Flood Risk Reduction Through Underground Detention

I-35W Corridor and Tunnel - Minneapolis

Prepared for MnDOT – Metro District
SEH No. MNTMD 131234

MnDOT Contract No. 07062

Part of:
MnDOT State Project No. 2782-327

December 1, 2015

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November 19, 2015

I hereby certify that this report was prepared by me or under my direct supervision, and that I am a duly Licensed Professional Engineer under the laws of the State of Minnesota.

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Executive Summary

The analysis presented in this report assesses the hydraulic capacity of the I-35W stormwater tunnel and its main trunk pipe, near-surface extension. The 35W tunnel has a circular cross section, 12 feet in diameter and flows approximately south to north, from 39th Street to Interstate 94 where it joins an equal size tunnel. From this location the 14-foot joint tunnel flows northeast and outlets at the Mississippi River. Equally important for the analysis and flooding solutions discussed in this report is the near surface storm trunk line that serves as the main drainage conduit for the highway corridor between 49th Street to 39th Street where it connects to the tunnel via a 8-foot diameter drop shaft (DS1). Two of the lowest points along I-35W corridor, are in fact located directly above this main trunk line, at 46th Street and 42nd Street, the latter being the lowest point along the I-35W corridor, upstream of the junction with I94 tunnel.

One key assumption of the analysis is that the tunnel surcharges rather smoothly. The model does NOT factor in the transient flows or air entrainment and release processes that have been documented and used to explain the occasional past violent upward ejection of water, referred to as “geysering”. In the interest of clarity, some general considerations are offered in Appendix A, along with the recommendation that the issue of transient flows and rapid pressurization within tunnel be revisited.

The analysis was performed using an XPSWMM model built from hydrologic data and the storm sewer geometrics of the XPSWMM model assembled as part of the completion of the 2014 Preliminary Drainage Report for I-35W Corridor (2014 Study) prepared for Hennepin County. A simplified but more robust model, discussed in Section 2, was assembled to better estimate the flooding levels and possible underground detention solutions. The Simplified Model was validated by comparing its predictions of real rainfall events, against known peak levels that were documented during these rainfall events (Section 3, Appendix D). All standard storm considered (i.e., 5, 10, and 50-year) assume a 24-hour duration, with total depths and distributions based on NOAA’s Atlas 14 data and procedures.

Estimates of existing conditions (Section 4) based on the validated Simplified Model indicate that the 42nd Street low point appears to be the most vulnerable location to flooding that can be associated with limited flow capacity within the tunnel. Thus, the evaluation of solutions (Section 5) revolves around reducing the risk of flooding at 42nd Street low point.

Two categories of solutions were investigated: (1) solutions that involve creation of underground detention space in the vicinity of 42nd Street low point, coupled with a backflow prevention mechanism and (2) underground detention space built at the upstream end of the tunnel in the vicinity of DS1 and/or DS2. The latter category, however, was deemed to present enormous construction challenges, some perhaps unsurmountable, and enormous costs as well. Therefore, based on feasibility and cost assessment, the option referred to as Option 1A, was selected as the preferred option.

Zeroing in the preferred Option 1A, Section 6 presents the volumes, possible construction options, and costs, associated with various level of rainfall levels. The detention volumes required to reduce the flooding risk for 5, 10, and 50-year storms are estimated to be 2.4, 13.8, and 34 acre-feet, respectively with estimated implementation costs of 4, 13, and 25.5 millions of dollars (see Table 4 for summary).

The exact shape and location of the underground stormwater storage are not unique. A design involving 12-ft by 12-box culverts rows was considered a good choice that combines pre-cast elements and fully utilizes the available vertical space between the highway grade at 42nd Street low point and the bottom of the existing 78-inch main trunk line. Section 7 discusses various aspects of the design that is captured in Figures 1 and 2.

The analysis does not specifically address flooding caused by local inlet restrictions. During the design phase, the local drainage at each location, particularly at the sag points and particularly at the 42nd Street low point need be evaluated separately in order to reduce the flooding risk due to inlet capacity or the size of the local collecting pipes.

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1.0 INTRODUCTION

The analysis presented herein assesses the hydraulic capacity to the 35W stormwater tunnel and its main trunk, near-surface extension, south of 39th Street. The 35W tunnel has a circular cross section, 12 feet in diameter and flows approximately south to north from 39th Street to Interstate 94 where it joins an equal size tunnel sloping west to east along I-94. The joint storm tunnel has is 14 feet in diameter, flows approximately in a northeast direction and outlets to the Mississippi River in the vicinity of the 35W Bridge. The elevation at the tunnel bottom drops about 14 feet over a length of about 2.35 miles, from elevation 750 at the upstream end to elevation 736 at the junction. The joint 14-foot tunnel's bottom elevation drops another 8 feet over a 1.56 mile distance, from elevation 734 at the junction to elevation 726 at the outlet. Overall, the slope of the tunnel is slightly greater than 0.1%. The tunnel depth varies from about 40 feet to 120 feet below ground surface.

This report follows the 2014 Preliminary Drainage Report for I-35W Corridor (Hennepin County Project No. 9864-01 / MnDOT SP No. 2782-327) a preliminary design document that addresses the stormwater treatment and runoff control needs in connection to the highway improvement project, due to the increase in impervious surface. The 2014 Preliminary Drainage Report reviewed the stormwater requirements and policies of the Mississippi Watershed Management Organization, City of Minneapolis, and Minnesota Pollution Control Agency (NPDES-SDS permit) and recommended two detention/filtration basins be built in order to meet the requirements of the MPCA Construction Stormwater Permit and offset the increase in runoff rates due to increase in impervious surface. The 2014 Preliminary Drainage Report also assessed the peak levels along the corridor showing that, in relative terms, the project would create no further increase in peak levels.

Given that over 95% of the drainage area and runoff volumes contributing to the tunnel consists of adjacent urban land outside the highway corridor, when significant rainfall levels are considered (i.e., 5-year level or greater) the proposed roadway improvements and the detention/filtration basins described above, can only make a marginal difference with respect to already existing flooding risk. The project area has experienced flooding conditions in the past, particularly within the “Gap” segment at 42nd Street. Other locations, particularly sag points, may have experienced limited flooding conditions attributable to limited intake capacity or capacity of the local storm pipes.

Because of the topographic constrains, there is simply not enough space within the I-35W corridor to create surface detention that could significantly reduce the already existing flooding risks. With this in mind, the main goal of this study is to identify feasible underground stormwater storage options that can significantly reduce the risk.

The sizing criteria of the detention storage space was that the proposed conditions model developed as part of this supplemental study would reflect a reduction in 10-year peak levels such that flooding would not spread beyond the highway shoulders.

Upstream (south) of the 35W tunnel there is a near surface main trunk storm sewer line serving the 35W corridor. This main trunk line stretches from approximately 49th Street to 39th Street where is connected to the 35W tunnel's upstream end, through a 8-foot diameter drop shaft, DS1. The upstream portion of this trunk line was recently replaced with larger diameter segments, notably a 7.5-foot section from 47th Street to 45th Street followed by a 10-foot section to north of 43rd Street. The remaining pipe sections between north of 43rd Street and 39th Street are 72 to 78 inches in size.

Two of the lowest points along 35W corridor, are located directly above this main trunk line, at 46th Street and 42nd Street, the latter being the lowest point along 35W tunnel upstream of the junction with I94 tunnel. During ordinary rainfall events the main trunk line discharges freely to the tunnel through the 8-foot shaft. However, during extreme storms the tunnel can surcharge above the main trunk elevation which in turn result in backflow and flooding. Thus, the hydraulic performance of the main trunk line and the tunnel has to be analyzed jointly.

The analysis presented in this report is confined to assessing the flow capacity along the corridor under various set of conditions, assuming that the tunnel collects the flow from lateral pipes draining the adjacent areas and surcharges in a rather smooth and efficient fashion.

The analysis does NOT factor in the transient flows or air entrainment and release processes that have been documented and used to explain the occasional violent upward ejection of water, referred to as "geysering". Investigation of the transient flow requires a considerably more expansive type of analysis, beyond the scope of this project. Nonetheless, because the geysering process has been a relatively common occurrence in the past, adding to the perception of flooding risk, a set of general considerations are presented as a separate text in Appendix F.

2.0 I-35W CORRIDOR – H&H MODELING APPROACH

2.1 Evaluation of I-35W Tunnel Flow Capacity

Before presenting the modeling analysis, since the vast majority of the runoff to the tunnel originates from the adjacent urban areas and not from the corridor itself, it is useful to compare the flow capacity of the tunnel against the collective flow capacity of the lateral pipes discharging to the tunnel.

A succinct evaluation of the flow capacity of I-35W tunnel relative to the collective flow capacity of the lateral storm sewer pipes draining the adjacent urban areas is presented below. This approximate evaluation is based on direct, hydraulic computations:

- Collectively, the normal flow capacity of the lateral pipes exceeds the normal flow capacity of the 12-foot diameter section under 35W by a factor of two or more. This is because the slope of the tunnel is considerably smaller than the slope of most pipes tributary to the tunnel. The normal flow capacity was estimated using the average slope of the tunnel and main lateral pipes. The existing pipe flow restrictions in the form of 12 to 27-inch orifice plates placed within larger lateral pipes between 43rd and 49th Streets were also factored into this analysis, although it should be noted that these orifices provide only limited flow control during large storms. The orifice flow equation predicts that, as the water mounds up on upstream side, the flow rate through orifices increases approaching or even exceeding the normal flow rates through the pipes they restrict.
- Under fully surcharged conditions the flow capacity of the 12-foot tunnel section, assuming free flow at the downstream end (i.e., the transition to the 14-foot section) is roughly equal to the sum of the normal flow capacity the pipes feeding in. In other words, **when surcharged, the tunnel could convey all the incoming lateral flow if the flow within the lateral pipes were somehow restricted to their normal flow rates (i.e., not surcharged)**.
- However, if all or at least some of the major lateral pipes draining to the tunnel are surcharged, collectively the lateral flow into the tunnel exceeds the tunnel carrying capacity to the point to which flooding can be expected.

This comparison, although crude and not a substitute for a model, suggests that **hypothetically, if it were possible**, additional flow restrictions to the pipes draining to the tunnel could translate into a flood prevention solution. Particularly if lateral flow restrictions were to be implemented at the first two drilled shafts, DS1 and DS2 located near 39th and 35th Street respectively where the largest fractions of urban drainage flow are delivered to the 12-foot section of the 35W tunnel.

2.2 Overview of Preceding Study and Model Series: 2014 Preliminary Drainage Report for I-35W Corridor (Hennepin County Project No. 9864-01 / MnDOT SP No. 2782-327)

The analysis of this study was performed using hydrologic data and the storm sewer geometrics of the XPSWMM model assembled as part of the completion of the 2014 Preliminary Drainage Report for I-35W Corridor (2014 Study) prepared for Hennepin County. However, to understand why that model was not used as such but a Simplified Model was developed instead, some clarifications are necessary:

- The model for the 2014 Study is a detailed one, built from previous versions of the model, developed by the City of Minneapolis but also other drainage studies of the I-35W tunnel. Although it contains valuable detailed hydrologic and geometric information, the detailed model is not the most effective approach to evaluating large rainfall events, predicting flooding levels along the I-35W corridor considerably above what has been observed during the largest storms in recent decades. This discrepancy can be in large part attributed to an unreasonable effectiveness of stormwater routing built in the model assumptions. Specifically, the hydrograph for each subcatchment is assigned to a model node that represents a storm manhole. Although the model includes hundreds of nodes and links (i.e., pipe segments) it does not capture the inlet restrictions imposed by catchbasins or the lead pipes from these catchbasins to manholes, which are typically small in diameter (12 to 15 inch). Consequently, when 5 to 50-year rainfall events are analyzed, some major storm sewer pipes connected to the tunnel appear heavily surcharged with the hydraulic grade line cresting several feet above the ground level in places. While surcharge is to be expected during heavy downpours, it is not realistic that many pipes will exhibit surcharge to the extent suggested by the detailed model. Instead, due to inlet restrictions, the surface water tends to spread laterally over large surfaces. Appendix A illustrates the restricted capacity concept.

- A secondary aspect contributing to the high flow rates and peak levels predicted by the detailed model is the choice of minor loss coefficients. Despite their traditional name these minor hydraulic head losses due to change in geometry are, cumulatively, significant. Conventionally, the junction loss coefficients used to model flow through manholes are 0.5 for the pipe entrance loss and 0.5 to 1 for pipe exit loss. These values are valid choices for flow through manholes with depressed channel shapes. However, most manholes collect several pipes which can bring about complex flow conditions and additional hydraulic losses due to the turbulence and secondary circulation within the structure itself, in addition to the entrance and exit losses. Losses within the structure itself also occur simply due to flow expansion. To account for these type of losses the both entry and exit coefficients can be set to 1. The loss coefficients for the tunnel, however, are likely much smaller, 0.2 and 0.4 respectively, since the transition from one section to another is hydraulically smooth, without sudden expansion or contraction.
- The purpose of the 2014 I-35W Preliminary Drainage Report for I-35W was to overview the stormwater regulations in connection with highway reconstruction and to identify viable solutions to meet the rules established by various agencies. The study did not specifically address the flooding levels associated with the capacity, or lack thereof, of the 35W tunnel. Instead, it identified solutions aimed to provide water quality treatment and to ensure that any potential increase in runoff rates due to expansion in impervious surface can be offset by a combination of detention and infiltration basins.

Flooding, however, is a top safety concern for MnDOT and assessing the peak water levels at vulnerable locations accurately along the 35W corridor is essential. Toward this goal, this study extends the hydraulic analysis to accurately determine the tunnel capacity issues and examine flood mitigation solutions in form of stormwater detention storage. This analysis was conducted using a simplified XPSWMM model discussed in more detail below.

2.3 The Simplified Model

The effort of evaluating flooding levels and required mitigation started with an evaluation of the 2014 I-35W Corridor Preliminary Drainage Study. As discussed above, a shortcoming of the detailed model developed as part of the I-35W Corridor Preliminary Drainage Study stems from fact that the runoff hydrographs are directly assigned to manholes nodes, thus eluding the inflow restrictions imposed by inlets and/or lead pipes and eluding much of the storage at the street level. For modeling small rainfall events for the purpose of evaluating the water quality criteria these limitations are not critical, as most of the runoff is conveyed, with little restriction, to the storm system. For larger storm events, however, in this approach due to lack of flow restriction at catchbasin level, high runoff rates are arbitrarily assigned directly to the storm system. As a consequence, a detailed model predicts that many of the storm pipes surcharge to unrealistically high levels, resulting in high peak flow rates to the tunnel.

Adding specific inlet restrictions for each catchbasin to an already very large and detailed model is not practical as the information for a detailed storage representation is not available.

The simplified model used for this analysis, retains all the hydrologic assumptions but relies only the larger lateral pipes directly tributary to the tunnel and not the myriad of smaller pipes that they collect. One can imagine that, regardless of the magnitude of the rainfall event, the runoff rate to the tunnel is ultimately restricted by the carrying capacity of the tributary pipes. With that in mind, a simplified model that retains all the lateral storm pipes was assembled. Each storm line tributary to the tunnel was traced from the tunnel to the first major sag intersection and assigned the acreage collected by that trunk line, thus ensuring all area contributing to the tunnel and runoff are preserved. Each of these lateral lines is allowed to surcharge up to about a foot above ground level which essentially implies storage at the street level. During large rainfall events some locations can indeed see water depths in excess of 1 foot, yet the number of drastically flooded intersections represents a small fraction of the total.

Consistent with the methodology developed by the City of Minneapolis (XP-SWMM Model Development Guidance Manual) that was used in previous versions of the detailed model as well as in the models for the 2014 Preliminary Drainage Report for I-35W Corridor, the Simplified Model used in this study employed the XPSWMM RUNOFF routing method.

The XPSWMM RUNOFF routing method does NOT employ the Curve Number (CN) and the Time of Concentration (Tc) is not a explicit parameter. Instead, the subcatchment hydrologic parameters under the RUNOFF method: are a) percentage impervious, b) subcatchment width, and c) subcatchment slope.

A schematic representation of the simplified model is shown on the General Map and the hydrologic parameters are summarized in Appendix B along with storage volumes for those nodes that surcharged (flooded) based on 10-year rainfall model (existing conditions).

The simplified model retains the acreage and the global hydrologic properties of the drainage areas tributary to the tunnel. Averaged hydrologic parameters were used to characterize these larger, aggregate subcatchments. The model does not impose any restrictions on the runoff rates but all the runoff is ultimately modulated by the carrying capacity of the trunk pipes in full surcharge mode. This is an essential aspect and enabling this simplified model to conservatively capture the sustained surcharge during large rainfall events without grossly overestimating the levels of flooding.

The simplified model not only captures the overall hydraulics of the system better but also executes much faster allowing for efficient scenario testing. More importantly, a simplified approach provides a more direct and clear understanding of the essential processes, unencumbered by many details which make only a marginal difference.

It should be noted that this simplified approach is still a conservative one as it allows the lateral pipes tributary to the tunnel to flow in surcharge mode for considerable amounts of time.

3.0 SIMPLIFIED MODEL VALIDATION AGAINST REAL RAINFALL EVENTS DATA

Given that the Simplified Model developed as part of this study differs from the modeling norms commonly used on complex systems such as this, an important component of the modeling effort was to compare the model prediction of peak levels against some peak levels observed in connection to some important rainfall events that resulted in significant flooding along I-35W, particularly the flooding at the 42nd Street low point in connection with the July 1, 1997, storm and June 25, 2010 storm. The rainfall distribution in connection with the storm events listed above at the closest location and the most detailed level (i.e., one minute) were obtained from NOAA.

Additionally, the results were compared against monitored levels within the tunnel, as documented by Barr Engineering 1999 Report titled “T.H. 35W Storm Tunnel Surge Chambers at 35th Street and 39th Street”. This excerpt depicts the levels within tunnel at two locations (35th Street and 27th Street) during the rainfall of July 3, 1999. The report also provides a one minute level rainfall distribution.

The comparison is discussed below and a visual summary, including photos is presented in Appendix C.

3.1 July 3, 1999 Storm (1.16” in 30 minutes) – Water Levels and Surcharge Time within Tunnel at 35th St.

The monitoring data from Barr Engineering 1999 report show: a first peak striking at approximately 804.5, followed by 9 minutes of transient oscillations between 777 and 823 levels, and a surcharge time (level above tunnel crown at 757.7) lasting for about 25 minutes. The Simplified Model captures some of the monitored data almost perfectly: a peak level of 804.5, an average level of about 796 for a 9-minute interval around the peak, and a surcharge time of 27 minutes. XPSWMM is not an adequate tool to capture rapid transient oscillations showed in Appendix C. Nonetheless, in an average sense the peak 9-minuted interval (i.e., duration of the oscillations) was assessed to be between 795 and 800.

3.2 July 1, 1997 Storm (2.67” in 30 minutes or less) – Flooding Depth along 35W at 42nd St Low Point.

The Barr Engineering 1999 report describes the July 1, 1997, storm as “the extreme 500-year rainfall event”. Other descriptions mention “3 inches in 30 minutes” (Star Tribune) or “2.1 inches in 20 minutes” (http://www.srh.noaa.gov/oun/?n=safety-overpass-slide19) an indication that Minneapolis has experienced some very extreme weather in the last two decades. For model evaluation purposes the MSP recording data available from NOAA was used: 2.67-inches of rainfall were rendered over 30 minutes. Photographic evidence showing water level reaching the lower window rim of regular vehicles suggests that the flooding depth at the 42nd Street low point reached 3 to 4 foot range. The Simplified Model predicts a maximum flood depth of 4 feet (~826 peak level relative to a low point elevation of about 822).

3.3 June 25, 2010 Storm (1.88” in less than 60 minutes) – Flooding Depth along 35W at 42nd St Low Point.

The June 25, 2010 storm was simulated using 1-minute rainfall data from NOAA. A Fox News photo and YouTube footage of this storm event suggest a maximum flooding depths at 42nd Street low point somewhere below knee level, perhaps between 1.2 and 1.5 feet. The

Simplified Model prediction for the maximum flooding depth at this location is 1.3 feet (823.3 peak level relative to low point elevation of about 822).

In addition to testing the model results against the known peak water levels mentioned above, a simulation of other large storms was performed using the model. For example, the simulation of a large storm that occurred on June 19, 2014 indicated no flooding conditions at 42nd St low point. To the best of our knowledge, no significant flooding has occurred during 2014 which lends further credence to the ability of the Simplified Model to correctly predict the peak levels.

In sum, the Simplified Model predictions of peak levels associated with various real rainfall events seem to match very well the levels observed at the surface or below surface.

4.0 EXISTING CONDITIONS

4.1 Results:

Simplified Model results for 2, 5, 10, and 50-year 24-hour Atlas 14 rainfall distributions, in terms of peak levels at certain key locations, are summarized in Table 1 below:

Table 1 - Simplified Model - High Water Levels Results for Existing Conditions*

Location	Node Name	TOC	2-year	5-year	10-year	50-year
13th at I94	00_DS6	840.1	774.3	783.1	787.5	790.6
18th Clinton	01_DS14	856.5	790.7	803.8	808.1	810.9
Portland	02_DS16	810.9	788.5	800.2	804.9	808.1
Junction	03_JUNCT	856.5	787.4	798.9	803.6	806.7
DS4 at 27th	04_DS4_27t	859.0	802.8	814.7	819.3	822.2
DS3 at 32st	05_DS3_31s	864.5	808.2	819.5	823.7	826.7
35th St Low Pt*	06_35StLOW	837.2	826.0	826.6	831.9	837.1
DS1 39th St	07_DS1_39	838.1	814.3	823.7	827.3	830.4
42nd St Low Pt^	08_42ndLOW	822.0	818.8	823.1	825.9	827.0
46th St Low Pt*	09_46thLOW	829.3	824.1	829.0	829.6	830.1

^Assuming local drainage upgrades at 42nd Street low point (see text for details).

Shaded values indicate flooding occurrence.

* The ten locations listed in Table 1 are approximately the same locations as in Tables 25-27 of the 2014 Preliminary Drainage Report for I-35W Corridor (Hennepin County Project No. 9864-01 / MnDOT Project No. 2782-327) with the notable difference that instead at the peak levels for the structures located exactly at 35th Street and 46th Street, Table 1 lists the peak levels for the nearby low points, where the flooding risk is highest.

The results are predicated on the assumption that there are no local drainage restrictions and the runoff within I-35W corridor is effectively captured into the tunnel and its southern main trunk pipe extension. In other words, the runoff is not restricted by the inlet capacity and the local collection pipes.

Flooding, particularly at low points can occur even when the water levels within tunnel remain relatively low, due to size and/or numbers of local catchbasins and collecting lead pipes, or sometimes due to debris blockages of the intakes.

4.1.1 42nd Street Low Point

For the sake of clarity it is useful to focus on the sag point at 42nd Street which appears to be the most vulnerable to flooding, based on model and historical evidence. The drawdown flood receding times for 5, 10, and 50-year rainfall events are 0.5, 2, and 4.5 hours, respectively.

The flooding levels at 42nd Street sag point were estimated assuming that, as part of the upcoming Transit Access project, the existing local storm sewer pipe system, specifically the 12-inch diameter lines collecting a few dozens of catchbasins will be upgraded to larger size pipes so that any flow intake restrictions will be minimized. Thus, the low area at 42nd Street was represented by a single node in the model assuming that all the runoff would, upon construction, be efficiently collected. Inclusion of the detailed existing pipe configuration at 42nd Street low point into this modeling effort would only complicate an already complex discussion related to the tunnel capacity and possible needs for detention storage.

From a drainage and flood risk reduction perspective, upgrading the local storm sewer pipe system at the 42nd Street low point should be an absolute priority. Given the size and configuration of the present system, flooding at 42nd Street low point can occur during flash floods of rather modest levels (i.e., 2-year or greater) as the fast accumulating runoff can demonstrably exceed the carrying capacity of the existing 12-inch lead pipes.

With local drainage upgrades at 42nd Street low point implemented, the model results suggest 0.7 feet levels of flooding at this location for a 5-year rainfall event and flooding depths of about 3.5 and 5 feet during 10 and 50-year rainfall events, respectively.

4.1.2 46th Street Low Point

The other location within the 35W corridor where flooding may occur is the sag point at 46th Street with a potential accumulation of 0.8 feet during a 50-year rainfall event, with a receding, drawdown time estimated at approximately one hour. The modeled peak water levels at 46th Street low point are predicated taking into account the capacity of local storm sewer pipes, namely the 48 to 54-inch diameter pipe on the east side of highway and the 60-inch cross pipe that collect most of the catchbasins within the highway corridor at or near the sag point. The peak hydraulic grade line within the main trunk line, recently upsized to 120-inch in diameter, is below the grade surface during a 50-year rainfall event. In other words, the model shows that for extreme rainfall events flooding conditions at 46th Street low point are possible due to fast runoff accumulation relative to intake capacity of the local pipes, not due to the overall capacity of the main trunk storm line and/or downstream tunnel.

4.1.3 35th Street Low Point

The 35th Street Low Point is located above the tunnel section in the vicinity of the second drill shaft, DS2 (8-foot diameter). The model results suggest that flooding is not likely to occur as direct result of tunnel surcharge. However, the predicted peak levels for 50-year rainfall are near grade level, due the capacity of the local drainage pipe (30-inch). Water expulsion has been observed in the past at this location and attributed to air escape and/or transient flow instant rise in pressure. Neither of these two processes were part of the scope and were not included in the analysis.

4.2 Hydraulic Analysis - Discussion

The low point elevation at 42nd Street is approximately 822 feet, while the surface elevation directly above the 35W tunnel ranges between about 837 and 860. The invert elevations of the largest lateral pipes draining to the tunnel at the first two drill shafts (DS1 and DS2) range from about 825 to 830. A rise in water levels within the tunnel to such levels would reduce the incoming lateral flows but this can only happen at the expense of backflow (i.e., from the tunnel southward along the 78-inch main trunk line) which in turn increases flooding levels at 42nd Street sag point.

If the water levels within the tunnel remain low, no major flooding is expected at 42nd Street assuming, again, that the local pipe collection will be upsized. This was tested by running a hypothetical scenario in which the tunnel is decoupled from the trunk line upstream. In other words, **the results tabulated below assume that the near surface storm trunk line south of the tunnel discharges freely, not to the first drill shaft DS1 and, similarly, the tunnel receives no flow from south of 39th Street where DS1 is located.**

Table 2 - Hypothetical “Decoupled” Model

(tunnel and upstream storm line analyzed independently)

Location	Node Name	TOC	2-year	5-year	10-year	50-year
13th at I94	00_DS6	840.1	769.1	779.7	787.5	791.8
18th Clinton	01_DS14	856.5	782.8	799.4	808.4	812.3
Portland	02_DS16	810.9	780.9	796.1	805.4	809.6
Junction	03_JUNCT	856.5	780.1	794.9	804.0	808.4
DS4 at 27th	04_DS4_27t	859.0	792.3	809.3	821.6	825.3
DS3 at 32st	05_DS3_31s	864.5	796.5	814.0	827.2	830.7
35th St Low	06_35StLOW	837.2	826.0	826.6	834.8	837.5
DS1 39th St	07_DS1_39	838.1	798.8	817.8	832.1	835.6
Tunnel Section (rows above) assumed to be disconnected from Main Trunk Line (rows below)						
42nd St Low	08_42ndLOW	**822.0**	816.2	818.2	821.0	822.4
46th St Low	09_46thLOW	829.3	823.7	826.4	829.5	830.1

This hypothetical model suggests that under free-fall conditions (i.e., no rise in water levels within tunnel above elevation 800), the 35W trunk line south of the tunnel has sufficient capacity to convey the runoff generated by a 10-year rainfall while flooding depth for a 50-year rainfall us is limited to about 0.4 feet. Again, these results are predicated on system capacity analysis and assume no inlet restrictions.

It is worth noting that this modeling exercise shows that during 10 and 50-year rainfall events, if the tunnel is (hypothetically) decoupled from the incoming 78-inch line, the tunnel would actually surcharge to even higher levels than with the existing connection in place. Which means that when the tunnel surcharge at high levels, backflow through the existing 78-inch pipe may occur, and the low area at 42nd Street acts as a buffer detention basin.

5.0 FLOOD RISK REDUCTION SOLUTIONS

The evaluation of solutions revolves around reducing the risk of flooding at 42nd Street low point which, as mentioned above, appears to be most vulnerable area in case of significant surcharge within tunnel. Absent from the list of solutions presented below and outside the scope of this study is the alternative of constructing a new tunnel of increased size.

Also, absent from the spectrum of options discussed here and outside the scope is a theoretical solution that involves raising the 35W road profile at 42nd Street, which in turn would trigger the removal or reconstruction (or relocation) of the bridge over 35W at that location, plus a host of challenging street profile and traffic reconfiguration. In principle, and strictly from a technical standpoint, such a scenario could in fact represent a viable flood mitigation approach.

In sum, in accordance to the scope of this study, the solutions center on identifying the volumes and placement of stormwater detention storage.

5.1 Detention Options Evaluation:

To the extent to which flooding along 35W corridor is caused the tunnel capacity being significantly exceeded, from a hydraulic standpoint there are many options to limit the flooding risk through construction of temporary runoff storage. These options fall broadly into two categories:

1. Runoff storage space in the vicinity of 42nd Street low point to temporary capture runoff excess. These options have to include a backflow prevention mechanism that would prevent water from a surcharged tunnel from flowing upstream (south) and filling the storage space causing flooding.
2. Detention space built at the upstream end of the tunnel in the vicinity of DS1 and/or DS2.

There is an important distinction between these two categories: The first one, because it includes a backflow prevention component, can provide flood protection even if the tunnel surcharges at levels exceeding the elevation of low point at 42nd Street of about 822 feet. During large rainfall events, a detention structure around 42nd Street low point would serve as a temporary runoff holding volume until the water levels within tunnel drop and gravity flow resumes. The second category must limit the surcharge levels within the tunnel considerably below 822, the roadway elevation at 42nd Street sag point, such that sustained flow rates along pipe slope (south to north) are continuously maintained within the system. Because of this important distinction, the detention volumes and associated costs required by the first category of solutions are considerably smaller than those required by the second category.

To further draw contrast between the first category and the second one, the options listed under the first category do not necessarily require that the 10-foot pipe section recently built as part of Crosstown project be further extended, from south 43rd Street to the tunnel (about 2,550 feet), whereas the second category essentially implies that the 10-foot section would be extended all the way to the tunnel, or else the volumes and costs in the second category, already deemed to be extremely high, would need to be nearly double to achieve the same level of flooding protection.

From a hydraulic perspective there are multiple options under each of the two categories described above. Several such options under each category are listed below.

The options under the first category include:

- 1A. Detention, overflow volume in form of rows of 12-ft x 12-ft box culverts, stretching south and north of the sag point at 42nd Street. The number of rows depends on the rainfall level (details below). This option does not require the 10-foot pipe section mentioned above be extended to the tunnel.
- 1B. Same as above, but in conjunction with extension of the 10-foot pipe section. This option would reduce the total length of 12-ft x 12-ft box culverts needed, for a given rainfall event but would add more challenges and costs associated with extending the 10-foot section from its present downstream end at 43rd Street to 39th Street at the tunnel's upstream end.
- 1C. A large sized tunnel section from 42nd Street low point to the upstream end of the existing deep tunnel at 39th Street. A large sized tunnel would serve both as to increase conveyance and to provide detention. Although the tunnel section would be built near the surface, mostly above the bedrock level, this option poses special challenges associated with the tunnel size and excavation depth. It is certainly not a feasible option for rainfall events larger than a 10-year one. For a 10-year rainfall event the diameter of this hypothetical tunnel is estimated at 19-feet.

The options under the second category would include:

- 2A. Detention, overflow volume in form of rows of 12-ft x 12-ft box culverts, stretching from the first drill shaft, DS1 to the second one, DS2 that would intercept a large fraction of the runoff originating from the city areas, adjacent to the tunnel and feeding into the tunnel through large diameter lateral pipes. The number of box culvert rows depends on the rainfall level (details below).
- 2B. Provide localized, vertical detention space in form of a series if interconnected large diameter (i.e., 40-ft) drill shafts extended from the surface to the bedrock level estimated at about 795 feet. The number of drill shafts is a function of rainfall level considered (details below).
- 2C. Same concept as above, except that drill shafts would be extended to all the way to the tunnel level. This option would require roughly half the number of drill shafts at the expense of extremely costly and challenging drilling through roughly 40 feet of bedrock.

All options under the second category (2A, 2B, 2C) pose enormous construction challenges with construction costs that could be prohibitively high given the large volumes and the number of shafts needed. Furthermore, these options assume that the 10-foot storm pipe section discussed above is extended from south of 43rd Street to the first drill shaft at 39th Street. With the extension of this 10-foot section, the existing tunnel surcharge level needs to be limited to approximately 818 in order to prevent flooding at 42nd Street low point. Without the extension of the 10-foot section, however, the surcharge levels within the existing tunnel would need to be limited to approximately 812 which would require the detention volumes associated with each of the three options listed above be nearly double (i.e., of what they would need to be if the 10-foot section is extended), resulting in cost differences far greater than the cost of extending the 10-foot section.

Table 3, summarizes the solutions examined as part of the hydraulic analysis. In short, the detention/storage volumes needed based on the model analysis vary

Table 3 - Summary of Detention Solutions

Cat.1	**Detention storage around 42nd Street Low Point and backflow prevention mechanism**		
	Description	**10-year Required Dimensions**	**50-year Required Dimensions**
1A	**12-ft x 12-ft box culverts**	**2 Rows ~2080 feet long each**	**5 Rows ~2060 feet long each**
1B	12-ft x 12-ft box culverts AND Extension of existing 10-ft pipe*	2 Rows ~1500 feet long each	5 Rows ~1500 feet long each
1C	Replace existing 78 pipe from 42nd St. (low point) to 39th St. (DS1) with New Shallow Tunnel*	19-foot Diameter Tunnel	Impractical (50 feet theoretical diameter)
Cat.2	**Detention Storage at Upstream End of Existing Tunnel (39th Street)***		
	Description	**10-year Required Dimensions**	**50-year Required Dimensions**
2A	12-ft x 12-ft box culverts*	2 Rows ~3000 feet long each	8 Rows ~3000 feet long each
2B	40-ft diameter Drop shafts extended to bedrock*	~24 Shafts	~Impractical (~100 Shafts)
2C	40-ft diameter Drop shafts extended to tunnel level*	~15 Shafts	~Impractical (~50 Shafts)

*Assuming also 10-ft pipe extension from 43rd St to Upstream End of Existing Tunnel at 39th St (see text).

5.2 Preferred Option Selection – Option 1A

In draft versions of this report, the first option within each category, 1A and 2A, were discussed in detail. However, as the investigation proceeded from the hydraulic analysis to the examination of the technical feasibility and the costs associated with each option it became apparent the options within the first category involve considerably smaller detention volumes, are more feasible and more cost effective that those in the second category. For example, assuming the 10-year flooding risk protection case, the cost associated with Option 2A, which is the most feasible and least expensive within second category, is estimated at approximately $36M, nearly three times the cost associated with Option 1A (approximately $13M).

Option 1A is the most feasible and cost effective of the three options under the first category and has been presented during meetings with MnDOT on June 25 and July 29, 2015 as the preferred alternative. Therefore, the design discussion below focuses on Option 1A – the preferred, recommended alternative.

6.0 OPTION 1A (PREFERRED) - DETENTION VOLUMES AND COSTS

The detention volumes required to provide flooding protection for 5, 10 and 50-year rainfall events (local 24-hour Atlas 14 curves) were determined using the Simplified Model, validated as described above (Section 3 and Appendix C). Additionally, at the request of MnDOT, a fixed, 30 acre-feet detention option was assessed. The analysis for the 30 acre-feet volume was presented in a form of a separate memo, attached as Appendix D. It was subsequently determined that a 30 acre-feet detention volume provides flooding protection for rainfall events up to 35-year level (i.e., roughly 3% chance of occurring in any given year).

For each rainfall event considered, Table 4 summarizes the volumes needed to reduce the flooding risk, the tentative geometric arrangement, and associated cost. Additionally, the flooding levels prediction at 42nd Street low point are given in terms of flooding depth and drawdown time for each of the detention volumes considered.

Table 4 - Detention Volumes Needed for Various Rainfall Events

(24-hour Atlas 14 distribution), Possible Arrangement, Cost Estimates, Flooding Depths and Drawdown Times.

Detention Vol. (ac-ft)	Detention Space Possible Arrangement (12'x12' box culverts)	Estimated Cost	Flooding Depth (ft)				Drawdown Time (hrs)			
			5-yr	10-yr	35-yr*	50-yr	5-yr	10-yr	35-yr*	50-yr
2.4 (5-yr)	One row 730-ft long	**$4.0M**	-	3.0	4.6	4.7	-	2.0	3.8	4.0
13.8 (10-yr)	Two rows 2080-ft each	**$13.0M**	-	-	3.9	4.2	-	-	2.5	3.0
30.0 (35-yr)	Five rows 1815-ft each	**$23.1M**	-	-	-	1.0	-	-	-	1.0
34.0 (50-yr)	Five rows 2060-ft each	**$25.5M**	-	-	-	-	-	-	-	-

*35-yr Rainfall is the event estimated to fill up 30 ac-ft, without resulting in flooding.

Detailed Cost Estimates are provided in Appendix E.

The estimates presented above and the results in Tables 5-8 below imply detention space near 42nd Street low point and a backflow prevention mechanism.

Table 5- Proposed Conditions Results - Assuming 2.4 ac-ft of Storage (5yr level)

Location	Node Name	TOC	5-year	10-year	35-year	50-year
13th at I94	00_DS6	840.1	**782.8**	**787.7**	**791.1**	**791.8**
18th Clinton	01_DS14	856.5	**803.6**	**808.7**	**811.7**	**812.3**
Portland	02_DS16	810.9	**800.1**	**805.8**	**809.0**	**809.6**
Junction	03_JUNCT	856.5	**798.7**	**804.5**	**807.7**	**808.3**
DS4 at 27th	04_DS4_27t	859.0	**814.2**	**821.9**	**824.7**	**825.3**
DS3 at 32st	05_DS3_31s	864.5	**818.9**	**827.5**	**830.2**	**830.7**
35th St Low Pt*	06_35StLOW	837.2	**826.6**	**835.2**	**837.4**	**837.5**
DS1 39th St	07_DS1_39	838.1	**822.6**	**832.5**	**835.1**	**835.6**
42nd St Low Pt^	08_42ndLOW	822.0	**821.9**	**825.0**	**826.6**	**826.7**
46th St Low Pt*	09_46thLOW	829.3	**828.9**	**829.5**	**830.0**	**830.1**

^Assuming local drainage upgrades at 42nd Street low point (see text for details).

Shaded values indicate flooding occurrence.

* The ten locations listed in Table 5 are approximately the same locations as in Tables 25-27 of the 2014 Preliminary Drainage Report for I-35W Corridor (Hennepin County Project No. 9864-01 / MnDOT Project No. 2782-327) with the notable difference that instead at the peak levels for the structures located exactly at 35th Street and 46th Street, Table 1 lists the peak levels for the nearby low points, where the flooding risk is highest.

Table 6- Proposed Conditions Results - Assuming 13.8 ac-ft of Storage (10yr level)

Location	Node Name	TOC	5-year	10-year	35-year	50-year
13th at I94	00_DS6	840.1	**782.7**	**787.7**	**791.1**	**791.8**
18th Clinton	01_DS14	856.5	**803.4**	**808.8**	**811.8**	**812.3**
Portland	02_DS16	810.9	**800.0**	**805.7**	**809.0**	**809.6**
Junction	03_JUNCT	856.5	**798.6**	**804.3**	**807.8**	**808.3**
DS4 at 27th	04_DS4_27t	859.0	**813.8**	**821.8**	**824.7**	**825.3**
DS3 at 32st	05_DS3_31s	864.5	**818.5**	**827.4**	**830.2**	**830.7**
35th St Low Pt*	06_35StLOW	837.2	**826.6**	**835.2**	**837.4**	**837.5**
DS1 39th St	07_DS1_39	838.1	**822.3**	**832.5**	**835.2**	**835.6**
42nd St Low Pt^	08_42ndLOW	822.0	**819.5**	**819.7**	**825.9**	**826.2**
46th St Low Pt*	09_46thLOW	829.3	**828.2**	**829.5**	**830.0**	**830.1**

Table 7- Proposed Conditions Results - Assuming 30 ac-ft of Storage (~35yr level)

Location	Node Name	TOC	5-year	10-year	35-year	50-year
13th at I94	00_DS6	840.1	**782.7**	**787.7**	**791.2**	**791.8**
18th Clinton	01_DS14	856.5	**803.4**	**808.8**	**811.8**	**812.3**
Portland	02_DS16	810.9	**800.0**	**805.7**	**809.0**	**809.6**
Junction	03_JUNCT	856.5	**798.6**	**804.3**	**807.8**	**808.4**
DS4 at 27th	04_DS4_27t	859.0	**813.8**	**821.8**	**824.7**	**825.3**
DS3 at 32st	05_DS3_31s	864.5	**818.5**	**827.4**	**830.2**	**830.7**
35th St Low Pt*	06_35StLOW	837.2	**826.6**	**835.2**	**837.4**	**837.5**
DS1 39th St	07_DS1_39	838.1	**822.3**	**832.5**	**835.2**	**835.6**
42nd St Low Pt^	08_42ndLOW	822.0	**819.5**	**819.5**	**821.9**	**823.0**
46th St Low Pt*	09_46thLOW	829.3	**828.2**	**829.5**	**830.0**	**830.1**

Table 8- Proposed Conditions Results - Assuming 34 ac-ft of Storage (50yr level)

Location	Node Name	TOC	5-year	10-year	35-year	50-year
13th at I94	00_DS6	840.1	**782.7**	**787.7**	**791.2**	**791.8**
18th Clinton	01_DS14	856.5	**803.4**	**808.8**	**811.8**	**812.3**
Portland	02_DS16	810.9	**800.0**	**805.7**	**809.0**	**809.6**
Junction	03_JUNCT	856.5	**798.6**	**804.3**	**807.8**	**808.3**
DS4 at 27th	04_DS4_27t	859.0	**813.8**	**821.8**	**824.7**	**825.3**
DS3 at 32st	05_DS3_31s	864.5	**818.5**	**827.4**	**830.2**	**830.7**
35th St Low Pt*	06_35StLOW	837.2	**826.6**	**835.2**	**837.4**	**837.5**
DS1 39th St	07_DS1_39	838.1	**822.3**	**832.5**	**835.2**	**835.6**
42nd St Low Pt^	08_42ndLOW	822.0	**819.5**	**819.5**	**819.5**	**822.0**
46th St Low Pt*	09_46thLOW	829.3	**828.2**	**829.5**	**830.0**	**830.1**

^Assuming local drainage upgrades at 42nd Street low point (see text for details).

Shaded values indicate flooding occurrence.

* The ten locations listed in Tables 6-8 are approximately the same locations as in Tables 25-27 of the 2014 Preliminary Drainage Report for I-35W Corridor (Hennepin County Project No. 9864-01 / MnDOT Project No. 2782-327) with the notable difference that instead at the peak levels for the structures located exactly at 35th Street and 46th Street, Table 1 lists the peak levels for the nearby low points, where the flooding risk is highest.

For large rainfall events such as 50-year, the model predicts a slight increase in peak water levels and minor flooding of approximately 0.3 feet at 35th Street low point. This is partly because of the backflow prevention mechanism but also partly because of the capacity of the 30-inch pipe draining this low point (to the drill shaft DS2). Replacing the 30-inch pipe with a larger diameter pipe would eliminate this slight increase in peak level and would in fact reduce the peak level, relative to existing conditions. Given the model results indicating no flooding during a 10-year rainfall and minimal flooding during a 50-year rainfall, it is difficult to say whether replacing this local 30-inch drainage pipe (approximately 250 feet in length) with a larger diameter pipe (i.e., 48-inch) warrants the benefits.

While the design concept is roughly the same for all events, there are significant differences in scale (i.e., detention volume needed) and associated costs:

- The detention volume required to provide protection for a 5-year flooding event is estimated at 2.4 acre-feet with a cost estimate of about $4M.
- Conversely, estimated at 34 acre-feet, the detention volume required to provide protection for 50-year flooding would be considerably more expensive, with an approximate construction cost estimated at $24.5M. Furthermore, the implementation would require the use of the entire width of the highway corridor, involving extremely challenging traffic staging accommodations and utility relocation.
- The challenges associated with the 30 acre-feet detention volume scenario (35-year rainfall) are equally great and the cost estimate of $23M almost as high as for the 50-year case.
- Estimated at 13.8 acre-feet, the detention volume required to protect against 10-year level flooding and the implementation cost estimated at about $13M lie somewhere in between those for 5 years and 50 years.

The flood risk reduction was also analyzed in conjunction with the rainfall distribution for the July 1, 1997 storm, the largest of the real rainfall events previously discussed under the model validation section. The model indicates 10 acre-feet of detention storage volume was suffice to reduce the flooding risk when a July 1, 1997 rainfall distribution was considered.

7.0 DETENTION STORAGE AT 42ND STREET LOW POINT (PREFERRED OPTION 1A) - DESIGN

The intended location and design described in this report is based on the assumption is that any detention storage is to be placed within the I-35W right-of-way. The exact choices of storage space shape, specific product used or placement are not unique. Various design options are possible, as long as gravity emptying can be ensured.

The design should provide for the following special features:

- Spillway – a special structure designed to convey stormwater from the existing 78-inch main trunk line into the detention storage space during large storms, once a certain level is reached.
- Emptying pipes – special conduits designed to ensure the drainage of the detention space once the flooding recedes.
- Backflow Prevention – A mechanism designed to prevent stormwater from the tunnel flowing back (i.e., south) towards 42nd Street low point
- Maintenance Access – a series of special structures to provide access for inspection and cleaning.

7.1 Location and Geometric Arrangement

A series of 12-ft by 12-ft box culvert rows, stretching south and north of the 42nd Street sag point, is one practical, and economical choice that minimizes the linear extent of storage space and fully utilizes the vertical space between roadway elevation and the invert of existing 78-inch pipe which can serve as an empting route once the rainfall recedes.

The number of box culvert rows and their lengths varies according to the target detention volume. For example, the detention volumes required to reduce the risk of flooding when 10-year and 50-year rainfall events are considered, are 13.8 acre-feet and 34 acre-feet, respectively. Assuming a two-row arrangement for the 13.8 acre-feet case and a five-row arrangement for the 34 acre-feet case, the lengths of the rows in each case works out to be roughly the same, about 2060 to 2080 feet. Tentatively, the bottom of the box culverts would slope south to north at 0.15%. The “tightest” vertical fit would be at the sag point.

The recommended design described here focusses on a compact arrangement that minimizes the depth and amount of excavation required. With that in mind, it would be advantageous to extend the box culvert rows, roughly equal south and north of the sag point. However, a configuration in which the box culvert rows extend about 1400 feet north of the sag point has the advantage of placing the northern, downstream end of the box near the manhole structure at 40th Street. MnDOT geo-database indicates that at this manhole the invert of the existing 78-inch main trunk line drops by 0.5 feet which would make it possible to use it for emptying the box culverts once the storm recedes (south of 40th street, the projected elevation of the box culverts bottom lies is approximately the elevation as the invert of the 78-inch line, or slightly lower).

Plan and Profile Figures 1 and 2 show the proposed plan and vertical location of the proposed box culverts rows assuming a two-row scenario and a detention storage target volume of 13.8 acre-feet, corresponding to the 10-year flooding risk reduction.

The two rows of box culverts can be placed on one side and the other of the existing 72 to 78-inch main trunk storm sewer pipe which runs approximately in the middle of the highway. This arrangement may be later amended if construction staging, traffic consideration, or conflicts with other utilities point to a better placement. It is anticipated that excavation work would proceed one box culvert row at a time in order to preserve a reasonable width for traffic. Access/maintenance manholes at the upstream and downstream (south and north) ends of each box culvert rows and at an intermediary location near 41st Street.

The envisioned 12-ft by 12-ft culvers occupy a vertical space of about 15 feet, when the wall thickness is factored in. Conflicts with other utilities, including the lateral drainage storm sewer pipes, are therefore likely. These conflicts and can be resolved by inserting shorter box culvert section (e.g., 6 feet high by 12 feet wide) at key locations, particularly near the low point at 42nd Street where vertical space is limited.

7.2 Spillway Structure

The hydraulic analysis indicates that to be most effective at reducing the flooding risk, the stormwater diversion from the existing 78-inch main trunk line into the detention storage space during large storms should happen as the water level reaches approximately 818.5 in elevation. A spillway crest that is considerably lower would result in prematurely filling the detention volume in the earlier stage of the storm before the peak.

One possible construction option is a special spillway structure in form of rectangular chamber with inside cast in place concrete spillways, for each row of culverts (Figure 1) in each direction (i.e., north and south). The spillway design needs to be subject to special optimization. Tentatively, for modeling purposes the width of one individual spillway was assumed to be about 10 feet, the hydraulically effective width of a 12-ft wide culverts. Thus, for two rows of box culverts in each south and north direction, the total effective spillway width would be about 40 feet, a value that was used to model the 10-year level proposed conditions (i.e., 13.8 ac-ft of storage rendered as two parallel rows of 12’ x 12’ box culverts).

A good spillway location choice is north of the 42nd Street Bridge. Inside the chamber, the existing 72-inch main trunk line would be converted into a semi-circular concrete channel. This particular design would require a “gap” in 12-ft by 12-ft culvert rows, linked through culvert section of lesser height (e.g., 4 feet), to allow for construction of the spillway and also for the connection of the local drainage pipe to the existing 78-inch storm line.

7.3 Emptying Pipes

The simplest scheme for emptying the box culverts is through small size (i.e., 10-inch) drainage pipes that would connect the downstream (northern) end of the box culverts to the manhole at 40th Street where the invert of the 78-inch main trunk line drops by 0.5 (Figure 2). For redundancy, two such pipes should be provided for each culvert row, one placed at the bottom of the culvert as low as practically possible and one slightly (4 inch) higher, in case the lower emptying pipe become plugged with sediment. An simple estimate indicates that, using two 10-inch pipes, the emptying time for a 13.8 ac-ft volume (i.e., 10-year flood reduction level) is approximately 10 hours while the emptying time for a 34 ac-ft volume (i.e., 50-year flood reduction level) is approximately 22 hours.

Alternatively, the emptying pipes can be directly connected to the first drop shaft (DS1), at the upstream end of the tunnel at 39th Street, using directional drilling. While more expensive to construct, this alternative has the advantage of enabling emptying pipe larger in diameter and steeper which in turn can reduce the amount of sediment build up and the maintenance needed for cleaning. This alternative emptying design also allows for an optional sub-drain to be installed under the box culverts, a good yet not absolutely necessary feature.

7.4 Backflow Prevention Mechanism

To minimize the flooding risk at 42nd Street low point, a backflow preventer is needed. In the event that the tunnel surcharge to high levels (i.e., elevation 820 or more), the role of the backflow preventer is to keep stormwater from the tunnel from flowing south through the existing 78-inch main trunk storm pipe, a scenario that could cause or amplify flooding at 42nd Street low point. While various complex schemes for backflow prevention could be envisioned, a simpler design along the existing 78-inch trunk line is preferable.

Various commercial options are available. A good product example in an in-line type rubberized check valve “CheckMate” manufactured by Tideflex. Although the manufacturing data sheet indicates that this type of valve can be used in pipes up to 72-inches in size, and possibly even larger, it is recommended that multiple valves of intermediate size are used instead.

A special flow expansion-contraction structure is needed to distribute the flow along the 78-inch pipe among multiple conduits (Figure 2). One possible flow routing scheme consists of the following parallel pipes:

- Three 54-inch pipes fitted with in-line check valves, with inverts about 6 to 12 inches above the flow line (i.e., the invert of the existing 78-inch pipe)
- One 12 to 15 inch pipe along the flow line, without a check valves.

The larger pipes would convey large flows. Collectively the three 54-inch pipe provide more conveyance than the 78-inch trunk line. They also provide some redundancy in case one of check valves fails to open properly. At the same time, in the less likely event that one of the valves fails to close properly, the amount of backflow is limited. The reason for the smaller pipes is to route the regular flows directly, in order keep the debris out of the larger pipes that are equipped with check valves. The lower pipe would be the default conduit.

The expansion-contraction chamber is likely to be fairly large in scale (i.e., 100 feet long by 20 feet wide or even larger) and it should be the subject of a special design process aimed primarily at minimizing flow losses and sediment accumulation.

From a hydraulic viewpoint, this massive structure would be best placed near tunnel’s first drop shaft, DS1, at 39th Street and the existing 78-inch connection tunnel be reconstructed at a lower level in order to provide steeper slopes, prevent sediment build up, and offset the losses through the structure and valves. However, this option would be challenging from a construction point of view, requiring deep excavation (~40 feet) near the drop shaft and a new special connection. Furthermore, compensating for hydraulic losses by lowering the connection to the tunnel is advantageous only in a situation in which the 78-inch main trunk line becomes surcharge but the water level within the tunnel is still relatively low, at about elevation 800 or lower.

Conversely, to minimize the excavation depth and volume, the structure would be better placed near the low point at 42nd Street. However, it may be difficult to accommodate both a structure of this size as well as the box culverts.

A possibly good trade-off between the two constraints presented above would be to place the expansion contraction structure hosting the pipes equipped with backflow prevention be constructed at 40th Street, just north of the downstream end of the row of culverts.

Placement at this location would also take advantage of the fact that the invert of the existing 78-inch trunk line drops 0.5-feet, offsetting in part the hydraulic losses which shall not exceed 1 foot. The required excavation depth would be approximately 30 feet.

7.5 Access Structures

Access for inspection, cleaning and maintenance should be provided at several points along the length of each culvert row. Thus, access should be provided at the upstream (south) and downstream (north) end of each box culvert row and at the 42nd Street low point (Figure 1, and Figure 2).

Because the box culverts are likely to be located in the traffic lanes, access can be provided from the shoulders of the highway, via side galleries in the shape of a large size culverts (i.e., 8 feet wide x 8 feet high).

Additional inspection and maintenance access from the median is needed to service the spillway structure as well as the backflow prevention structure.

It is recommended that the access from the median at the spillway structure and the backflow prevention structure be as well as the access to the galleries at the upstream end of the tunnel be equipped with open grate in order to provide proper aeration of the detention space. However, from a hydraulic point of view the exact size of the open grate openings is not critical, and will be decided in the final design based on access needs.

8.0 CONCLUSION AND RECOMMENDATIONS

The analysis performed as part of this study only addresses the flooding risks that are directly related to the I-35W tunnel capacity, or lack thereof. The analysis does not include flooding assessment and mitigation for flooding conditions stemming from insufficient inlet capacity or limited capacity of the local collecting pipes. Furthermore, the analysis does factor in the transient flows or air entrainment and release processes that have been documented and used to explain the occasional violent upward ejection of water, referred to as “geysering”.

Therefore, it is very important that local drainage at each location, particularly at the sag points and particularly at the 42nd Street low point be evaluated separately during the Design Phase, in order to reduce the flooding risk due to inlet capacity or the size of the local collecting pipes. Also, as highlighted in Appendix F, it is recommended that the issue of rapid pressurization be revisited.

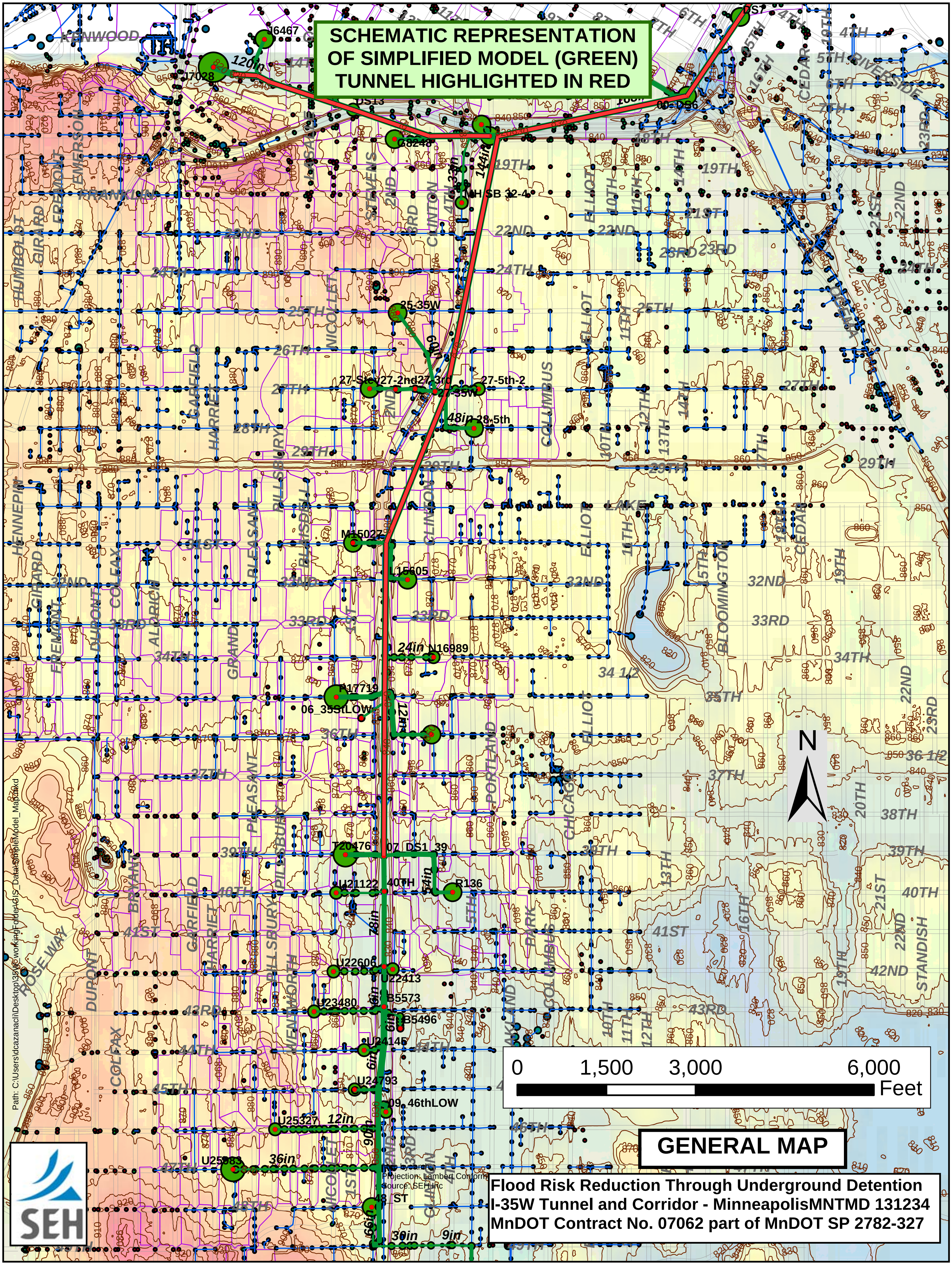
The analysis presented in this report evaluates the stormwater detention volumes needed to minimize the flooding risks for various rainfall levels, from 5-year to 50-year. However, implementing a large detention storage, say greater than the 10-year volume of 13.8 acre-feet, comes with significant challenges and costs that may not warrant representative benefits. The flooding history of the last two decades indicates two significant flooding events within this section of I-35W corridor, both at the 42nd Street low point: July 1, 1997 and June 25, 2010. The analysis shows that 10 acre-feet of storage are sufficient to reduce the flooding risk when the larger of the two events (July 1, 1997) is considered.

The preferred option identified in this study consists of providing near surface detention storage space in the vicinity of (i.e., south and north of) the 42nd Street low point. Under this preferred option, a backflow prevention mechanism to be installed along the main trunk pipe between the 42nd Street low point and the most upstream drill shaft of the tunnel (DS1 at 39th Street) is also recommended.

The design concept discussed in this report, assumes that the storage space would be constructed in form of 12-feet by 12-feet box culverts, installed in parallel rows, south and north of the 42th Street low point (Figures 1 and 2). However, the design options, materials, and exact placement of the detention space are not unique. Other structural options for underground storage can be considered during the final design. Similarly, the exact design and location of the overflow structure, the backflow prevention structure, and the access structures presented in Figures 1 and 2 and discussed above, are not unique.

Regardless of the final solution adopted, to reduce the risks of accidents, property, or life loss in connection with extreme storms it is recommended that an automated flood warning and alert system is implemented. One possibility could be a series of pressure transducers located in the vicinity of 42nd Street low point and calibrated such that as the water level nears the top of the box culverts, a flooding alert is issued and displayed along the highway corridor. The pressure transducers data should be connected in real time to the MnDOT Regional Transportation Management Center (RTMC).

General Map

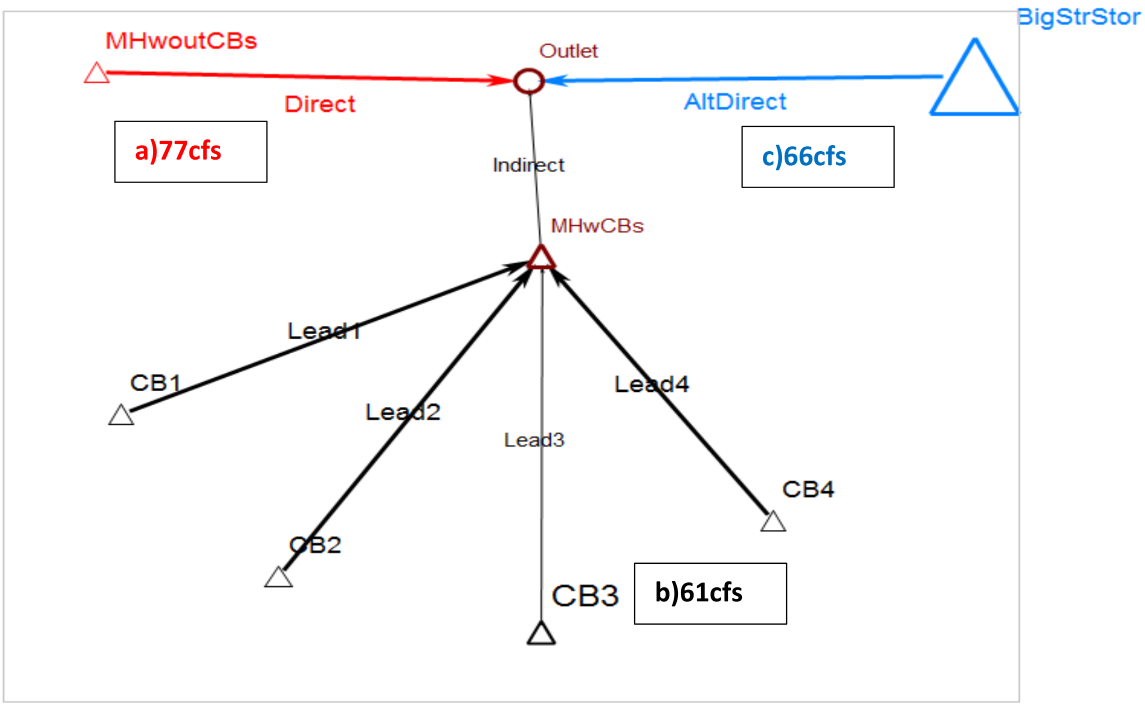


SCHEMATIC REPRESENTATION
OF SIMPLIFIED MODEL (GREEN)
TUNNEL HIGHLIGHTED IN RED
N
0 1,500 3,000 6,000
Feet
GENERAL MAP
Flood Risk Reduction Through Underground Detention
I-35W Tunnel and Corridor - MinneapolisMNTMD 131234
MnDOT Contract No. 07062 part of MnDOT SP 2782-327
SEH

Appendix A

Inlet Restrictions Effect

Appendix A – Illustration of upstream pipe flow restrictions - Alternative Routing Reasoning



a) A common practice in creating XP-SWMM models is to assign the runoff directly to manhole nodes (Left, Red branch above). This practice does not capture flow restrictions imposed by CB intakes and lead pipes and results in unreasonably high surcharge and peak flow rates.

b) In this simple exercise the same simple hydrograph for a) was also assigned to same pipe, indirectly, via four catchbasins with lead pipes of 15-inch diameter (Middle, Black network).

In a) and b) the two manholes (MHwoutCBs, MHwCBs) are identical. Also, the total flow volumes, hydrographs, outlet pipes (36-inch), and the cumulative storage volumes are identical. Nonetheless the peak flow in the no-catchbasins case a) is nearly 30% larger than the peak flow for catchbasins case b), specifically 77cfs vs 61cfs because surcharge level within outlet pipe is higher for case a).

c) Given that modeling every catchbasin is impractical due to volume, quality, or lack of data, one way to account for the reduction in peak flows due to catchbasin leads is by assuming larger storage volume at the street level which in essence reduces the surcharge in the outlet pipe (Right, blue branch). The result is a peak flow reduction from 77cfs (case a) to 66cfs (case b).

The alternative approach described under case c) reduces the surcharge to less than1 foot above ground, yielding results closer to a detailed catchbasin modeling scenario b) than the commonly used method a) which, again, results in unreasonably high surcharge and peak flow rates.

In sum, the practice of directly assigning runoff to manholes eludes the flow restrictions imposed by catchbasins and/or catchbasin lead pipes, resulting in unrealistically high level of surcharge and high peak flows rates within main pipes. One practical way to compensate for this effect is to define ample storage at the street levels at each manhole, thus reducing the surcharge levels within the main trunk pipes.

Appendix B

Hydrologic Parameters

Appendix B   Simplfied Model - Hydrologic Parameters and Storage Volumes:

Hydrologic Parameters (RUNOFF Method)

Node Name	Area (ac)	Width (ft)	Imp.%	Slope
48_ST	72	1250	44%	4.8%
U25983	178	1970	44%	1.0%
U25327	38	910	44%	1.7%
09_46thLOW	32	834	95%	0.7%
U24793	30	808	44%	1.8%
U24145	30	808	44%	1.8%
B5496	7.2	400	95%	0.9%
U23480	61	1150	44%	1.8%
B5573	4.8	230	80%	1.9%
U22606	26	752	44%	5.7%
U22413	25	738	44%	5.7%
08_42ndLOW	13	530	61%	1.9%
U21122	43	968	44%	5.7%
R136	131	1690	44%	1.8%
40TH	4.5	313	57%	0.9%
07_DS1_39	6.9	181	64%	0.8%
T20476	262	2400	44%	1.0%
O18174	90	1400	44%	1.4%
06_35StLOW	13.5	100	75%	1.9%
P17719	198	2000	44%	2.2%
N16989	32	835	44%	0.6%
L15605	80	1320	60%	0.2%
M15027	77	1295	66%	0.6%
28-5th	87	1377	50%	1.9%
27-35W	4.3	1464	55%	9.3%
27-5th-2	25	738	50%	0.0%
27-Stev	121	1630	50%	1.0%
25-35W	122	1630	50%	0.0%
27-Stev	121	1630	50%	1.0%
25-35W	122	1630	50%	1.0%
MH SB 32-4	19	643	60%	2.2%
G8248	120	1617	52%	1.0%
03_JUNCT	14.9	750	46%	1.1%
02_DS16	67	141	50%	1.0%
MH 2030	67	1208	45%	2.0%
DS13	23	164	56%	1.5%
00_DS6	110	1814	59%	1.6%
I7312	19	643	51%	1.3%
J7028	444	3100	51%	1.0%
D6865	110	1548	66%	4.8%
J6467	114	1575	60%	1.0%
DS7	94	3433	52%	0.9%

Storage Volumes (10-year level)

Node Name	TOC	Max HGL	Surcharge	Storage Volume (ac-ft)
08_42ndLOW*	822.0	825.9	3.9	11.2
09_46thLOW**	829.3	829.6	0.3	0.1
25-35W	855.3	855.5	0.3	0.7
27-5th-2	858.8	858.9	0.1	0.2
27-Stev	867.4	868.0	0.6	3.3
28-5th	850.3	850.8	0.5	2.2
43RD_ORIF	826.7	826.8	0.1	0.2
43RD-2	825.2	825.7	0.5	2.3
43RD-3	825.2	825.6	0.5	1.8
48_ST	859.1	859.7	0.7	5.9
C5429	826.3	826.5	0.2	0.3
D6852	840.3	840.7	0.4	1.2
D6853	840.3	840.7	0.4	1.1
D6894	840.8	840.9	0.1	0.2
G8248	858.8	859.3	0.5	2.1
J6467	828.1	828.6	0.5	2.6
J6822	825.7	825.9	0.2	0.6
J7028	824.6	825.3	0.6	4.6
J7073	824.6	824.8	0.2	0.5
L15605	868.8	869.3	0.5	2.4
M15027	866.4	866.9	0.5	2.4
MH 2030	828.3	828.4	0.1	0.2
N16989	866.3	866.8	0.5	2.5
O18174	850.3	850.7	0.4	1.5
P17719	860.8	861.5	0.7	5.2
R136	837.3	837.9	0.6	3.4
T20476	852.5	852.7	0.2	0.3
U21122	844.5	845.0	0.5	1.8
U22606	865.3	865.8	0.5	2.7
U23480	864.3	864.9	0.6	4.6
U24145	855.6	856.0	0.4	1.4
U24793	847.3	847.6	0.3	0.7
U25327	875.3	875.8	0.5	2.8
U25983	871.5	872.4	0.9	17.6

Assumed deflault storage in Simplified Model:
Area=exp(5*depth)
EXCEPT storage nodes along Hwy corridors
where actual area was used:

***Low Pt at 42nd St**

Elevation	Area(ac)
822	1.2
824	3.0
826	4.8
828	6.7
830	8.8

****Low Pt at 46th St**

Elevation	Area(ac)
819.3	0.01
820	3.0
822	5.5
824	23.5
826	26.0

Nodes not listed did not flood - no surface storage

Appendix C

Model Results Compared To Real Rainfall Events Data

Appendix C:

Model Results Compared To Real Rainfall Events Data (XPSWMM MODEL VALIDATION)

EVENT	LOCATION	SEH MODEL RESULTS:	SUBSURFACE and SURFACE DATA:
July 3, 1999 (see Slide 2)	Water Levels inside Tunnel at 35th St (DS2)	• Peak Level 804.5 • Total Tunnel Surcharge ~27 min	Pressure Data from Barr 1999 Report via MnDOT: • First peak strikes at ~804.5 • Total Tunnel Surcharge ~25 min
July 1, 1997 (see Slide 3)	42nd St Low Pt - Flooding Depth	4 feet	Approx. 3 to 4 feet (See Slide 3 photo)
June 25, 2010 (see Slide 4)	42nd St Low Pt - Flooding Depth	1.3 feet	Approx. 1.2 to 1.5 feet (see Slide 4 Photo)

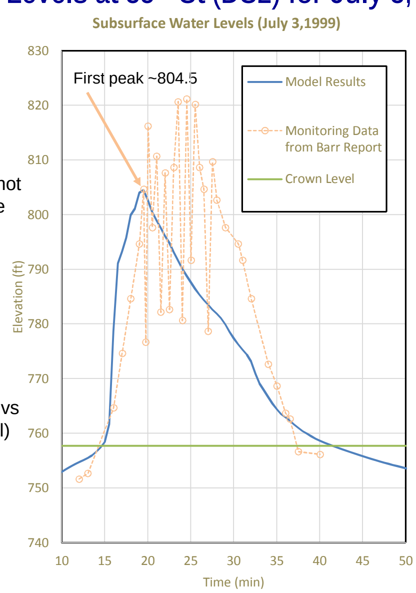
Rainfall Data used in Model simulation of the above storms was acquired from NOAA, except for the July 1999 event which the rain data already assembled in the Barr report.

Comparing in-Tunnel Levels at 35th St (DS2) for July 3, 1999 storm

XPSWMM Model does not (and cannot) capture the transient oscillation.

However, the model accurately captures:

- First peak at approximately 804.5
- The surcharge time (above crown level):
  25 minutes (data) vs
  27 minutes (model)



Crown at 757.7'

Pressure and Rainfall Data (1-minute) provided by MnDOT (Barr 1999 Report)

July 1, 1997 storm – Star Tribune Photo (I-35W near 42nd St)

© 1997, Star Tribune/Minneapolis-St. Paul

Stalled cars along Interstate 35W near the 42nd street overpass in south Minneapolis on July 1, 1997. Three inches of rain fell in 30 minutes in some areas, causing widespread flash flooding.

SEH Model prediction for max. flooding depth of **4.0 feet** compares well to the reality depicted in the photo.

- Barr 1999 Report Describes it as "500-year extreme event"
- Star Tribune mentions "3 inches in 30 minutes"
- This NOAA link mentions "2.1 inches in 20 minutes on campus"

http://www.srh.noaa.gov/oun/?n=safety-overpass-slide19

- NOAA Data at MSP lists 2.67 inches

June 25, 2010 – 35W at 42nd St (YouTube caption and Fox News photo)

SEH model prediction for max. flooding depth of **1.3 feet** (~below knee level) compares well to the news photo and YouTube footage caption.

- Above: Cars from opposite site visible within short distance
- Right: Water below knee level (notice hubcaps and right door lower corner above water level)

CONCLUSION

- Assessment of several real rainfall events clearly shows that the model developed by SEH, simplified as is, represents a reliable approximation of the reality on the ground (or under). This statement is validated by monitoring data and photographic evidence.

Appendix D

Evaluation of Flooding Risk Reduction Assuming 30 AC-FT Detention Volume

TECHNICAL MEMORANDUM

TO:	Scott Pedersen, Bruce Irish, Beth Neuendorf, John Griffith - Mn/DOT
FROM:	Dan Cazanacli, Ron Leaf - SEH
DATE:	August 10, 2015
RE:	**Evaluation of Flooding Risk Reduction along 35W Corridor Assuming 30 ac-ft of Near-Surface Detention Storage Volume in the Vicinity of 42nd Street Low Pt.**

At the conclusion of the July 29, 2015 meeting attended by representatives of MnDOT, City of Minneapolis, FHWA, CDM Smith and SEH, SEH has been directed to evaluate the impact of providing storm water detention space totaling 30 ac-ft on reducing the storm water crest levels along 35W corridor for 10-year and 50-year rainfall events in particular. Our understanding was that we would assume the same design concept that SEH presented at the meeting.

Given the complexities of the drainage along the 35W corridor and the importance of the decision processes, before elaborating on the results of this task, it is important to review the premise of our analysis:

SEH Analysis of Existing Conditions

SEH analysis indicates that the most vulnerable location to flooding due to tunnel capacity limits is the low point at 42nd Street where significant ponding has been observed several times in the past. However, while the analysis carried out to assess large rainfall events would suggest that flooding at 42nd Street is caused by backflow from the 35W tunnel, it is entirely plausible that some of the observed flooding was caused mainly by the collective capacity of the local drainage system. Specifically, the drainage at 42nd Street low point is serviced by a large and adequate number of catchbasins but they are ultimately connected to four 12-inch pipes whose collective capacity can be exceeded by the runoff occurring during a flash flood.

We conducted the analysis using 24-hour rainfalls of various frequencies, following Atlas 14 guidelines, rainfall depths and nested distributions (i.e., not the older and less conservative SCS Type II distribution).

SEH Preliminary Cost Effective Solution

SEH has determined that the most economical way to pursue a flood reduction solution based on detention storage is in the form of near surface (shallow) underground storage space in the vicinity of the low point at 42nd Street. Assuming that the storm water would spill into the storage space through a broad spillway as the local water crest approaches ground levels, our evaluation of storage space needed to limit the flood crest to no more than elevation 822 (proposed centerline low point elevation) requires approximately 14 ac-ft of detention storage when a 10-year rainfall event is considered. If a 50-year rainfall event is considered, the detention storage needed is estimated at approximately 41 ac-ft. These estimates do not necessarily assume a backflow prevention mechanism (preventing water from the tunnel from flowing back south towards 42nd Street low point) which, if implemented, would reduce the detention storage volumes needed by about 10% to 20% for the 10-year and 50-year rainfall, respectively.

In defining the placement of the storage volume, SEH understood that the detention storage needs to be within the 35W right-of-way corridor. As we pointed out previously, the exact choice of storage space shape and location is not unique. Various design options are possible, as long as gravity emptying can be ensured. A series of 12-ft by 12-ft box culverts is a good practical and economical choice that minimizes the linear extent of storage space and fully utilizes the vertical space between roadway elevation and the invert of existing 78-inch pipe to be used to empty of the box culverts once the rainfall recedes. Thus, to achieve the target storage volumes of 14 ac-ft and 41 ac-ft, we suggested two rows of box culverts spanning 2,080 feet each and six rows of similar length and shape box culverts, respectively.

<u>The cost estimate for constructing the 10-year storage level of 14 ac-ft is approximately $13M.</u>

<u>The cost estimate for constructing the 50-year storage level of 41 ac-ft is approximately $30.2M.</u>

SEH Modeling Approach - Overview

For very good reasons outlined below SEH developed a simplified model to better estimate the flooding levels during large rainfall events. To recap, we started the effort of evaluating flooding levels and required mitigation with an evaluation of the 2014 35W Corridor Preliminary Drainage Study large model consisting of hundreds of nodes (representing manholes) and links (representing pipes and street flow). Although this detailed model contains valuable hydrologic and geometric information, it quickly became apparent to us that it is not the adequate approach to evaluating large rainfall events, predicting flooding levels considerably above what has been observed during largest storms in recent decades. The main shortcoming of the detailed model is the fact that the runoff hydrographs are directly assigned to manholes, thus eluding any inflow restrictions that are imposed by inlets and/or lead pipes and implicitly eluding much of the storage at the street level. Of secondary importance are the hydraulic losses within manholes, not adequately captured in the large model. For relatively small rainfall events these aspects may not be critical as most of the runoff is conveyed by the drainage networks but for larger events, it introduces a fundamental error allowing many of the storm pipes to surcharge to unrealistically high levels and high peak flow rates.

We disagree with the premise that the original larger model is more correct because it has been “calibrated and validated”. The calibration study referred to in the 2006 report indicates that the hydrologic parameters have been adjusted such that the predicted flow rates best match the flow rates for a specific area and for a limited series of rainfall events. While the referred study has certain merits the results cannot be reliably extrapolated to reflect much larger events and applied to a much larger area. More importantly, the chief difference between the detailed model and our simplified one is not about the hydrologic assumptions. It is the fact that the detailed model does not factor in any flow restrictions upstream manholes, thus assigning arbitrarily high peak flow rates into the drainage system, a fundamental and serious limitation that results in unrealistically high level of flooding when large rainfall events are considered.

To circumvent this deficiency we took the view that, regardless of the magnitude of the rainfall event, the runoff rate to the tunnel is ultimately restricted by the carrying capacity of the tributary pipes. With that in mind, we assembled a simplified model that retains all the main trunk storm pipes and allow for surcharge up to about a foot above ground level. This simplified model retains the acreage and the global hydrologic properties of the drainage areas tributary to the tunnel. It does not impose direct restrictions on the runoff but all the runoff is ultimately modulated by the carrying capacity of the trunk pipes in full surcharge mode. This is an essential aspect and we feel confident that our simplified model conservatively captures the level flooding during large rainfall events without grossly overestimating the levels of flooding.

30 ac-ft DETENTION STORAGE EVALUATION

Our understanding was that the evaluation of the 30 ac-ft detention storage would assume the same design concept that SEH presented before, namely near-surface detention storage in the vicinity of 42nd Street low point. Peak levels estimates and flooding or freeboard levels for 5, 10, and 50-year rainfall levels (24-hour Atlas 14 distribution) are summarized in Tables 1 and 2 below:

TABLE 1. HIGH WATER LEVELS (30 ac-ft STORAGE)

Location	Node_Name	Ground	5-year	10-year	*50-year^*	50-year
13th at I94	00_DS6	840.1	782.4	787.4	*791.7*	790.2
18th Clinton	01_DS14	856.5	803.3	808.8	*812.3*	810.5
Portland	02_DS16	810.9	799.8	805.8	*809.6*	807.5
Junction	03_JUNCT	856.5	798.5	804.4	*808.4*	806.2
DS4 at 27th	04_DS4_27t	859.0	814.0	821.9	*825.3*	821.2
DS3 at 32st	05_DS3_31s	864.5	818.6	827.4	*830.7*	825.5
35th St Low*	06_35StLOW	837.2	826.6	835.2	*837.5*	837.0
DS1 39th St	07_DS1_39	838.1	822.3	832.5	*835.6*	829.0
42nd St Low	**08_42ndLOW**	**822.0**	**819.3**	**819.4**	***822.9***	**825.5**
46th St Low*	09_46thLOW	829.3	827.6	829.4	*830.1*	830.1

TABLE 2. FREEBOARD(-) or FLOODING(+) LEVELS

Location	Node_Name	Ground	5-year	10-year	*50-year^*	50-year
13th at I94	00_DS6	840.1	-57.7	-52.7	*-48.4*	-49.9
18th Clinton	01_DS14	856.5	-53.2	-47.7	*-44.2*	-46.0
Portland	02_DS16	810.9	-11.1	-5.1	*-1.3*	-3.4
Junction	03_JUNCT	856.5	-58.0	-52.1	*-48.1*	-50.3
DS4 at 27th	04_DS4_27t	859.0	-45.0	-37.1	*-33.7*	-37.8
DS3 at 32st	05_DS3_31s	864.5	-45.9	-37.1	*-33.8*	-39.0
35th St Low*	06_35StLOW	837.2	-10.6	-2.0	*0.3*	-0.2
DS1 39th St	07_DS1_39	838.1	-15.8	-5.6	*-2.5*	-9.1
42nd St Low	**08_42ndLOW**	**822.0**	**-2.7**	**-2.6**	***0.9***	**3.5**
46th St Low*	09_46thLOW	829.3	-1.7	0.1	*0.8*	0.8

^Assumes a backflow prevention mechanism.
*Limited flooding at these low points predicated on capacity limits of local drainage pipes. Model does NOT indicate that Tunnel / main trunk sewer trunk surcharge to these levels.

Under 30 ac-ft of detention storage assumption, analysis indicates no flooding for rainfall levels of 5 and 10 years, whether a backflow prevention mechanism is used or not. However, for a 50-year rainfall level, a backflow prevention mechanism is quite important. The last column in the above tables implies no backflow prevention mechanism and shows a considerably higher level of flooding at 42nd Street low point for a 50-year rainfall level. In essence, for such an event a backflow prevention mechanism considerably reduces the risk of flooding at 42nd Street low point, at the expense of higher crest along the tunnel section.

Drawdown time estimates at two important locations, the low point at 42nd Street and the drop shaft at the upstream end of the tunnel (DS1 at 39th Street) are summarized in Tables 3 and 4 below:

TABLE 3. DRAWDOWN TIMES (minutes) for 42nd ST LOW PT

Reference Level Considered for Drawdown Time	Ref. Elev.	5-year	10-year	*50-year^*	50-year
Ground (Highway centerline) *	822.0	0	0	*61*	141
Crown of existing 78-inch pipe	815.2	46	80	*161*	208

*Drawdown time at ground level is essentially the duration of flooding

TABLE 4. DRAWDOWN TIMES (minutes) for DS1 at 39th ST

Level considered for drawdown time	Ref. Elev	5-year	10-year	*50-year^*	50-year
Ground (Highway centerline)	838.6	N/A - No flooding, HGL below ground			
Crown of 12-ft Tunnel	**761.5**	**50**	**102**	***183***	**203**
Crown of Incoming 78-inch pipe**	**809.2**	**21**	**45**	***110***	**106**
Back flow (from tunnel to 42nd St)		**1**	**19**	***0***	**60**

** Approximate level below which tunnel surcharge does not affect flow from 78-inch pipe
^ Assuming a backflow prevention mechanism

The drawdown time was estimated relative to the ground level (i.e., flood duration) and relative to the crown of the outflowing pipe (i.e., surcharge duration). Additionally, at the first drop shaft DS1, the drawdown time was estimated relative to the crown of incoming 78-inch main trunk pipe from the south that ensures the drainage along the 35W corridor south (upstream) of the tunnel. Once water level in the tunnel recedes below this level, the flow within the 78-inch pipe can be approximated as free fall. The last row in Table 4 is an estimate of the backflow duration, where applicable.

Discussion:

Under the proposed design concept of 30 ac-ft of detention storage to be built in the vicinity 42nd Street, using a broad spillway with a crest elevation of about 818.5 as assumed above, significantly reduces the level of flooding when a 50-year rainfall is considered, particularly in conjunction with a backflow prevention mechanism. However, <u>setting the spillway crest at this level leaves much of the 30 ac-ft volume unutilized when 5-year or 10-year rainfall levels are considered</u>. <u>Setting the spillway crest at a lower level would utilize more storage and lower the peaks listed in the first two columns in Table 1, but that gain in freeboard for 5 and 10-year rainfall cases would come at the expense of higher peaks for a 50-year rainfall.</u>

This is because during such an extreme event, a lower spillway means that much of the storage space may fill up before the peak of the storm. Other diversion schemes can be considered as alternatives to a broad spillway in order to optimize the use of detention storage but the fact remains that optimization for a lower rainfall event increases the flooding risks during larger rainfall events.

Since 30 ac-ft seems more than adequate for a 10-year event, it makes sense to assume a spillway level at elevation 818.5, which consistent with the results listed in Tables 1-4 above and helps lowering the crest and reducing the flooding risk associated with larger rainfall events (e.g., 50-year). Table 5 shows the storage volume utilized for each rainfall event considered:

TABLE 5. STORAGE VOLUME / FRACTION UTILIZED:

		5-year	10-year	50-year
Storage Vol. Used	ac-ft	2.5	16.3	30
Fraction of 30 ac-ft	%	8.3%	54%	100%

Cost estimate: <u>The preliminary construction costs estimates for 30 ac-ft of detention storage assumed to be in form of six rows of 12 ft by 12 ft box culverts, approximately 1,512 feet long each, is **$23.1M.**</u>

Conclusions:

1. Consistent with our previous findings, a detention storage volume of 30 ac-ft seems more than adequate to reduce the risk of flooding associated with 5-year and 10-year rainfall events.
2. By setting the spillway crest level at elevation about 818.5 the analysis shows that less than 10% of the 30 ac-ft storage volume would fill up when a 5-year rainfall event is considered, and slightly more than half when a 10-year rainfall event is considered.
3. The same analysis shows that the 30 ac-ft volume may not be sufficient to completely eliminate the risk of flooding when a more extreme, 50-year rainfall event is considered. However, if used in connection with backflow prevention mechanisms, this storage volume can reduce maximum flooding depth at 42nd Street low point considerably. Analysis indicated approximately 1 foot or less for 50-year rainfall.
4. We reaffirm our previous findings presented earlier and we believe that the detention volumes of approximately 14 ac-ft and 41 ac-ft are conservative estimates of what is needed to contain the flooding risks associated with 10-year and 50-year rainfall levels, respectively.
5. We also reaffirm our preliminary design concept consisting of near the surface, gravity drained detention storage in the vicinity of 42nd Street low point as the most economical solution. The exact geometric arrangement of the storage volumes to be implemented is subject to further optimization.
6. Thus, we maintain that the flood risk can be substantially reduced through a temporary detention storage – gravity draining system. In our opinion solutions involving galleries, deeper storage, and pumping are not warranted and involve significantly higher construction and maintenance costs in addition to tremendous implementation challenges.
7. <u>The construction estimates for our 10-year and 50-year storage target volumes of 14 and 41 ac-ft are approximately $13.0M and $30.2M, respectively. The cost for 30 ac-ft of storage is estimated at $23.1M</u>
8. Finally, we want to restate that, as part of the upcoming projects, it is essential that the local drainage systems be re-assessed and upsized accordingly, particularly at the sag points and particularly at 42nd Street low point where the existing 12-inch collecting pipes can rapidly surcharged during a flash flood which in turn can result in water ponding, irrespective of the crest levels within the tunnel.

Appendix E

Cost Estimates

APPENDIX E:

COST ESTIMATES FOR STORMWATER STORAGE BUILT S and N OF 42ND ST LOW PT*
***THIS FLOOD REDUCTION APPROACH INVOLVES A BACKFLOW PREVENTION MECHANISM**

"5-YEAR" - STORAGE				**2.4 acre-feet**	
12'x12' BOX CULVERTS AT 42ND - 1 ROWS ~730-FT LONG					
MOBILIZATION (10%)	LUMP SUM	1	$ 147,770	$	147,770
12x12 BOX CULVERT	LIN FT	730	$ 850	$	620,500
SPECIAL SPILLWAY STRUCTURES	EACH	1	$ 230,000	$	230,000
ACCESS MANHOLES	LIN FT	30	$ 1,050	$	31,500
SPECIAL CONNECTIONS	EACH	1	$ 90,000	$	90,000
BACKFLOW MECHANISM (TBD)	LUMP SUM	1	$ 500,000	$	500,000
CASTING ASSEMBLY	EACH	6	$ 950	$	5,700
DRAINAGE ELEMENTS COST SUBTOTAL				**$**	**1,625,470**
OTHER COSTS (PAVEMENT, TRAFFIC, UTILITIES)	ASSUME	90%		**$**	**1,462,923**
CONTINGENCIES (DESIGN, ADMIN)	ASSUME	30%		**$**	**926,518**
TOTAL				**$**	**4,014,911**

"10-YEAR" - STORAGE				**13.8 acre-feet**	
12'x12' BOX CULVERTS AT 42ND - 2 ROWS ~2080-FT LONG EACH					
MOBILIZATION (10%)	LUMP SUM	1	$ 478,475	$	478,475
12x12 BOX CULVERT	LIN FT	4160	$ 850	$	3,536,000
SPECIAL SPILLWAY STRUCTURES	EACH	2	$ 230,000	$	460,000
ACCESS MANHOLES	LIN FT	90	$ 1,050	$	94,500
SPECIAL CONNECTIONS	EACH	2	$ 90,000	$	180,000
BACKFLOW MECHANISM (TBD)	LUMP SUM	1	$ 500,000	$	500,000
CASTING ASSEMBLY	EACH	15	$ 950	$	14,250
DRAINAGE ELEMENTS COST SUBTOTAL				**$**	**5,263,225**
OTHER COSTS (PAVEMENT, TRAFFIC, UTILITIES)	ASSUME	90%		**$**	**4,736,903**
CONTINGENCIES (DESIGN, ADMIN)	ASSUME	30%		**$**	**3,000,038**
TOTAL				**$**	**13,000,166**

30ac-ft STORAGE				**30.0 acre-feet**	
12'x12' BOX CULVERTS AT 42ND - 5 ROWS ~1815-FT LONG EACH					
MOBILIZATION (10%)	LUMP SUM	1	$ 949,100	$	949,100
12x12 BOX CULVERT	LIN FT	9060	$ 850	$	7,701,000
SPECIAL SPILLWAY STRUCTURES	EACH	2	$ 230,000	$	460,000
ACCESS MANHOLES	LIN FT	240	$ 1,050	$	252,000
SPECIAL CONNECTIONS	EACH	6	$ 90,000	$	540,000
BACKFLOW MECHANISM (TBD)	LUMP SUM	1	$ 500,000	$	500,000
CASTING ASSEMBLY	EACH	40	$ 950	$	38,000
DRAINAGE ELEMENTS COST SUBTOTAL				**$**	**10,440,100**
OTHER COSTS (PAVEMENT, TRAFFIC, UTILITIES)	ASSUME	70%		**$**	**7,308,070**
CONTINGENCIES (DESIGN, ADMIN)	ASSUME	30%		**$**	**5,324,451**
TOTAL				**$**	**23,072,621**

"50-YEAR" - STORAGE				**33.6 acre-feet**	
12'x12' BOX CULVERTS AT 42ND - 5 ROWS ~2040-FT LONG EACH					
MOBILIZATION (10%)	LUMP SUM	1	$ 1,046,000	$	1,046,000
12x12 BOX CULVERT	LIN FT	10200	$ 850	$	8,670,000
SPECIAL SPILLWAY STRUCTURES	EACH	2	$ 230,000	$	460,000
ACCESS MANHOLES	LIN FT	240	$ 1,050	$	252,000
SPECIAL CONNECTIONS	EACH	6	$ 90,000	$	540,000
BACKFLOW MECHANISM (TBD)	LUMP SUM	1	$ 500,000	$	500,000
CASTING ASSEMBLY	EACH	40	$ 950	$	38,000
DRAINAGE ELEMENTS COST SUBTOTAL				**$**	**11,506,000**
OTHER COSTS (PAVEMENT, TRAFFIC, UTILITIES)	ASSUME	70%		**$**	**8,054,200**
CONTINGENCIES (DESIGN, ADMIN)	ASSUME	30%		**$**	**5,868,060**
TOTAL				**$**	**25,428,260**

Appendix F

Rapid Pressurization General Observations

Appendix F: 35W Storm Tunnel - General Considerations on Rapid Pressurization

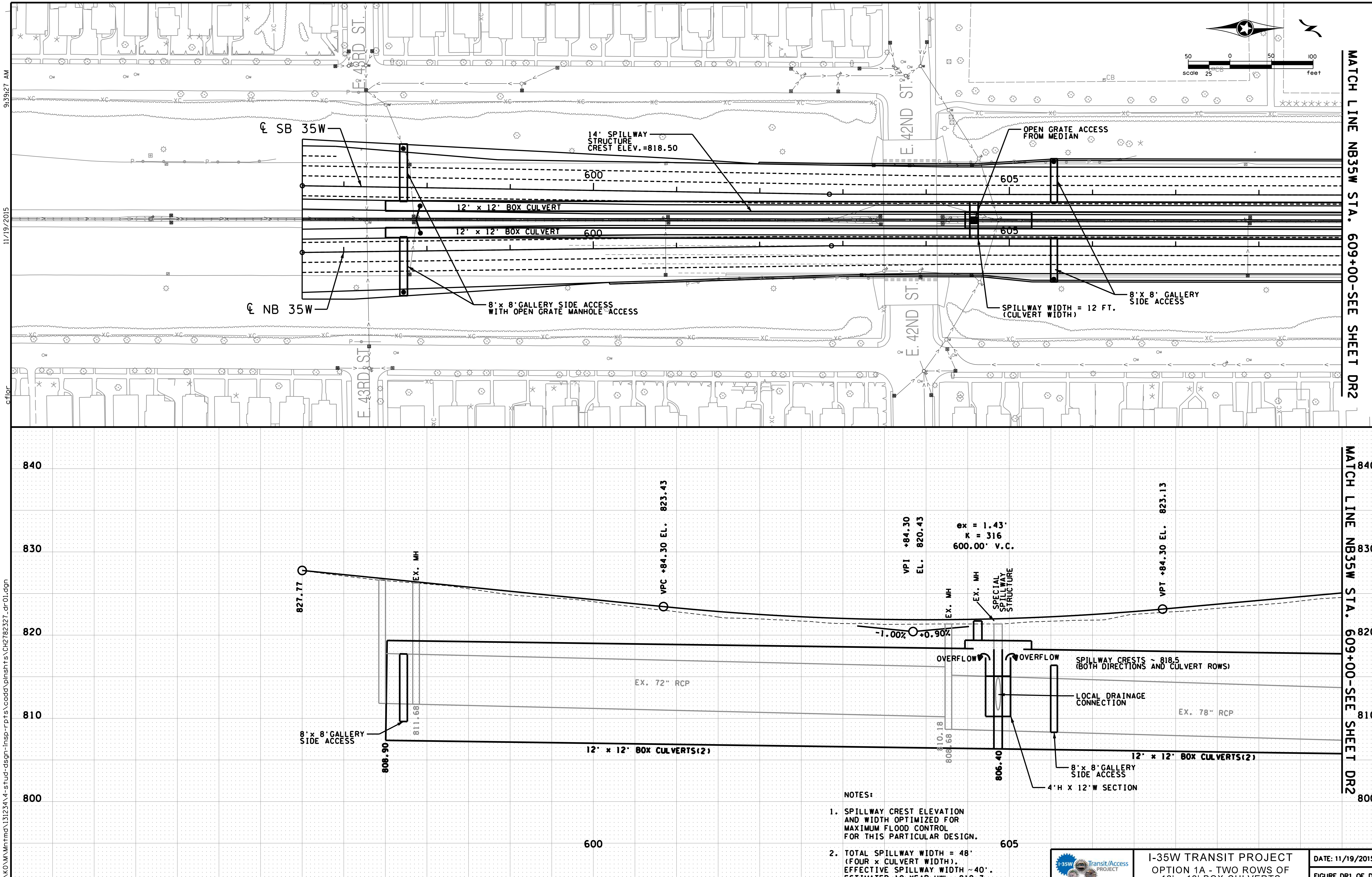
Drainage aspects associated with the I-35W tunnel are not limited to flooding due to lack of conveyance capacity and flood risk reduction through the detention storage. Given the history of sudden water expulsion along the I-35 corridor in south Minneapolis, some considerations on a different aspect, rapid pressurization within the tunnel, might be useful.

The sudden expulsion of water referred to as geysering and thought to be associated with transient flows and/or air release, requires a considerably more expansive and specialized type of analysis, not included in the scope of this study. Furthermore, the XPSWMM model is not an adequate tool to assess transient flows dynamic which requires a more sophisticated specialized analysis with time steps in the order of milliseconds. Given that SEH has not been involved in "geysering" studies, based on our knowledge of similar systems, we simply want to offer a few general considerations that may help clarifying some lingering confusion between past episodic expulsion of water and the more gradual and prolonged surcharge can trigger extensive flooding. The history of "geysering" may have added or distorted the perception of flooding linked to tunnel capacity, or lack thereof.

- In principle, geysering can occur any time the tunnel surcharges, even to modest levels above crown. There is little disagreement that the tunnel surcharges fairly often but rarely reaches, for a considerable amount of time, levels that can result in backflow and surface flooding (ponding) at 42nd Street low point. Thus, it is possible that the "geysering" occurrence has amplified the perception of flooding risk.
- From a structural point of view, the level of surcharge is less important. What matters more is how the surcharge occurs. When the tunnel surcharges gradually, the hydrostatic pressure levels are considerably below the limits of tensile resistance of concrete. Sudden pressurization, however, may pose a risk to the structural integrity of the unreinforced concrete walls of the tunnel.
- The flow deflection structures built at the first two drill shafts at the upstream end of the tunnel (DS1 at 39th St and DS2 at 35th St) would suggest that few years ago a decision was made to contain the violent manifestation of the of rapid water or water-air mix release, such as manhole cover blowout, but not address the sudden pressurization process directly.
- The detention storage solutions to flooding discussed thus far do not reduce the risk of rapid pressurization in significant ways. Thus, to the extent to which there is evidence of rapid pressurization that can adversely affect the concrete structure and undermine the expansive rehabilitation efforts, the reconstruction the 35W corridor may serve as an opportunity to reassess this undesirable process and possibly diverting a portion of the investment into countering it.
- One possible way to protect against rapid surges is through a series of oversized drop shafts (i.e., considerably greater than the tunnel diameter) placed at key locations along the tunnel. Collectively, the volume of surge chambers may help very little in reducing the flooding risk related to lack of capacity but could be essential in suppressing the effect of rapid surges and sudden pressurization.

These are just some general considerations with a recognition that MnDOT and its partners involved in the studying this complex processes in the past are in a better position to determine to what extent the rapid pressurization is an issue that needs to be addressed further.

List of Figures



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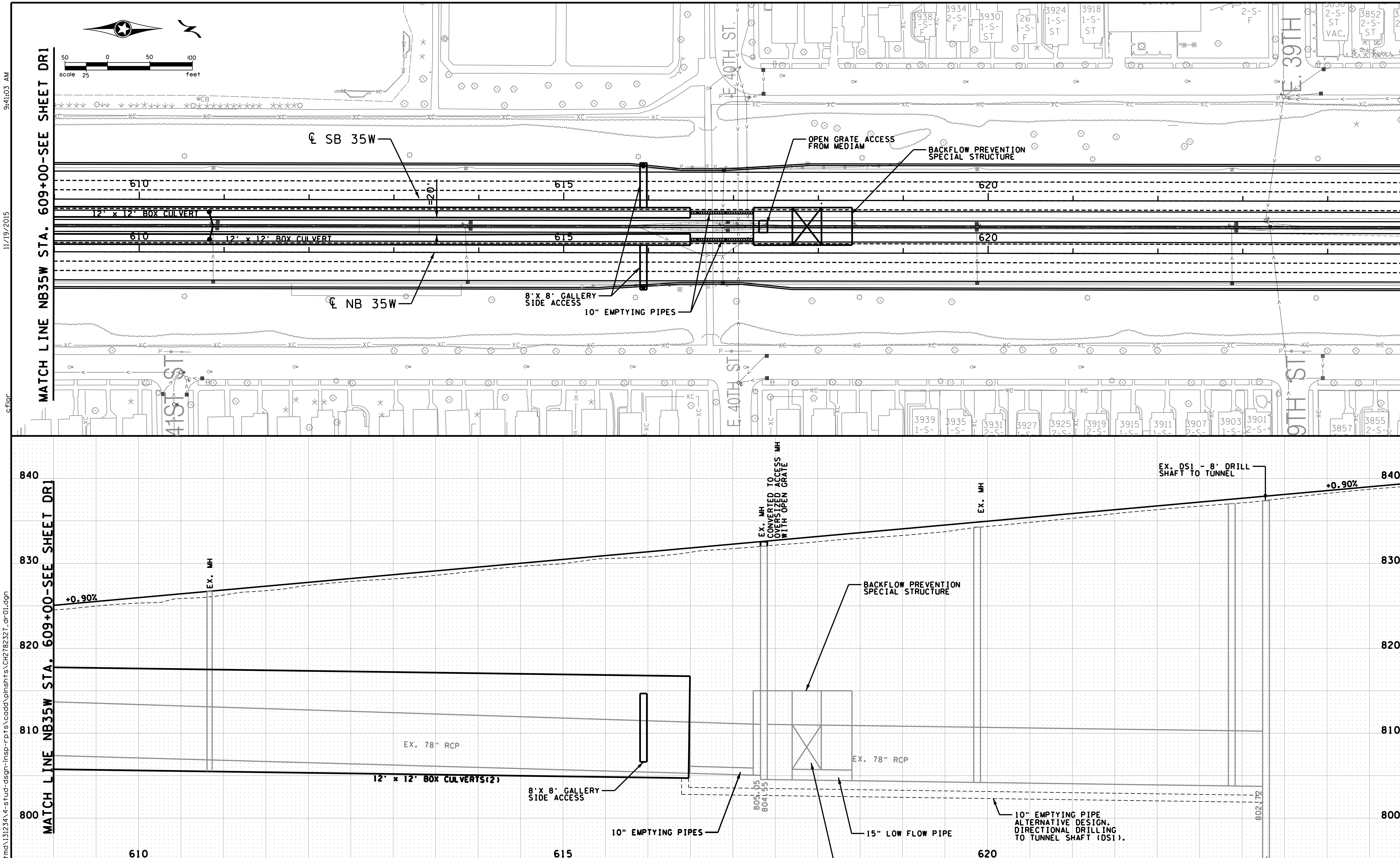
scale
feet
50
0
50
100
25
E. 43RD ST.
E. 42ND ST.
℄ SB 35W
℄ NB 35W
14' SPILLWAY STRUCTURE CREST ELEV.=818.50
OPEN GRATE ACCESS FROM MEDIAN
600
605
12' x 12' BOX CULVERT
12' x 12' BOX CULVERT
8'x 8' GALLERY SIDE ACCESS WITH OPEN GRATE MANHOLE ACCESS
SPILLWAY WIDTH = 12 FT. (CULVERT WIDTH)
8'X 8' GALLERY SIDE ACCESS
MATCH LINE NB35W STA. 609+00-SEE SHEET DR2
840
830
820
810
800
827.77
EX. MH
VPC +84.30 EL. 823.43
VPI +84.30 EL. 820.43
ex = 1.43'
K = 316
600.00' V.C.
EX. MH
EX. MH
SPECIAL SPILLWAY STRUCTURE
VPT +84.30 EL. 823.13
-1.00%
+0.90%
OVERFLOW
OVERFLOW
SPILLWAY CRESTS ~ 818.5 (BOTH DIRECTIONS AND CULVERT ROWS)
EX. 72" RCP
LOCAL DRAINAGE CONNECTION
EX. 78" RCP
8'x 8' GALLERY SIDE ACCESS
811.68
808.90
12' x 12' BOX CULVERTS(2)
810.18
808.68
806.40
12' x 12' BOX CULVERTS(2)
8'x 8' GALLERY SIDE ACCESS
4'H X 12'W SECTION
NOTES:
1. SPILLWAY CREST ELEVATION AND WIDTH OPTIMIZED FOR MAXIMUM FLOOD CONTROL FOR THIS PARTICULAR DESIGN.
2. TOTAL SPILLWAY WIDTH = 48' (FOUR x CULVERT WIDTH). EFFECTIVE SPILLWAY WIDTH ~40'. ESTIMATED 10-YEAR HWL ~819.7.
600
605
I-35W Transit/Access PROJECT
I-35W TRANSIT PROJECT
OPTION 1A - TWO ROWS OF 12' x 12' BOX CULVERTS
DATE: 11/19/2015
FIGURE DR1 OF DR2



I-35W Transit/Access PROJECT

I-35W TRANSIT PROJECT

OPTION 1A - TWO ROWS OF 12' x 12' BOX CULVERTS

DATE: 11/19/2015

FIGURE DR2 OF DR2

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