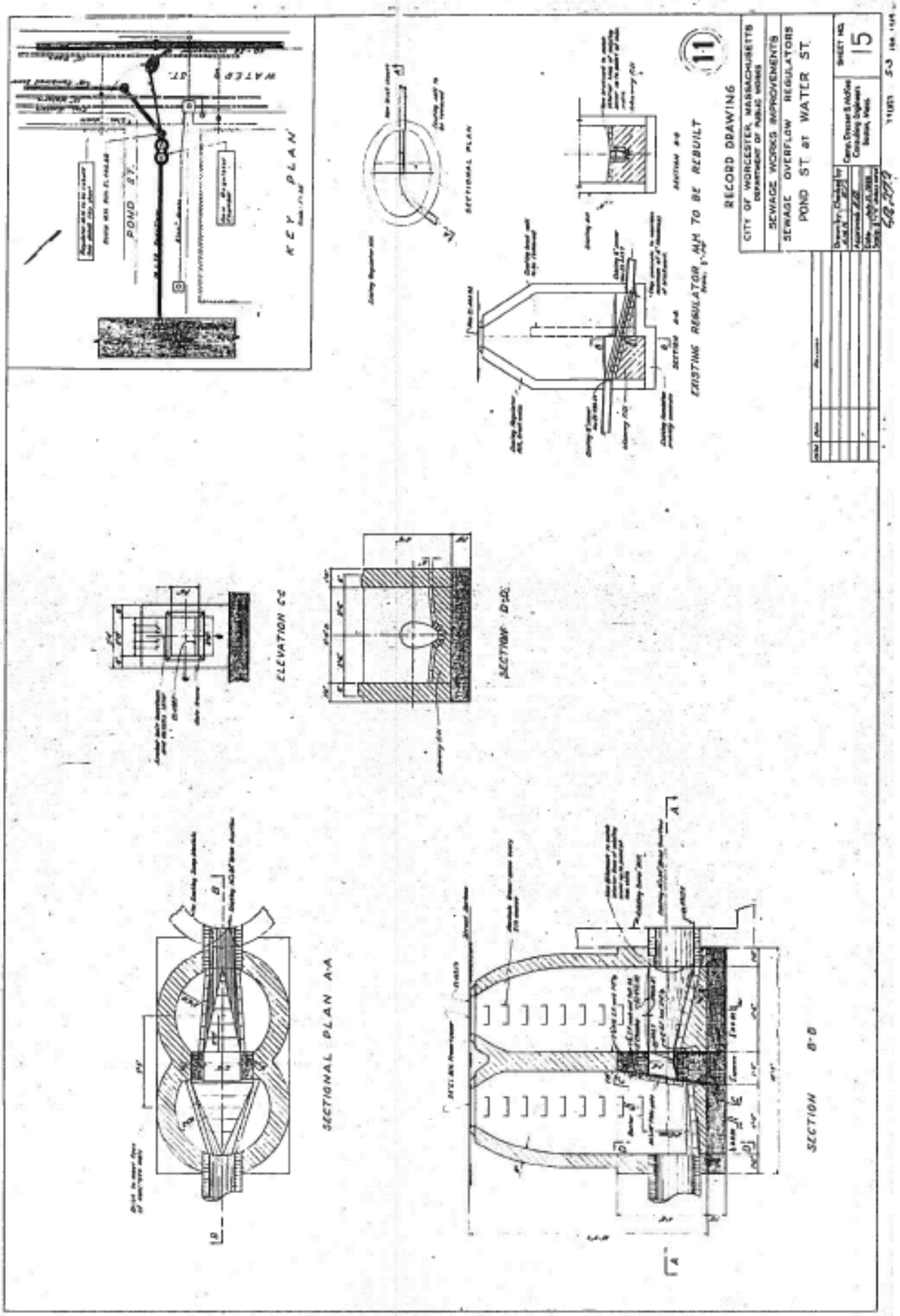


Figure C. 9: Sewer Overflow Regulators Contract No. 5 - Pond St. at Water St.

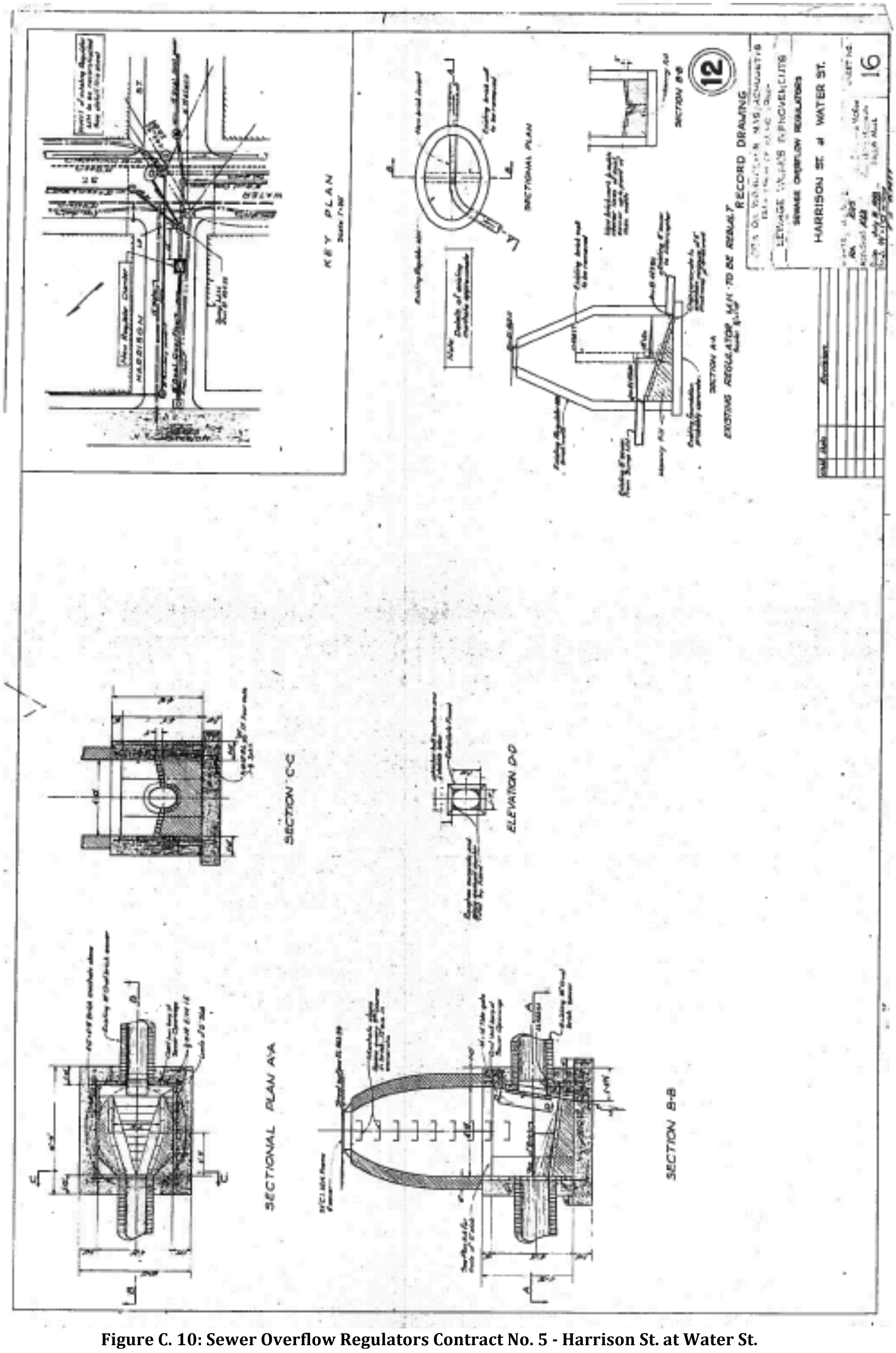


Figure C. 10: Sewer Overflow Regulators Contract No. 5 - Harrison St. at Water St.