Addendum 3

Central City Tunnel System Hydrologic and Hydraulic Modeling Using XP-SWMM

Central City, Eleventh Avenue, and Chicago Avenue Tunnel Systems

Prepared for the
City of Minneapolis

June, 2015

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Central City Tunnel System Hydrologic and Hydraulic Modeling Using XP-SWMM

June, 2015

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Certifications

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

June 4, 2015

Brandon Barnes

PE #: 49540

Date

1.0 Introduction and Background

The goal of this project was to develop an XP-SWMM model for the Central City (west of Chicago Avenue /Eighth Avenue), Chicago Avenue (along Eighth Avenue), and Eleventh Avenue tunnel systems (Figure 1.1). The total contributing watershed area is 539 acres, with 302 acres contributing to the Central City tunnel system, 45 acres to the Chicago tunnel system, and 192 acres to the Eleventh Avenue tunnel system. All three systems are located within downtown Minneapolis. The model was calibrated to measured pressure data in the Central City tunnel system for two storm events.

1.1 Tunnel System Description

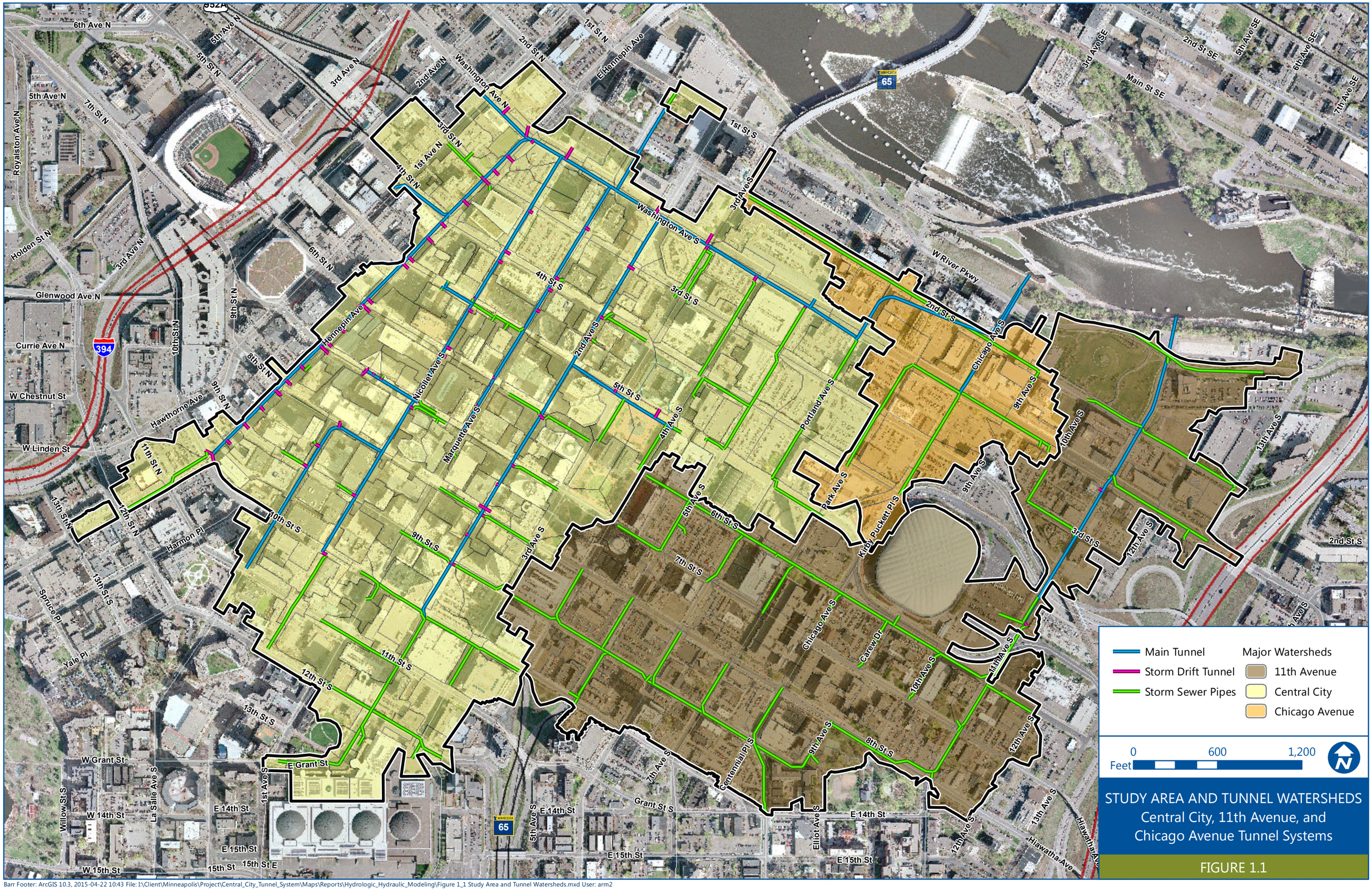
The Central City, Chicago Avenue, and Eleventh Avenue tunnel systems convey stormwater runoff from downtown Minneapolis to the Mississippi River. The tunnel system contains three main conveyance components: the main tunnel, drift tunnels, and storm sewer pipes (Figure 1.1). The main tunnel is deep beneath the surface—typically between 60 and 90 feet below ground elevation, with invert elevations at or below 775 feet (NGVD29). The main tunnel sections are generally located along city streets and have large, typically non-circular, cross sections. Typical widths range from 4 to 7.5 feet and heights from 5.5 to 8 feet.

Drift tunnels are smaller tunnel sections that feed into the main tunnel and are generally located perpendicular to it. They have cross sections similar to the main tunnel and are at comparable elevations, but are much shorter (typically less than 100 feet). Storm sewer pipes are closer to the surface, typically 3 to 20 feet below ground and generally have a circular cross section. Stormwater is collected in manholes and catch basins which transport water through the storm sewer pipes and down drill holes or drop-shaft connections to the main tunnel system or the drift tunnels.

The Central City tunnel system includes tunnels located along Hennepin Avenue, Nicollet Avenue, Marquette Avenue, Second Avenue S., and Washington Avenue (Figure 1.1). Stormwater is conveyed to a 6-foot-high tunnel located on Washington Avenue between Hennepin and Portland Avenues. The tunnel turns north along Portland Avenue and then runs under Second Street South before discharging to the Mississippi River near Chicago Avenue.

The Chicago Avenue tunnel spans approximately two city blocks and joins the Central City tunnel system just prior to discharging to the Mississippi River. Together these systems comprise approximately 9.5 miles of storm sewer pipes and tunnels.

The Eleventh Avenue tunnel system collects stormwater along Eleventh Avenue. This tunnel system comprises approximately 4.2 miles of storm sewer pipes and tunnels.



STUDY AREA AND TUNNEL WATERSHEDS
Central City, 11th Avenue, and
Chicago Avenue Tunnel Systems

FIGURE 1.1

Barr Footer: ArcGIS 10.3, 2015-04-22 10:43 File: I:\Client\Minneapolis\Project\Central_City_Tunnel_System\Maps\Reports\Hydrologic_Hydraulic_Modeling\Figure 1_1 Study Area and Tunnel Watersheds.mxd User: arm2

2.0 Methodology

2.1 Hydrologic Model Parameters

Hydrologic model parameters were calculated using the methodology defined in *XP-SWMM Hydrology and Hydraulics Model Development Guidance Manual* for the City of Minneapolis – Public Works Department (SRF 2005), hereafter referred to as the *Minneapolis XP-SWMM Manual*. The following sections summarize how individual model parameters were calculated.

2.1.1 Subwatershed Divides

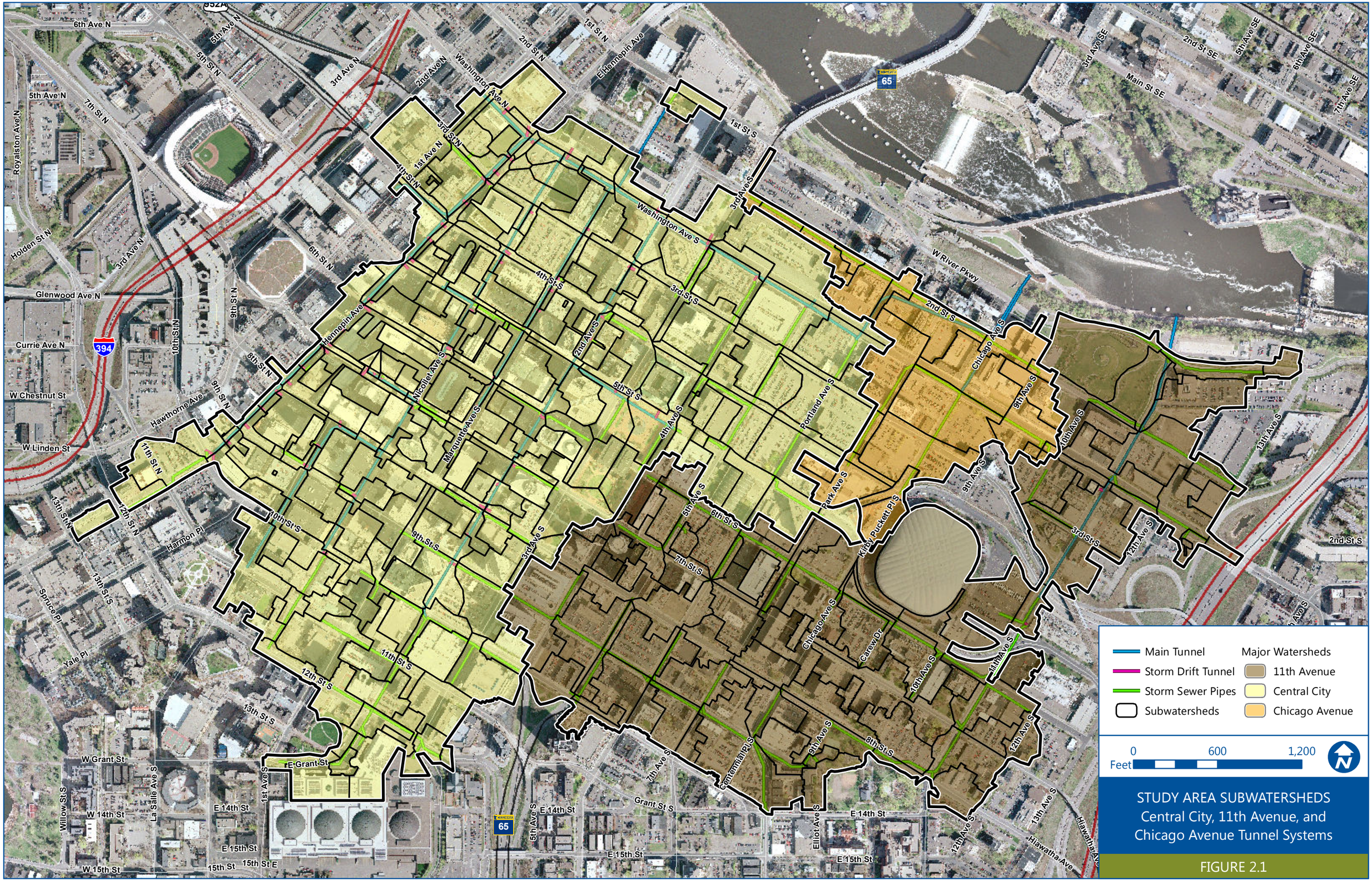
Subwatershed divisions were delineated in ArcGIS using the digital elevation model (DEM) developed from the Minnesota DNR's (MnDNR) 2011 light detection and ranging (LiDAR) elevation dataset. At the City's request, the DEM was converted from NAVD88 to NGVD29. LiDAR is a remote-sensing technology that measures the distance to the earth's surface, allowing elevation to be calculated. LiDAR data is typically provided in the form of a DEM which can be used to generate contour data.

In areas where the DEM did not capture drainage patterns (i.e., curb and gutter direction, downspout locations from building roofs, etc.), city-provided storm sewer database, 2012 aerial imagery, roof drain data, and publicly available aerial and street-view images were referenced to delineate subwatersheds. Subwatersheds were delineated to catch-basin "clusters"—groups of catch basins connected to the same storm sewer pipe. A preliminary subwatershed map was submitted for review by City staff and adjustments were made based on their feedback. Figure 2.1 shows the subwatershed delineations for the study area used in the XP-SWMM model.

2.1.1.1 Roof Drains

The City provided data on private storm sewer connections to the municipal storm sewer system. Publicly available aerial and street-view images were also referenced to identify external roof drains.

The City also provided locations of roof drains connected to the City's sanitary sewer system instead of the storm sewer system (rain-leader violations). These roof drains were excluded from the model calibration because they were not connected to the drainage system during the selected rainfall events. However, anticipating that these areas will eventually be properly connected, they were connected to the model's drainage system after it was calibrated to evaluate design storms.



STUDY AREA SUBWATERSHEDS
Central City, 11th Avenue, and
Chicago Avenue Tunnel Systems

FIGURE 2.1

Barr Footer: ArcGIS 10.3, 2015-04-22 10:45 File: I:\Client\Minneapolis\Project\Central_City_Tunnel_System\Maps\Reports\Hydrologic_Hydraulic_Modeling\Figure 2_1 Study Area Subatersheds.mxd User: arm2

2.1.2 Impervious Area

Land cover within a subwatershed affects the quantity and timing of runoff. Each land cover type generates a different quantity of runoff due, primarily, to its impervious area. The impervious area input into the XP-SWMM model is, by definition, hydraulically connected to the drainage systems being analyzed. This includes driveways, rooftops, and parking areas that are directly connected to the stormwater collection system. Runoff from the portion of a rooftop draining onto adjacent pervious areas was not considered connected impervious area.

Pervious areas were delineated using the aerial imagery provided by the City. Impervious areas that drain to pervious areas were considered disconnected. The remaining impervious areas were considered directly connected. Only directly connected impervious areas were entered into the model as impervious. This method is consistent with the City's preferred methodology, described in the *Minneapolis XP-SWMM Manual* (SRF 2005). As a whole, the study area consists of 96% directly connected impervious area.

2.1.3 Subwatershed Slope

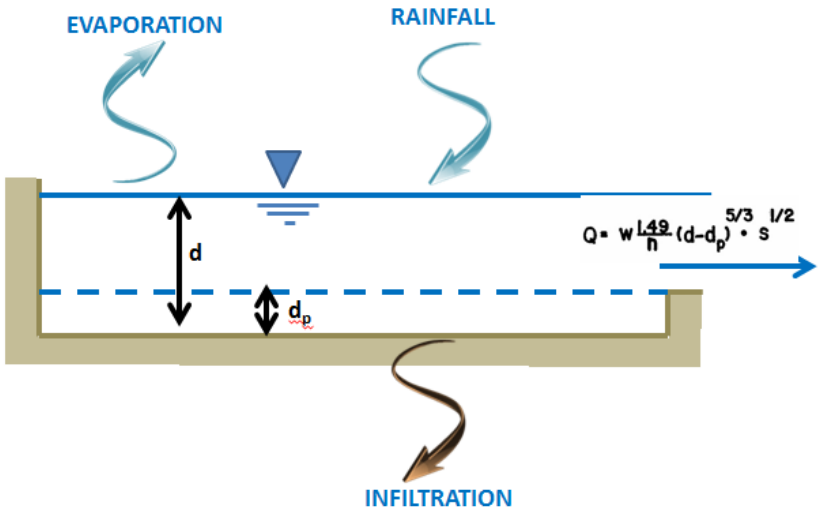
The average runoff slope (ft/ft) for each subwatershed was calculated in ArcGIS using the one arc second DEM from the USGS National Elevation Dataset (Gesch et al. 2009). The DEM data is in a grid (raster) format and the area-weighted average slope was calculated by measuring the difference in elevation between adjacent grid cells within the subwatershed. The USGS DEM dataset was used instead of the 2011 LiDAR dataset due to high slopes calculated using LiDAR. The high slopes from the 2011 LiDAR were caused by irregularities in the surface in the form of large deep "holes" or "hills" where buildings were removed from the LiDAR data.

2.1.4 Subwatershed Width

In XP-SWMM, surface runoff from subwatersheds is routed to the outlet of each subwatershed using the nonlinear reservoir method. During each time step, XP-SWMM calculates the surface runoff from the subwatershed as shown in Figure 2.2.

The flow rate from a subwatershed is directly related to the subwatershed slope, overland flow surface roughness, depression storage, and width parameter. As the subwatershed width increases, the peak flow rate from the subwatershed also increases. With a higher runoff rate, less runoff is stored within the subwatershed and less infiltration occurs. This increases the runoff volume for a given rainfall event over pervious surfaces. However, as the watershed width decreases the opposite occurs; the peak flow rate from the subwatershed decreases, infiltration increases, and less runoff volume is generated.

The SWMM user's manual (U.S. EPA 1988) suggests estimating subwatershed width by dividing the subwatershed area by the longest flow path. This is the methodology used for this model. This method was not the preferred method provided in the *Minneapolis XP-SWMM Manual* (SRF 2005); however, it was discussed and approved by City staff prior to use.



In the equation, "Q" is the flow rate from the subwatershed (cfs), "n" is the Manning's roughness coefficient, "d" is the depth of water (ft), "d_p" is the depression storage (ft), and "s" is the slope (ft/ft).

Figure 2.2 Nonlinear reservoir schematic of a subwatershed used in XP-SWMM

2.1.5 Infiltration

Infiltration is the vertical movement of water into the soil. The infiltration rate for a given rainfall event varies with time. Typically, the initial infiltration rate at the beginning of the rainfall event is higher because the soil surface is generally drier and full of void spaces. As the rainfall continues, the void space in the soil fills with water and the infiltration rate gradually decreases. For a long-duration storm, the infiltration rate will reach a constant value. The Green-Ampt equation was used to approximate infiltration rates in the subwatersheds.

2.1.5.1 Green-Ampt Infiltration

The Green-Ampt parameters include average capillary suction, initial moisture deficit, and saturation hydraulic conductivity. Capillary suction and initial moisture condition vary over time due to changes in moisture conditions. For this model it was assumed that average capillary suction and initial moisture deficit are constant over the entire study area. Table 2-1 summarizes the infiltration parameters used in the model, which are consistent with the infiltration parameters for commercial/industrial areas listed in the *Minneapolis XP-SWMM Manual* (SRF 2005).

Table 2-1 Green-Ampt infiltration parameters

Average Capillary Suction (inch)	Initial Moisture Deficit (-)	Saturation Hydraulic Conductivity (inch/hour)
10	0.32	0.25

2.1.6 Depression Storage

Depression storage accounts for areas that must be filled with water prior to generating runoff from both pervious and impervious areas. The values for impervious and pervious depression storage, 0.094 inches and 0.1 inches, respectively, were for commercial/industrial areas, as specified in the *Minneapolis XP-SWMM Manual* (SRF 2005).

2.1.7 Overland Flow Roughness

Overland flow is surface runoff that occurs as sheet flow prior to concentrating in defined channels. To estimate the overland flow or runoff rate, a modified version of Manning's equation is used by XP-SWMM. A key parameter in Manning's equation is the roughness coefficient. The shallow depths typically associated with overland flow result in substantial increases in surface friction. As a result, the roughness coefficients typically used in open channel flow calculations are not applicable to overland flow conditions. These differences can be accounted for by using an effective roughness parameter instead of the typical Manning's roughness coefficient. The selected roughness coefficients for overland flow were 0.2 for pervious surfaces and 0.014 for impervious surfaces. These are consistent with the values recommended for commercial/industrial areas in the *Minneapolis XP-SWMM Manual* (SRF 2005).

2.2 Hydraulic Model Parameters

Hydraulic model parameters were calculated using the methodology defined in the *Minneapolis XP-SWMM Manual* and based on data of existing storm sewer system infrastructure provided by the City. The following sections summarize how individual hydraulic model parameters were calculated.

2.2.1 Storm Sewer Data

The City provided GIS geodatabases of tunnel systems. The GIS database was formatted to import data into the XP-SWMM model and was the primary source of storm sewer and tunnel information. The GIS database was reviewed and data was updated, as necessary, using as-built drawings provided by the City. Data used in the XP-SWMM model included information on manholes, catch basins, sewer pipes, private connections to the storm sewer system, and tunnels. Detailed information included elevations, lengths, material type, shape, and size. City staff helped fill data gaps (missing information about the tunnel system).

2.2.2 Tunnel Extents and Geometry

The XP-SWMM model was created for three tunnel systems covering downtown Minneapolis. The tunnel systems modeled include the Central City Tunnel (west of Chicago/Eighth Avenue), Chicago Avenue Tunnel (along Eighth Avenue), and Eleventh Avenue Tunnel drainage systems. The entire tunnel system, including the drift tunnels and storm sewer pipes connected to the tunnels, was included in the model.

Tunnel geometry was determined based on drawings provided by the City. Predefined pipe shapes in XP-SWMM were used where possible to model sections with the same or similar shape. If the tunnel geometry was not similar to a predefined shape in XP-SWMM, then a user-defined geometry was developed.

User-defined tunnel shapes were developed using computer-aided drafting (CAD) software and based on the cross sections shown on the drawings. The depth, area, wetted perimeter, and top surface width were computed at incremental depths and entered into XP-SWMM. Tunnel cross sections used in the model are shown in Figure 2.3. Figure 2.4 shows where each user-defined cross section was applied.

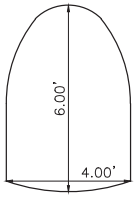
2.2.3 Drill Holes and Drop Shafts

Drill holes and drop shafts are long vertical shafts that connect the storm sewer network to the tunnel system, typically 60 to 90 feet below the ground elevation. There are 201 drill holes and 15 drop shafts within the study area (Figure 2.5). In the model, water was only allowed to enter the tunnel system through a drill hole or drop shaft. Overflow water was conveyed through surface flow to the next system inlet. Drill holes were modeled using the orifice feature in SWMM. The diameter for the majority of the drill holes was set to 16 inches, as provided by the City. The City provided different diameters for only 22 drill holes, with a maximum diameter of 48 inches. The calibrated orifice coefficient value assigned to each drill hole was 0.55.

Drop shafts, which have a larger diameter than drill holes (typically greater than 48 inches), were modeled assuming no restriction to the tunnel section.

2.2.4 Tunnel Outfalls

Three major outfalls exist in the model: the combined Central and Chicago Avenue tunnel systems outfall, the 11th avenue tunnel system outfall, and a connector pipe to the I-35W tunnel system at Chicago Avenue S. and Ninth Street S. All three outfalls were modeled as a free outfall in XP-SWMM without tailwater effects. The two major tunnel system outfalls discharge directly into the Mississippi River. It was assumed that peak flood elevations in the Mississippi River would not coincide with peak flood levels in the tunnel system. Therefore, unrestricted flow from the tunnel systems into the Mississippi River was applied. Hydraulic grade lines in the I-35W tunnel system were unknown for this project, therefore the outfall from the 11th Avenue tunnel system into the I-35W system was assumed to be only restricted by the size of the outflow tunnel.



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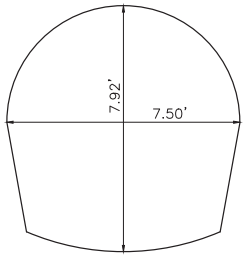

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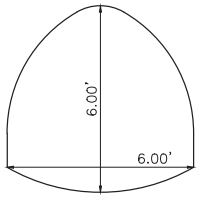

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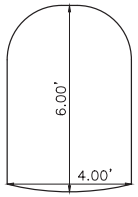

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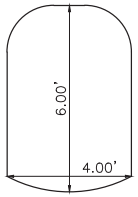
AREA: 22.4



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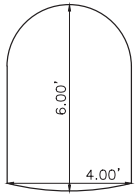

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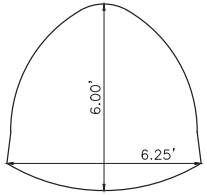

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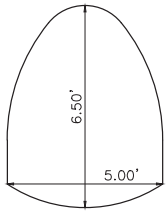

CROSS SECTION H
AREA: 26.2 SF

NOTE:
CROSS SECTIONS ARE DRAWN TO REPRESENT THE TUNNEL AREAS IN XPSWMM. THESE CROSS SECTIONS ARE BASED ON PLAT DRAWINGS PROVIDED BY THE CITY OF MINNEAPOLIS.

Figure 2.3 User-Defined Tunnel Cross Sections

NOT ISSUED FOR CONSTRUCTION

NO.	BY	CHK.	APP.	DATE	REVISION DESCRIPTION

I HEREBY CERTIFY THAT THIS PLAN, SPECIFICATION, OR 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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CONSTRUCTION							
	DATE RELEASED						

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CITY OF MINNEAPOLIS
MINNEAPOLIS, MINNESOTA

CENTRAL CITY TUNNEL H&H MODEL
MINNEAPOLIS, MINNESOTA

TUNNEL CROSS SECTION SHAPES

BARR PROJECT No. 23271397.01
CLIENT PROJECT No.
DWG. No. XS-01
REV. No.

CADD USER: Alex Chizmadia FILE: P:\WPS\23 MN\27\23271397 CENTRAL CITY TUNNEL H&H-FEAS\WORKFILES\XPSWMM MODELING\B-XPSWMM MODEL DEVELOPMENT\INPUTS\TUNNEL_SHAPEZLING PLOT SCALE: 1:2 PLOT DATE: 6/4/2015 8:02 AM
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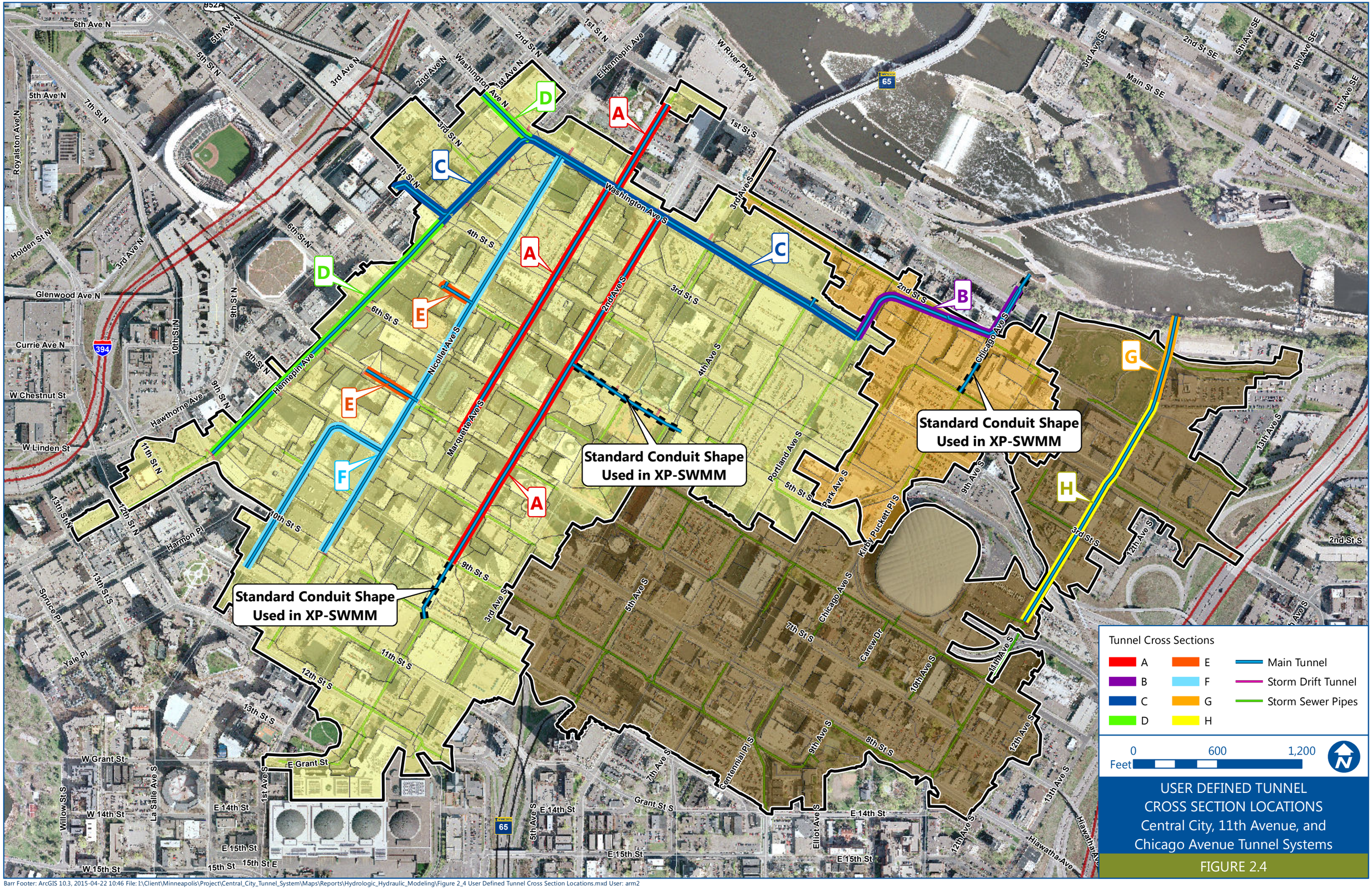
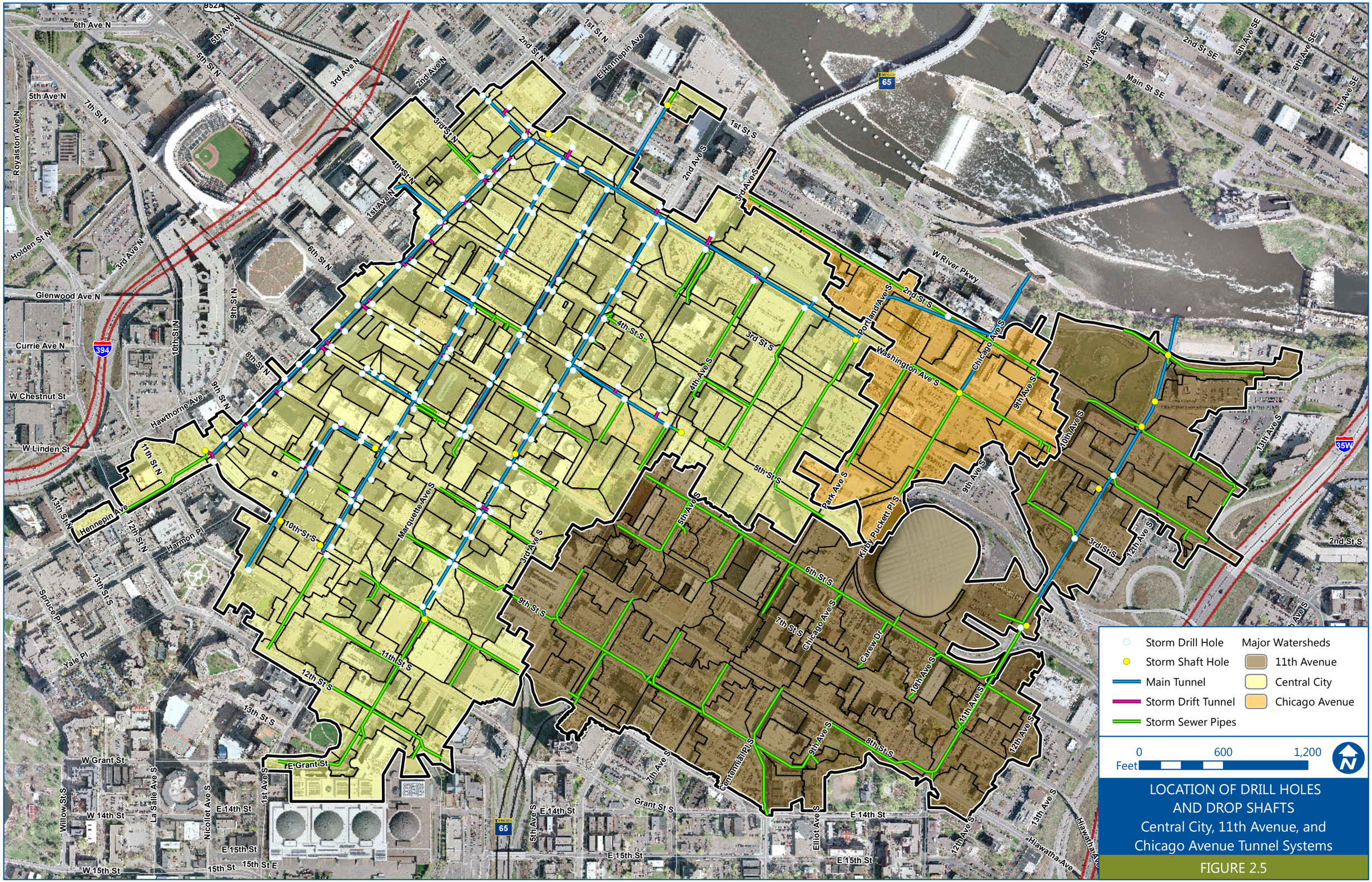


Barr Footer: ArcGIS 10.3, 2015-04-22 10:46 File: I:\Client\Minneapolis\Project\Central_City_Tunnel_System\Maps\Reports\Hydrologic_Hydraulic_Modeling\Figure 2_4 User Defined Tunnel Cross Section Locations.mxd User: arm2



LOCATION OF DRILL HOLES
AND DROP SHAFTS
Central City, 11th Avenue, and
Chicago Avenue Tunnel Systems

FIGURE 2.5

Barr Footer: ArcGIS 10.3, 2015-04-22 10:47 File: I:\Client\Minneapolis\Project\Central_City_Tunnel_System\Maps\Reports\Hydrologic_Hydraulic_Modeling\Figure 2_5 Location of Drill Holes and Drop Shafts.mxd User: arm2

2.2.5 Manning's Roughness Coefficient

Manning's roughness coefficient is used in XP-SWMM as part of the Manning's formula for flow calculations to account for the friction between the conduit and the stormwater. Manning's coefficients were selected based on the conduit material using information from the *Minneapolis XP-SWMM Manual* (SRF 2005), as summarized in Table 2-2.

Table 2-2 Manning's roughness coefficient values

Conduit Material	Manning's n
Brick	0.015
Cement	0.013
Ductile-Iron Pipe	0.013
Other	0.013
Plastic – PVC, HDPE	0.010
Reinforced Concrete	0.013
VCP	0.014

The roughness coefficients in the tunnel sections were used as a calibration parameter in the model. The final roughness coefficients for all tunnel sections were set to 0.011, adjusted from the original value of 0.013.

2.2.6 Surface Flow

The storm sewer system may surcharge when the hydraulic capacity of the system is exceeded. This occurs when the water surface elevation at catch basins or manholes exceeds the ground level and water is discharged to the surface. Surface flow for storm sewer sections of the tunnel system were modeled following the "two multi-link option" described in Appendix F of the *Minneapolis XP-SWMM Manual* (SRF 2005). This option used a single trapezoidal channel to represent the flow path above and below the curb. For tunnel sections, water can only discharge from the drill holes or drop shafts connecting the tunnels to the surface. Surface flows in these sections were routed between drill holes/drop shafts and catch basins using the same trapezoidal cross section used in the storm sewer system. This method of surface flow was discussed with and agreed upon by City staff.

Stormwater storage-area locations, such as low spots along streets where water is able to pool, were identified based on information provided by the City and LiDAR data. Storage-elevation curves for low spots were calculated in ArcGIS based on Hennepin County LiDAR data adjusted to NGVD29.

2.3 Rainfall Data

Two types of rainfall data were used in developing the model: Atlas 14 precipitation frequency estimates and observed rainfall events. The following sections summarize these rainfall data sets and how they were applied to model development.

2.3.1 Atlas 14 Rainfall

In 2013, the National Oceanic and Atmospheric Administration (NOAA) released Atlas 14, Volume 8, which revised precipitation frequency estimates for 11 Midwestern states, including Minnesota. The Atlas 14 rainfall estimates were developed for individual rainfall monitoring stations with long, consistent periods of record. After estimates were developed for individual stations, they were interpolated between stations to account for the spatial variability of rainfall depths. The interpolated frequency estimates at the center of the study area were selected for the analysis, as shown in Figure 2.6.

The model evaluated the 2-, 10-, 100-, and 500-year, 24-hour rainfall events using Atlas 14 precipitation depths and the MSE 3 MN rainfall distribution as recommended by the Minnesota Natural Resource Conservation Service (MN NRCS). The 24-hour precipitation depths are included in Table 2-3.

Table 2-3 Hypothetical rainfall event point precipitation from Atlas 14 (inches)

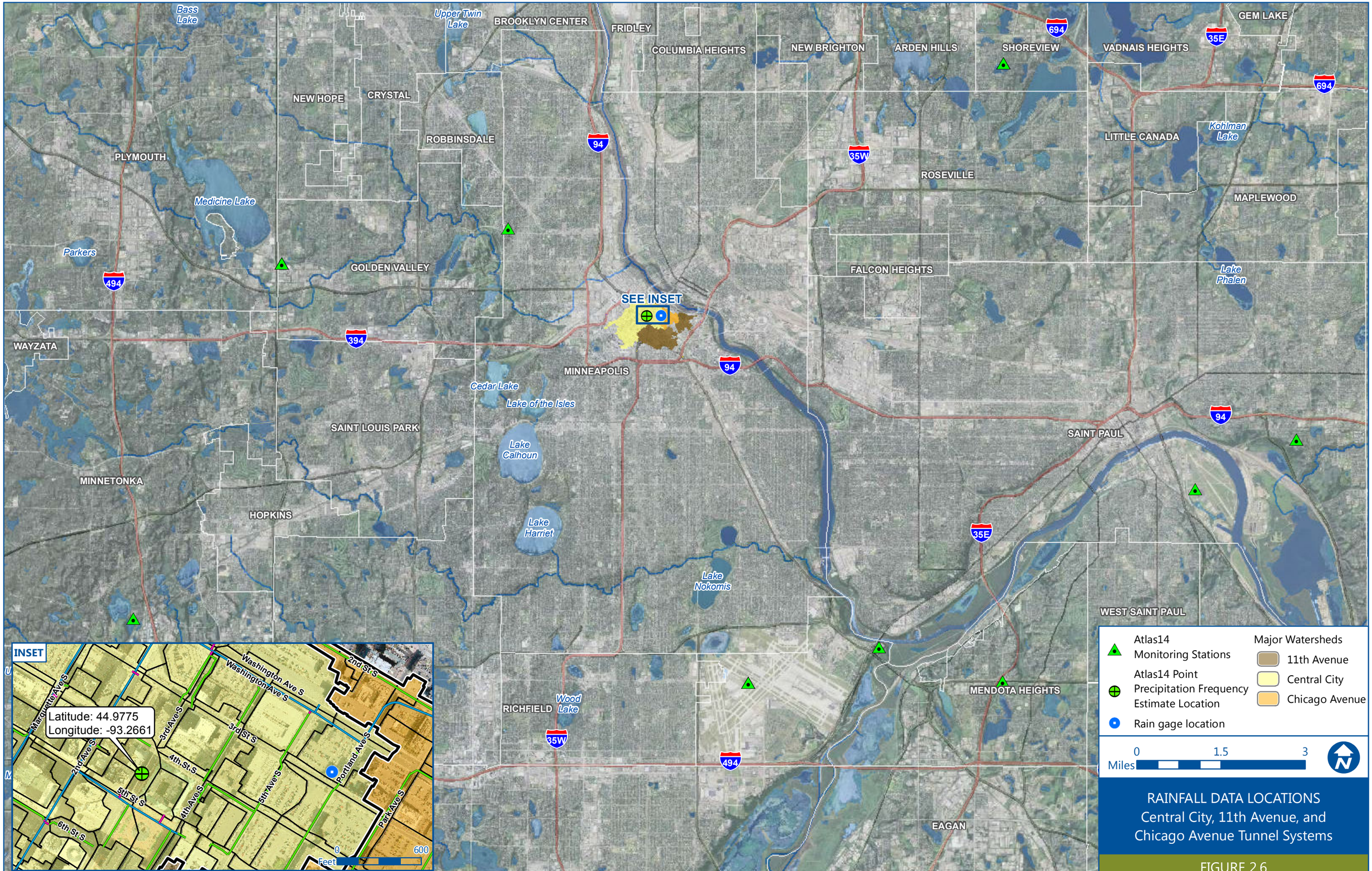
	Return Frequency			
Duration	**2-year**	**10-year**	**100-year**	**500-year**
24 hours	2.85	4.27	7.47	10.50

2.3.2 Observed Rainfall Events

The City provided 5-minute increment rainfall data from a rain gauge located within the study area at 530 Third Street S. (Figure 2.6). Rainfall data was collected from May 2011 through October 2014. Two calibration events and one validation event were selected from this data set.

2.4 Tunnel Pressure Data

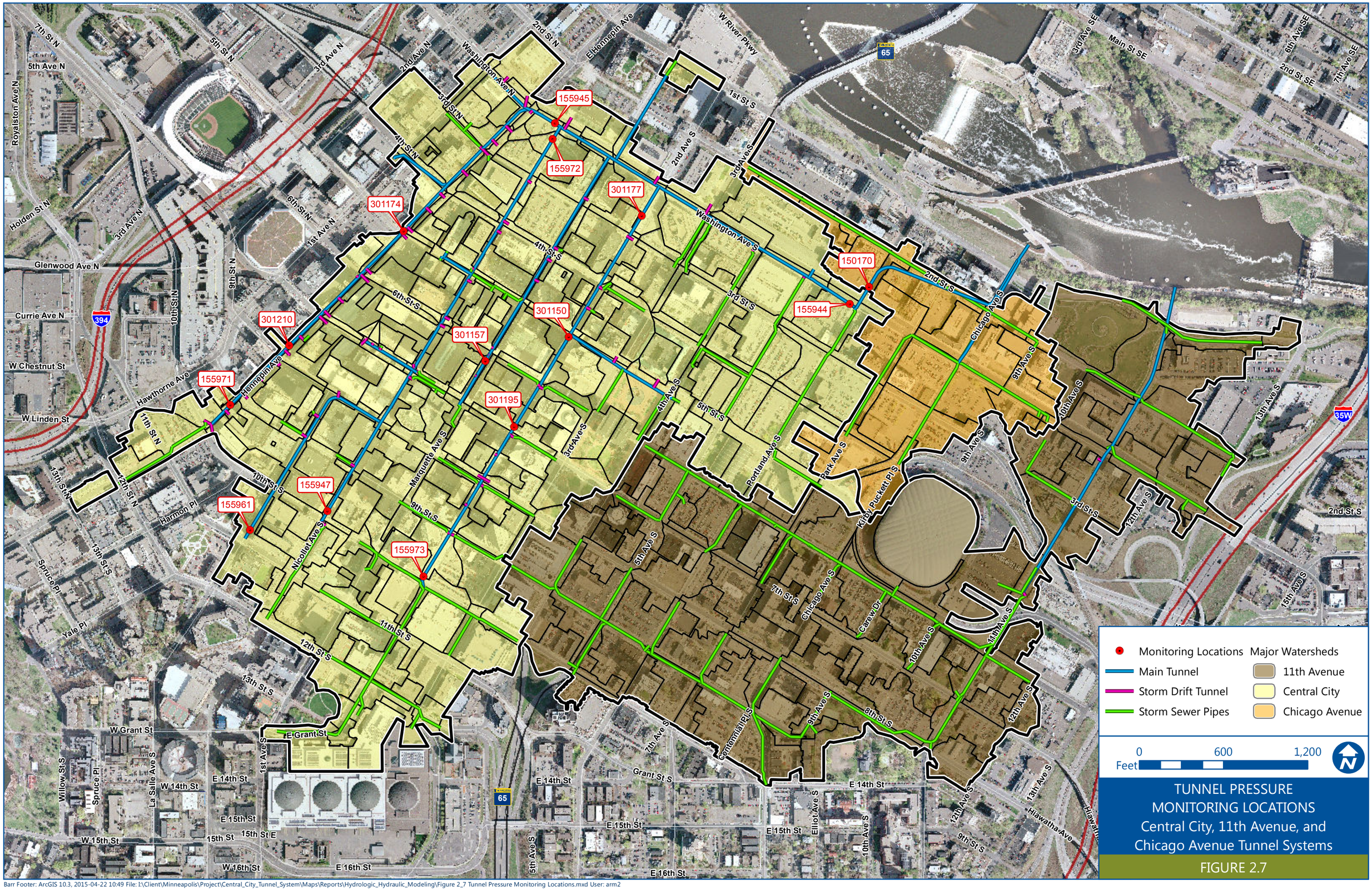
The City provided tunnel pressure data for 14 stations located within the Central City tunnel system shown in Figure 2.7. Stations with identification numbers (IDs) starting with “15” were monitored from March 2010 through May 2014. Stations with IDs starting with “30” were monitored from March 2012 through May 2014.



RAINFALL DATA LOCATIONS
Central City, 11th Avenue, and Chicago Avenue Tunnel Systems

FIGURE 2.6

Barr Footer: ArcGIS 10.3, 2015-04-22 10:48 File: I:\Client\Minneapolis\Project\Central_City_Tunnel_System\Maps\Reports\Hydrologic_Hydraulic_Modeling\Figure 2_6 RainFall locations.mxd User: arm2



Barr Footer: ArcGIS 10.3, 2015-04-22 10:49 File: I:\Client\Minneapolis\Project\Central_City_Tunnel_System\Maps\Reports\Hydrologic_Hydraulic_Modeling\Figure 2_7 Tunnel Pressure Monitoring Locations.mxd User: arm2

3.0 Model Calibration

The model was calibrated using two storm events and validated using a third storm event. The goal of model calibration was to match the model-simulated water surface elevations to the measured pressure (converted to water depths, as described in Section 3.2). Model calibration was completed by adjusting Manning's coefficients and drill-hole-orifice coefficients to simulate the hydrograph shape and peak-pressure measurements within the tunnel.

3.1 Calibration Event Selection

The calibration and validation events were selected based on a review of available rainfall and pressure measurements. The measured rainfall data with the calibration and validation events highlighted are shown in Figure 3.1. The two calibration events represent a range of rainfall depths, intensities, and durations, as shown in Table 3-1. The validation event is a short-duration but high-intensity rainfall event.

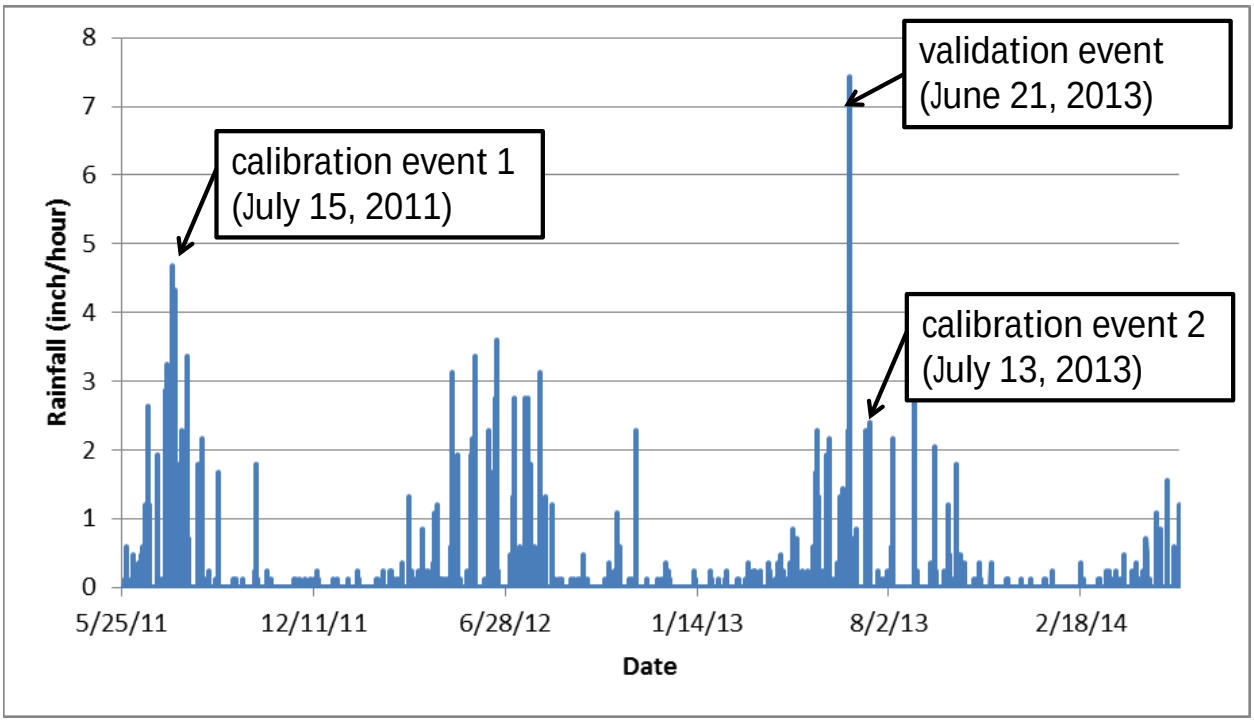


Figure 3.1 Measured rainfall data from downtown monitoring station with calibration and validation events highlighted

Table 3-1 Summary of calibration and validation events

Event	Event Date	Rainfall Depth (inches)	Peak Intensity (inches/hour)	Event Duration (hour)
Calibration Event 1	July 15, 2011	4.9	4.7	22
Calibration Event 2	July 13, 2013	2.3	2.4	5
Validation Event	June 21, 2013	2.9	7.4	18

The first calibration event occurred on July 15, 2011, and produced 4.9 inches of water over a 22-hour period with a peak intensity of 4.7 inches per hour. Rainfall intensities for this event are shown in Figure 3.2. The peak rainfall intensity of this event was comparable to the peak rainfall intensity of the 1-year, 2-hour Atlas 14 design storm. The total rainfall depth was comparable to a 10–25 year Atlas 14 design storm.

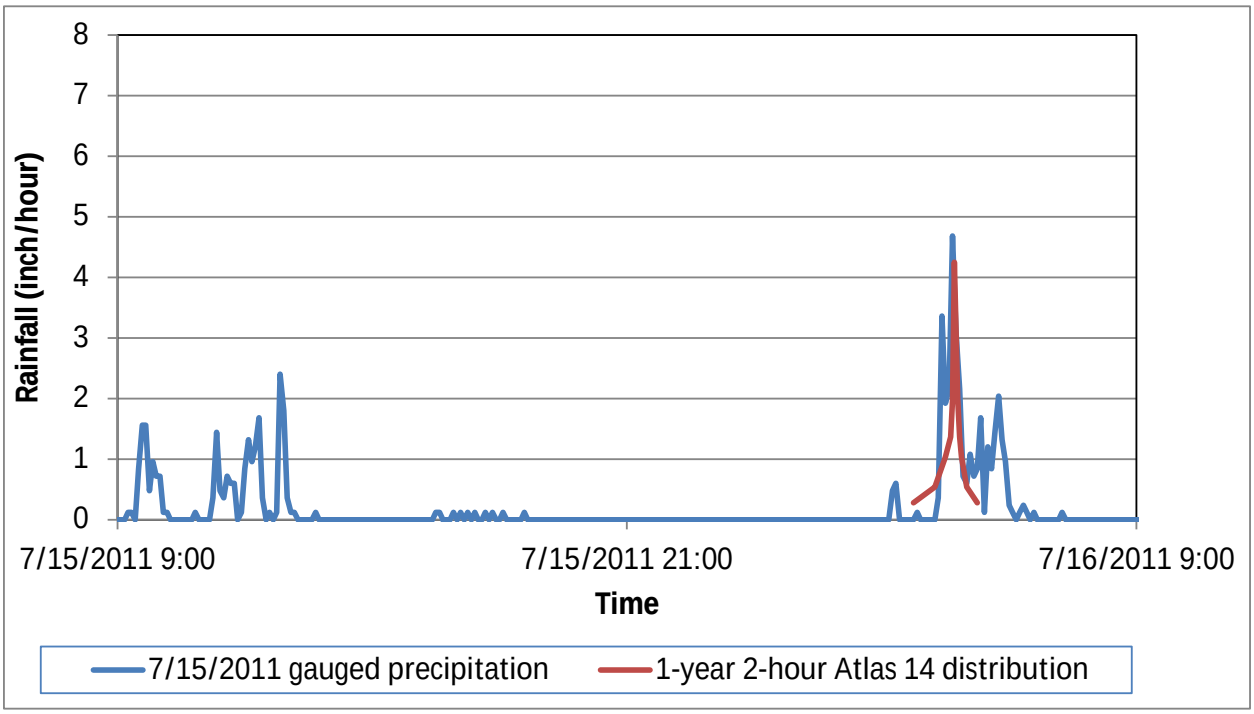


Figure 3.2 July 15, 2011, calibration event

The second calibration event occurred on July 13, 2013, and produced 2.3 inches of rainfall over a 5-hour period with a peak intensity of 2.4 inches per hour. The rainfall intensities for this event are displayed in Figure 3.3. The peak rainfall intensity was less than the peak rainfall intensity of the 1-year, 2-hour Atlas 14 design storm. The total rainfall depth was comparable to a 2–5 year Atlas 14 design storm.

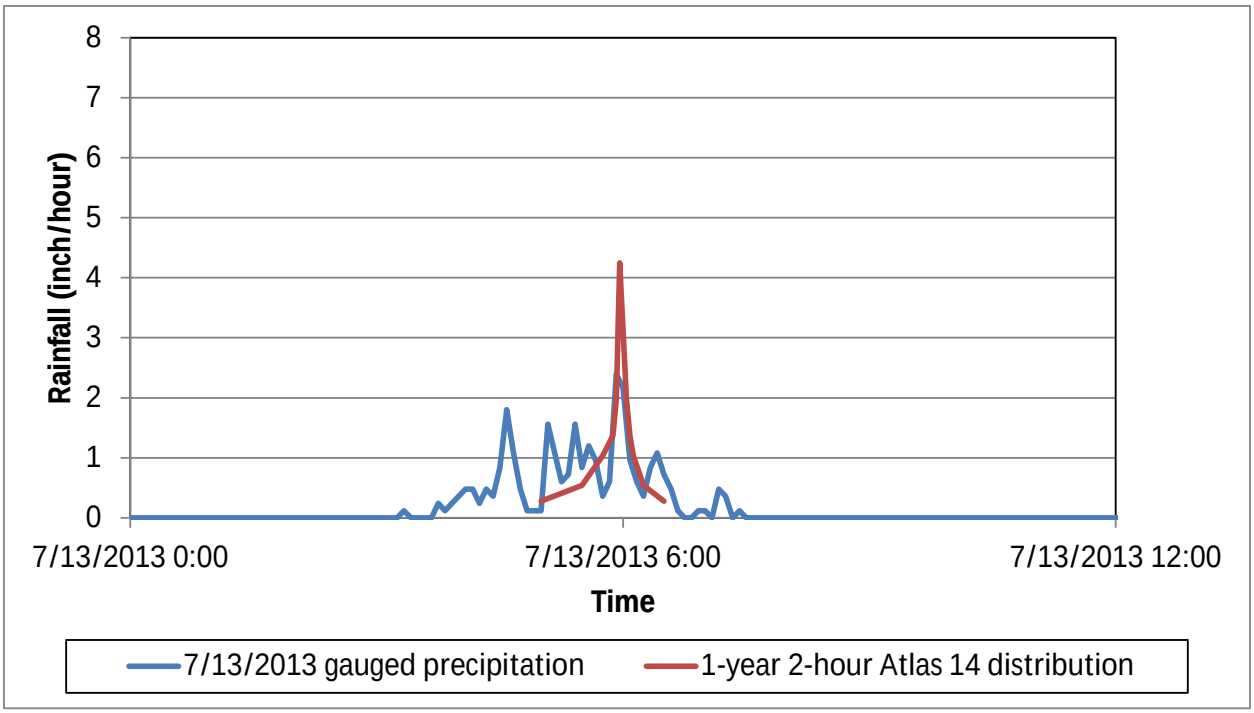


Figure 3.3 July 13, 2013, calibration event

The validation event occurred on June 21, 2013, and produced 2.9 inches in 18 hours with a peak rainfall intensity of 7.4 inches per hour. The rainfall intensities for this event are shown in Figure 3.4. The peak rainfall intensity of this event was comparable to the peak rainfall intensity of the 10-year, 2-hour Atlas 14 design storm. The total rainfall depth was comparable to a 2-year Atlas 14 design storm.

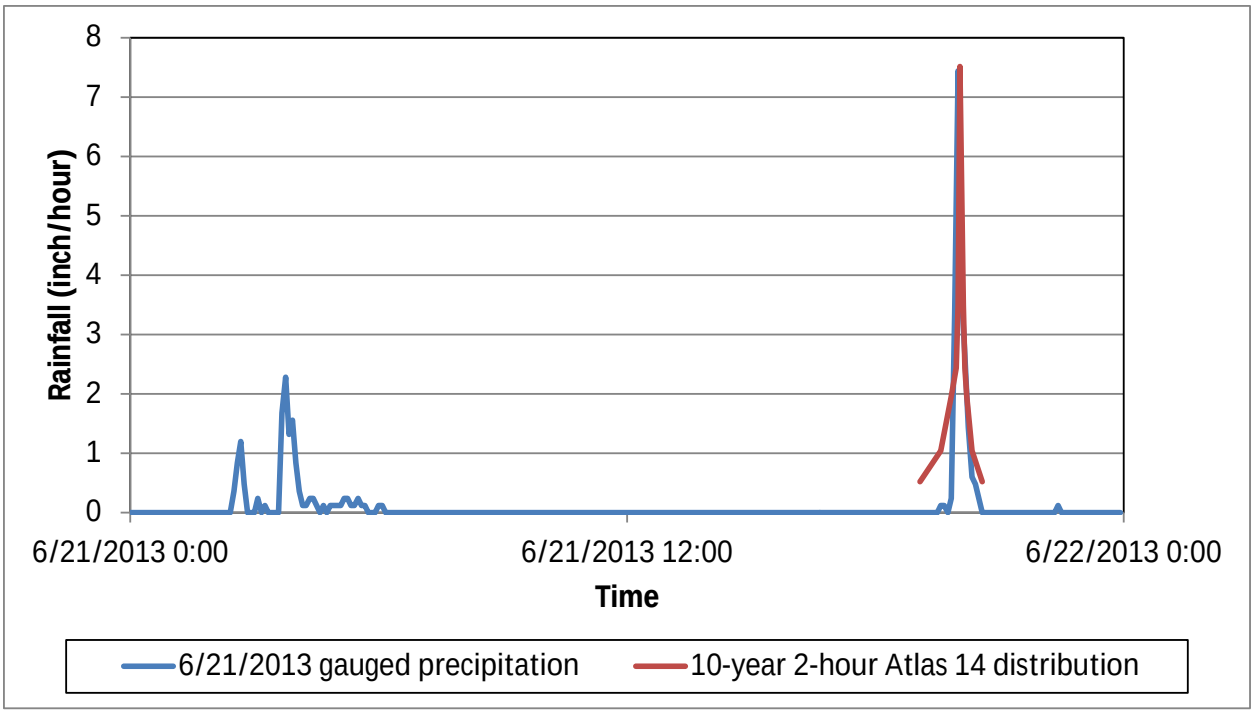


Figure 3.4 June 21, 2013, validation event

3.2 Conversion of Pressure Measurements to Water Depth

Monitoring gauges installed by the City measure pressure. Pressure measurements were converted to water depths for comparison with simulation results. The first step was to calculate the water density based on the measured temperature using Equation 3-1 (Greenberg et al. 1992)

Equation 3-1 $$\rho = \left(999.869 + 6.6741 * 10^{-2} * T - 8.8556 * 10^{-3} * T^2 + 8.2303 * 10^{-5} * T^3 - 5.516 * 10^{-7} * T^4\right) * C$$

Where: ρ is the density of the water in slugs/ft^3

T is the temperature of the water in ^{o}C

C is the conversion factor of 0.0019403 to convert from kg/m^3 to slugs/ft^3

After calculating the water density, the pressure measurements collected by the City were converted to water depth using Equation 3-2.

Equation 3-2 $$Z = \frac{(p_{meas} - p_{atm}) * 144}{g\rho}$$

Where: Z is water depth (foot)

p_{meas} is absolute pressure measurement (psi)

p_{atm} is atmospheric pressure (average pressure before event ~14.2–14.3 psi)

144 is conversion from square inches to square feet

g is gravitational acceleration (32.2 ft/sec^2)

ρ is density of fluid (slugs/ft^3)

3.3 Calibration Parameters

The XP-SWMM model was calibrated to match pressure measurements from 14 monitoring stations. The model parameters used for calibration included the drill-hole-orifice coefficient, Manning's coefficient of the tunnel, and the entrance and exit losses of the tunnel sections.

The first parameter used for calibration was the orifice coefficient for the 201 drill holes in the system. The orifice coefficient for drill holes in the model was adjusted to model the restriction of flow into the tunnel system. The calibrated drill-hole coefficient was 0.55.

The second parameter adjusted during model calibration was the Manning's roughness coefficient of the tunnels. The Manning's coefficients were initially set to a value of 0.013 based on guidance from the *Minneapolis XP-SWMM Manual*. During model calibration these were adjusted to a value of 0.011. Reducing the roughness coefficient allowed for water to travel at a faster velocity through the system, thereby reducing the hydraulic grade line of the tunnels.

Manning's roughness coefficients in all other storm sewer pipes were selected based on guidance provided in the *Minneapolis XP-SWMM Manual* and were not adjusted during model calibration.

The final parameters adjusted during model calibration were the entrance and exit losses in the tunnel. According to the *Minneapolis XP-SWMM Manual*, an entrance and exist loss of 0.5 should be applied to all pipe sections. Unlike a storm sewer system, water enters the tunnel system through a small drill hole opening at most locations. This small opening creates minimal losses in the tunnel system. Therefore, the entrance and exit losses recommended in the *Minneapolis XP-SWMM Manual* overestimate the losses in the tunnel system and were removed from the model. An exit loss of 1.0 was applied only to areas where the tunnel entered a drop shaft at 90-degree bends and "T" sections within the tunnel. Exit and entrance losses in the storm sewer sections of the model remained consistent with the guidance provided in the *Minneapolis XP-SWMM Manual* (SRF 2005).

3.4 Calibration Results

Visual assessment of the simulated and measured pressures in the tunnel system (Figure 3.5, Figure 3.6, Figure 3.7, and Figure 3.8) show that the XP-SWMM model adequately simulates pressure variations in the Central City tunnel system during the selected storm events. Two locations for each event (monitoring location 150170 and 155945 for the July 15, 2011, event and monitoring location 150170 and 301195 for July 13, 2013, event) are shown in Figure 3.5, Figure 3.6, Figure 3.7, and Figure 3.8. Results for other locations are shown in Appendix A. These selected monitoring locations were chosen based on position (one at the upstream and one at downstream end of the system) and to provide an overall representation of the calibration results throughout the system. In addition to the figures, the monitored and modeled peak water levels at each monitoring point are shown in Table 3-2 for the two calibration events.

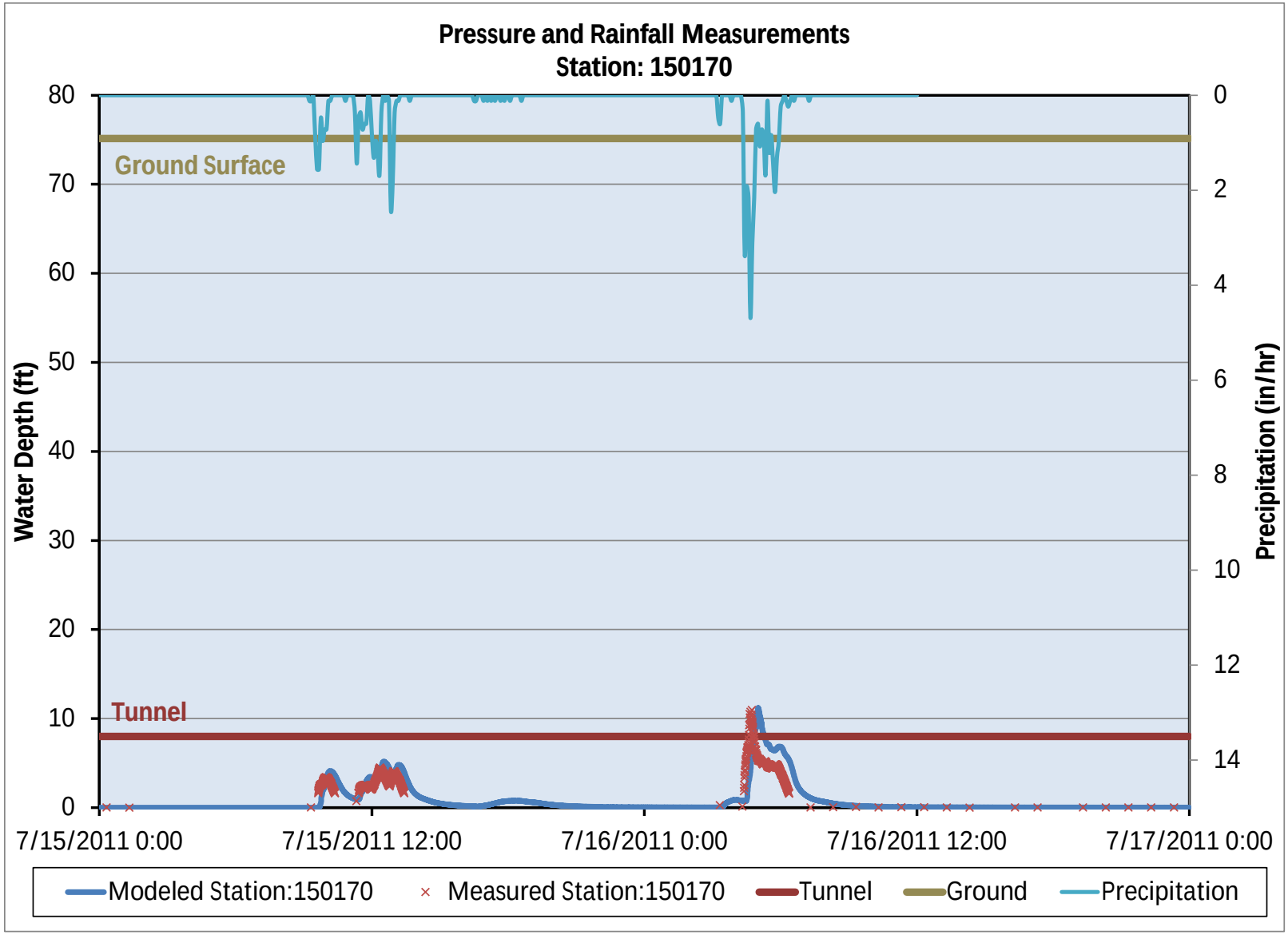


Figure 3.5 **Comparison between modeled and measured water depths at station 150170 for July 15, 2011, storm event**

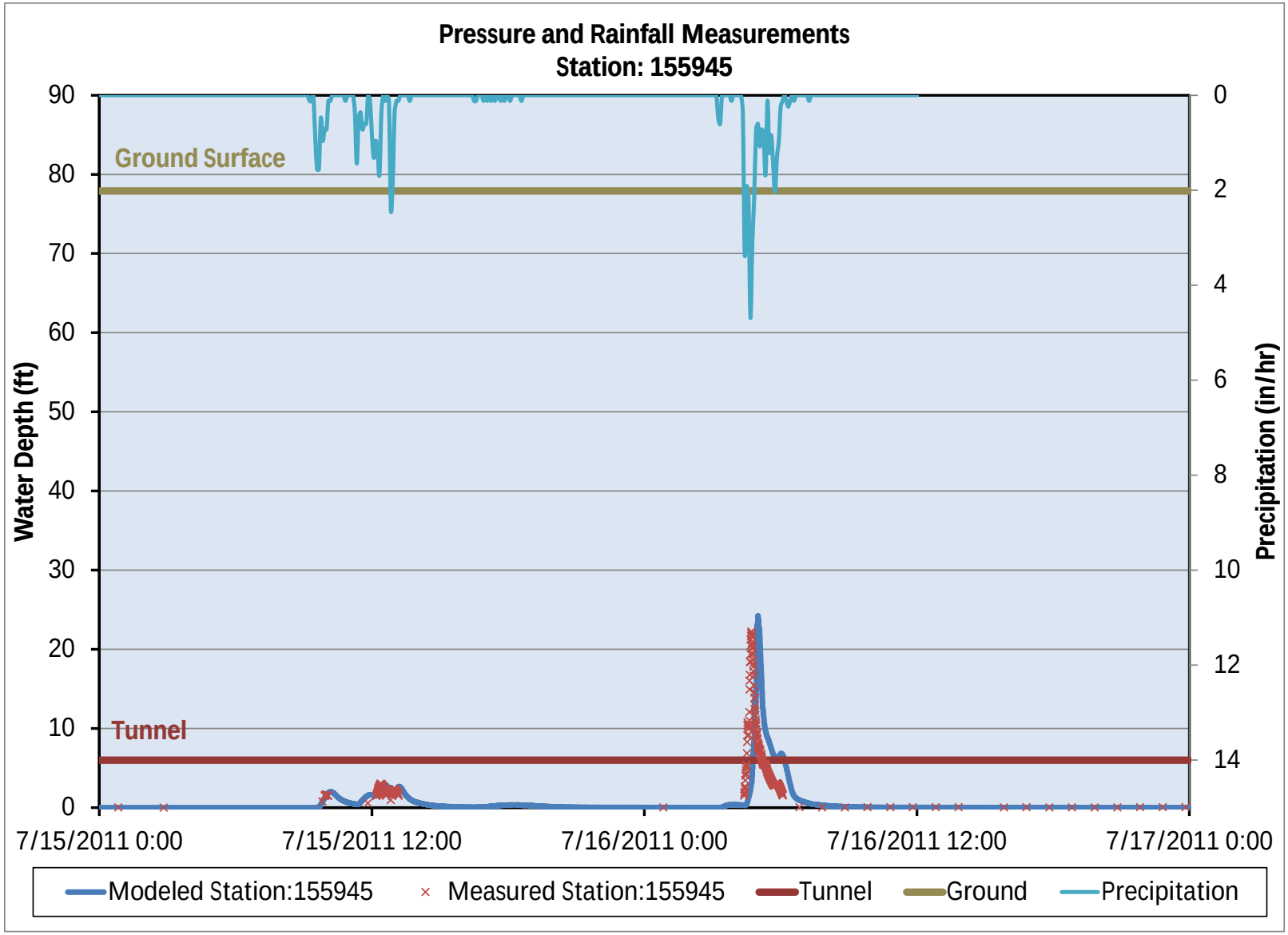


Figure 3.6 **Comparison between modeled and measured water depths at station 155945 for July 15, 2011, storm event**

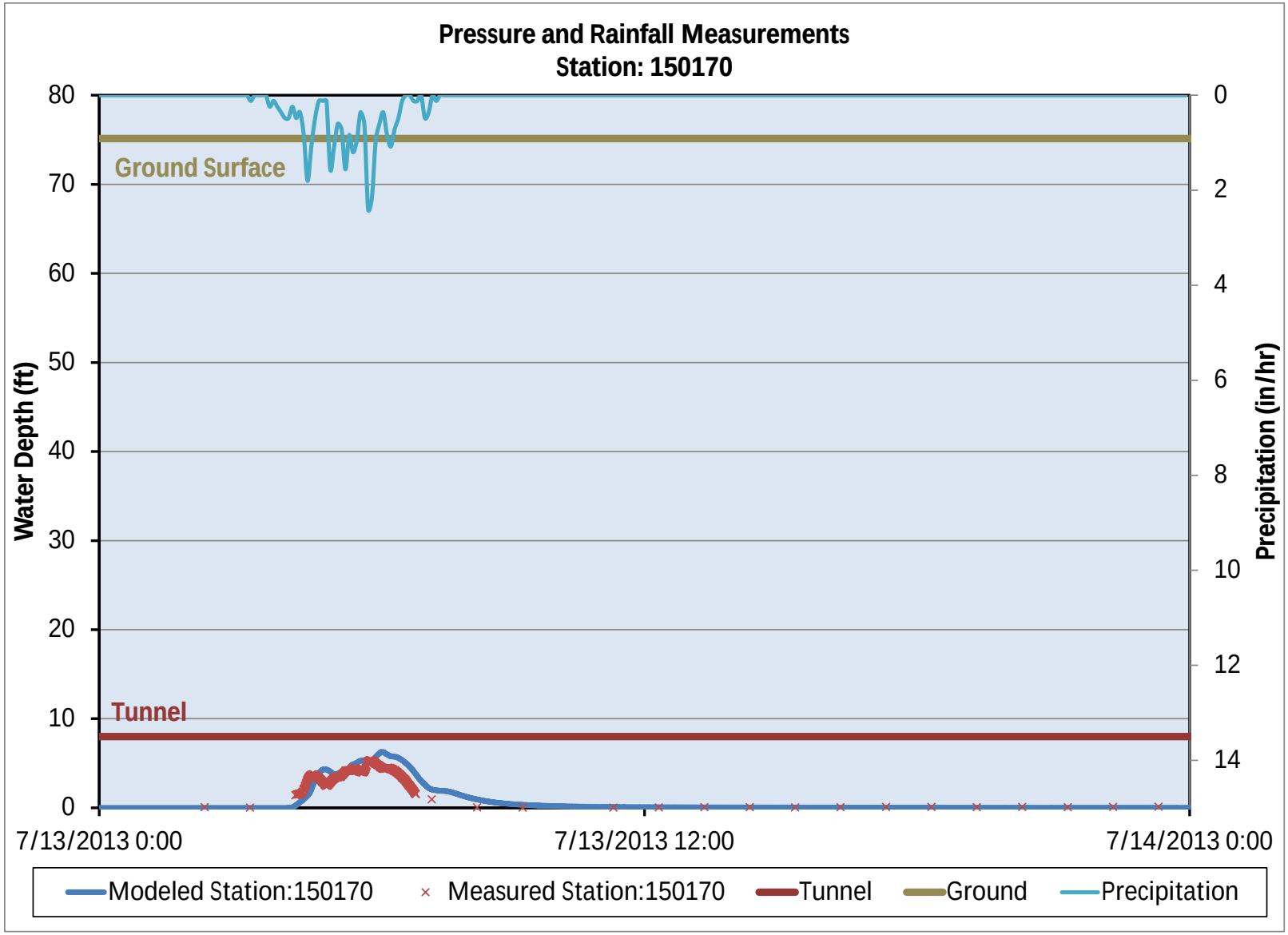


Figure 3.7 **Comparison between modeled and measured water depths at station 150170 for July 13, 2013, storm event**

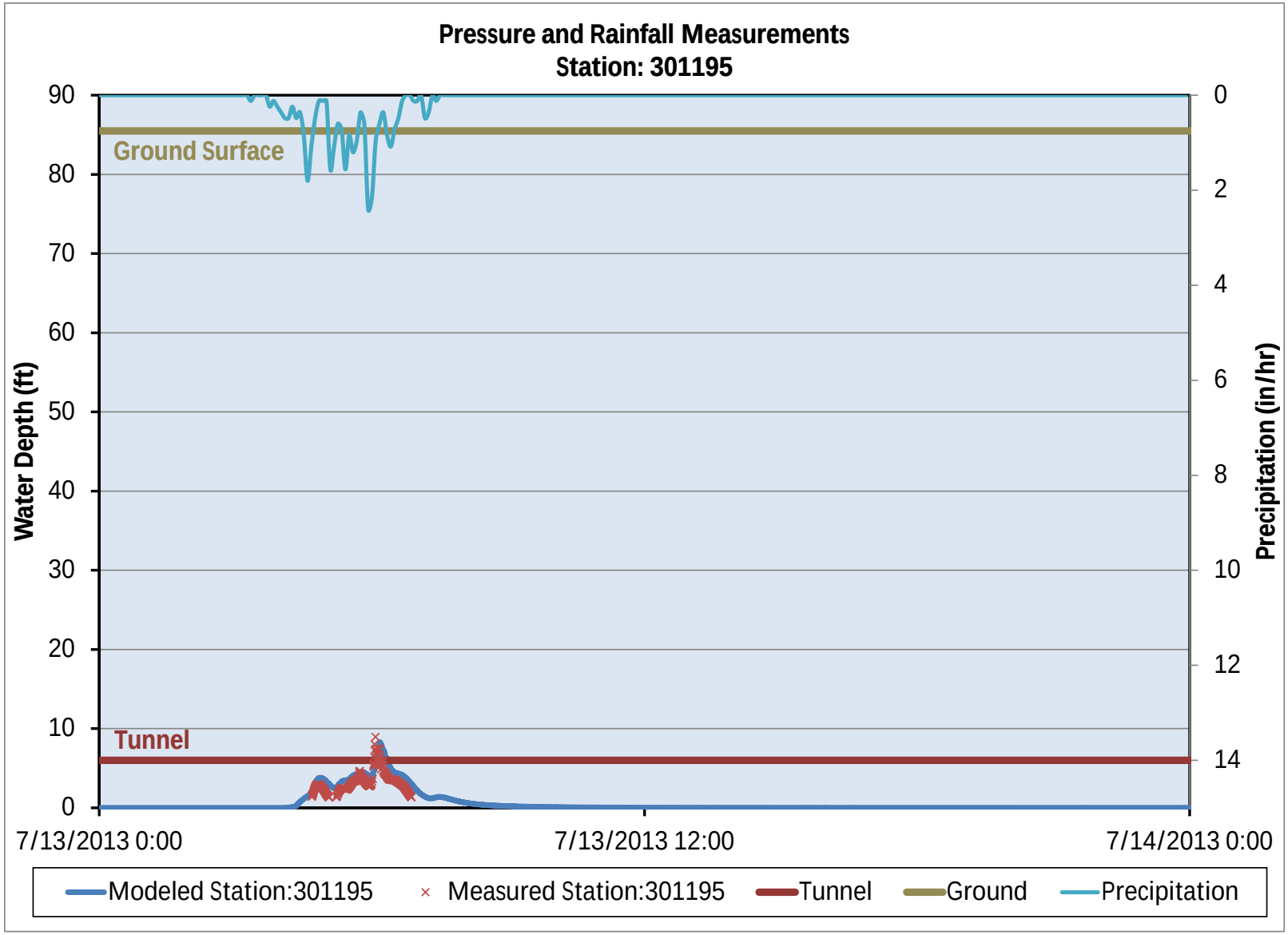


Figure 3.8 **Comparison between modeled and measured water depths at station 301195 for July 13, 2013, storm event**

Table 3-2 Modeled and measured peak water depths for calibration events

Monitoring Station	July 15, 2011, Calibration Event		July 13, 2013, Calibration Event	
	Measured Peak Water Depth (ft)	Modeled Peak Water Depth (ft)	Measured Peak Water Depth (ft)	Modeled Peak Water Depth (ft)
150170	10.9	11.2	5.3	6.3
155944	8.4	9.0	3.2	4.6
155945	22.2	24.3	5.1	4.6
155947	18.5	21.9	2.0	2.0
155961	[1]	25.0	[1]	1.1
155971	15.4	17.3	1.3	1.0
155972	22.2	23.9	5.0	4.1
155973	46.5	39.5	9.5	7.9
301150	[1]	32.9	7.4	7.9
301157	[1]	20.8	2.3	1.6
301174	[1]	20.9	1.7	1.8
301177	[1]	25.6	6.2	6.4
301195	[1]	35.8	9.0	8.3
301210	[1]	17.9	[1]	1.2

[1] Station did not have pressure measurements during the event.

Overall, the modeled water depths provide a good fit with the measured data in the tunnels during the calibration events. However, the peak water levels for both calibration events were higher than the measured data at most monitored stations. Higher simulation results may be a result of void spaces outside the tunnel system that cannot be accounted for in the model. In conversation with City staff it was learned that void spaces are present above the tunnel system and store water during the event. The exact volume of voids is unknown; although, several large caverns have been documented within the system. Higher simulations results could also be caused by the probe placement. The analysis conducted assumes that the probes were placed directly on the floor of the tunnel and measuring from the bottom of the tunnel up. It is likely that the probes are not measuring from the absolute bottom of the tunnel, but instead from a height between 0.5 to possible 1.5 feet above the tunnel floor. An adjustment for measurement height in the monitored results could bring the peak water elevations closer to the modeled results.

During model calibration it was assumed that inlets to the drainage system were not plugged by debris during the rainfall event. However, if inlets were partially plugged it could reduce inflows, resulting in lower peak water surface elevations in portions of the system. Since no anecdotal evidence was available, it was assumed that all inlets were clear and functioning as designed during the rainfall events.

In addition to visual evaluation, statistical assessment was completed to evaluate whether the results adequately simulate measured depths at monitoring stations in the tunnel system. The Nash-Sutcliffe

coefficient (NSC), Equation 3-3 (Nash and Sutcliffe 1970), is a widely used statistic to evaluate the "goodness of fit" between modeled results and measured data. This was calculated for each calibration event and at each location to evaluate the modeled results "goodness of fit" to the measured data. The values of the NSC range between negative infinity (-∞) and 1, with 1 indicating a perfect fit to the observed data. Results by locations and rainfall event for the Nash-Sutcliffe calculation are shown in Table 3-3.

Equation 3-3

$$E_f = 1 - \frac{\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right)^2}{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2}$$

Where: $\hat{Y}_i$ is simulated depth values

Y_i is measured depth values

$\bar{Y}$ is mean of the measured depth values

n is sample size

Table 3-3 Nash-Sutcliffe coefficients at monitoring locations for calibration events

Monitoring Station	July 15, 2011, Calibration Event Nash-Sutcliff	July 13, 2013, Calibration Event Nash-Sutcliff
150170	0.37	0.09
155944	-0.66	-7.93
155945	0.83	0.93
155947	0.84	[1]
155961	[1]	[1]
155971	0.82	[1]
155972	0.89	0.77
155973	0.61	0.81
301150	[1]	0.56
301157	[1]	[1]
301174	[1]	[1]
301177	[1]	0.34
301195	[1]	0.30
301210	[1]	[1]

[1] Station did not have pressure measurements during the event or pressure data throughout entire event for comparison

Note: a time shift was applied to each monitored result individually to account for assumed measurement drift. The time shift was applied to match the time step of the peak water depth between the monitored and modeled results.

The Nash-Sutcliffe results show fits above 0.5 at 9 of the 15 locations/event combinations. Locations 150170 and 155944 have the lowest Nash-Sutcliff values, with modeled results consistently higher than the monitored data. Figure 3.9 shows the modeled and measured results at station 155944 for the July 13, 2013, storm event. The model generally simulated the rise and fall of the hydrograph correctly; however, the magnitude of the peaks is higher in the modeled results than the measured data. The same relationship is present at station 150170. These two stations are the furthest downstream in the Central City tunnel system and located near an underground cavern near the intersection of Portland and Washington Avenues. Specific dimensions of the chamber are unknown; model inputs are based on anecdotal information provided by City staff. Simulation results at these stations are impacted by the cavern and could vary if additional information on this structure is identified. Monitoring locations further upstream in the system, where storm sewer and tunnel geometry is better defined, have Nash-Sutcliffe values as high 0.93. Probe placement could also be a factor at these locations. With water depth being less than 5 feet, the height at which the pressure probes are measuring from would have a greater impact on the comparison than at other locations.

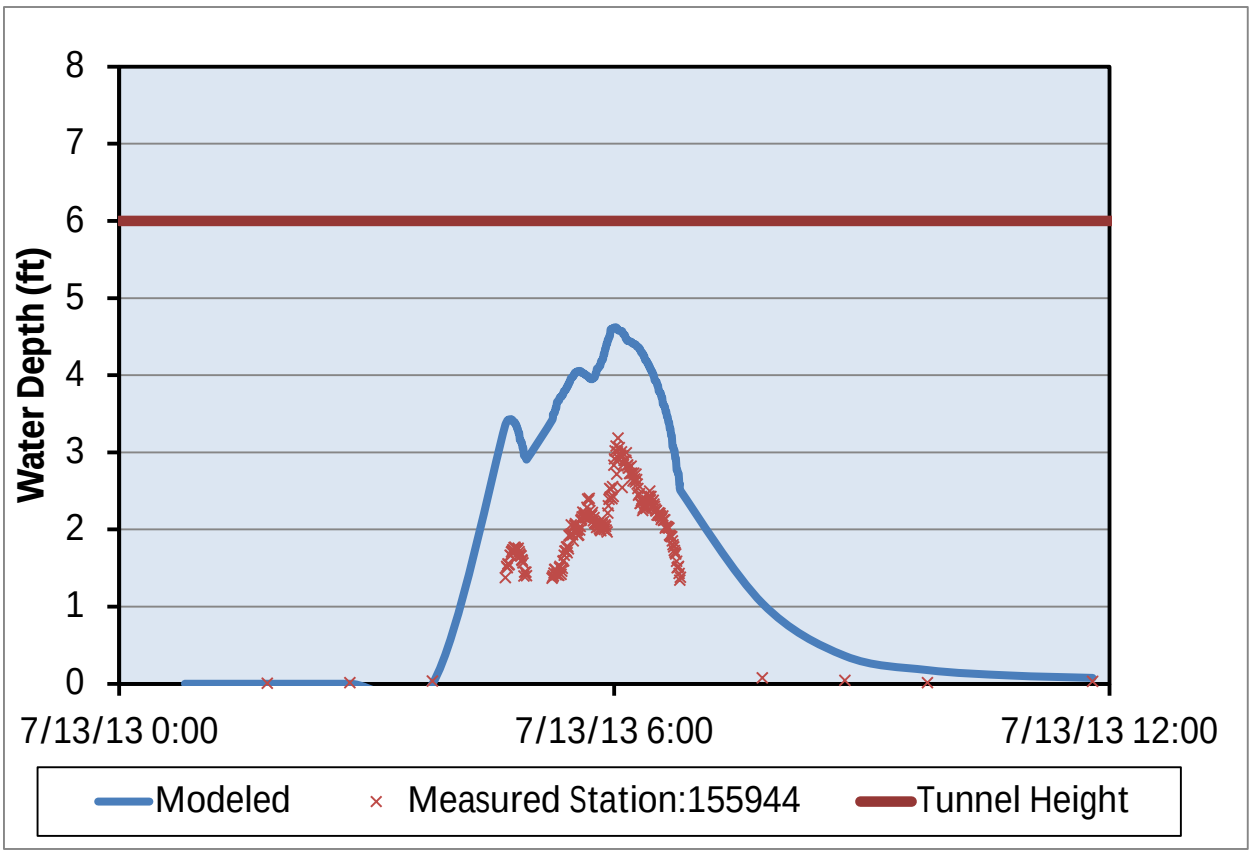


Figure 3.9 Comparison between modeled and measured water depths at station 155944 for July 13, 2013, storm event

3.5 Validation Results

The validation event occurred on June 21, 2012. This event has a peak intensity of 7.4 inches per hour which is similar to the peak intensity of the 10-year 2 hour Atlas 14 design storm event. In general the mode calculates higher water surface elevations than the measured water depths which were consistent with the calibration events. Similar to the calibration events, the unaccounted void spaces above the tunnel could be dampening the monitored peak water depths in the tunnel. With the water depths reaching higher elevations in the validation event than the calibration events, more of the void space would have been utilized. Figures showing modeled and measured results at all monitoring locations for the validation event are shown in Appendix B. The model simulated the shape and timing of the hydrograph; however, the peak water levels were higher in the modeled results.

Similar to the calibration event, it was assumed that all inlets to the tunnel system were functioning as designed during the validation event (i.e., not partially or fully plugged by debris). Since no anecdotal information was available, the inlet capacity was not adjusted prior to the simulation. However, if inlets were partially plugged, restricting inflows to the tunnel system, lower peak water surface elevations (compared to the simulation results) would be seen.

Table 3-4 Modeled and measured peak water depths for validation event

Monitoring Station	June 21, 2013, Validation Event	
	Measured Peak Water Depth (ft)	Modeled Peak Water Depth (ft)
150170	9.8	13.3
155944	7.0	11.2
155945	18.0	29.3
155947	16.9	28.6
155961	[1]	[1]
155971	10.4	20.2
155972	17.9	28.6
155973	41.8	45.7
301150	27.0	39.4
301157	17.4	26.0
301174	15.4	24.6
301177	19.8	32.9
301195	31.5	42.8
301210	[1]	[1]

[1] Station did not have pressure measurements during the event

4.0 Atlas 14 Design Event Results

The 2-, 10- and 100-year, 24-hour design events were used to map inundation areas throughout the study area (i.e., Central City, Chicago Avenue, and Eleventh Avenue tunnel systems). Peak water surface elevations at all drill-hole and drop-shaft locations in the main tunnel system and all manholes in the storm sewer system were imported into ArcGIS. A water surface raster for each event (i.e., 2-, 10-, and 100-year) was created using the Natural Neighbor spatial analyst tool in ArcGIS 10.3. The 2011 LiDAR data (adjusted to NGVD29) was subtracted from the water surface raster to create a water depth raster. The raster was converted to a polygon file and water depths less than or equal to 0 were removed (i.e., areas where the hydraulic grade line was below the ground and there was no surface flooding). Finally, inundation areas were manually adjusted to correct deep “holes” in locations where buildings were removed from the LiDAR.

Inundation areas are mapped for the 2-year event in Figure 4.1. Inundated areas above 5-tenths of a foot include:

- Intersection of Eleventh Street S. and Third Avenue S.
- Ninth Street S. between Fourth Avenue S. and Park Avenue S.
- Chicago Avenue S. between Ninth Street S. and Sixth Street S.
- Park Avenue S. between Seventh Street S. and Fourth Street S.
- Fifth Avenue S. between Fifth Street S. and Third Street S.
- Portland Avenue S. between Fifth Street S. and Fourth Street S.
- The intersection of Washington Avenue S. and Twelfth Avenue S.
- The intersection of Chicago Avenue S. and Third Street S.
- The intersection of Washington Avenue S. and Fifth Avenue S.

All inundation areas for the 2-year event occur in storm sewer sections of the model. Pipe capacity appears to be restricting flow in these areas as opposed to drill-hole capacity into the tunnel system. Drill-hole capacity could be contributing to upstream inundation in the storm sewer systems along Fifth Avenue S. and Portland Avenue S. as the water enters the Central City tunnel system. Considering that the storm sewer system and tunnel system are directly connected by drop shafts, flooding in the Chicago and Eleventh Avenue tunnel systems is likely caused by storm sewer pipe capacity. The deepest flooding occurs at the intersections of Park Avenue S. and Fifth Street S. and Third Street S. and Fifth Avenue S.

Inundation areas are mapped for the 10-year event in Figure 4.2. Inundated areas above 5-tenths of a foot include:

- Eleventh Street between Nicollet Avenue S. and Third Avenue S.
- Tenth Street S. between Fourth Avenue S. and Fifth Avenue S.

- Ninth Street S. between Fourth Avenue S. and Ninth Avenue S.
- Fifth Avenue S. between Fifth Street S. and Second Street S.
- Portland Avenue S. between Ninth Avenue S. and Washington Avenue S.
- Park Avenue S. between Ninth Avenue S. and Fourth Street S.
- Chicago Avenue S. between Ninth Avenue S. and Sixth Street S.
- The intersection of Chicago Avenue S. and Third Street S.
- Intersection of Ninth Avenue S. and Eight Street S.
- Tenth Avenue S. between Seventh St S and Sixth Street S.
- The intersection of Washington Avenue S. and Ninth Avenue S.
- The intersection of Washington Avenue S. and Twelfth Avenue S.
- The intersection of Fourth Avenue S and Fourth Street S.

Similar to the 2-year event storm, all flooding occurred in storm sewer sections of the model. The storm sewer sections in the Central City tunnel system enter the tunnel through drill holes. These drill holes could be impacting the hydraulic grade line of the storm sewer system and contributing to the flooding at the upstream locations. Considering that the storm sewer system and tunnel system are directly connected by drop shafts, flooding in the Chicago and Eleventh Avenue tunnel systems is likely caused by storm sewer pipe capacity. The deepest flooding occurs at the same locations as the 2-year event at the intersection of Park Avenue S. and Fifth Street S, and Third Street S. and Fifth Avenue S.

Inundation areas are mapped for the 100-year event in Figure 4.3. Inundation areas with depths greater than 5-tenths of a foot during the 100-year event cover a large section of the study area. Almost every street in the study area is inundated with the following exceptions:

- Sections of Hennepin Avenue S. between Tenth Street S. and Fourth Street S.
- Nicollet Avenue S. between Eighth Street S. and Fifth Street S.
- Marquette Avenue S. between Seventh Street S. and Fourth Street S.
- La Salle Avenue S. between Tenth Street S. and Eight Street S.
- Washington Avenue S. between Hennepin Avenue S. and Third Avenue S.

The deepest flooding occurs on Ninth Avenue S. between Ninth Street and Eight Street S. For the 100-year event, inlet capacity of the drill holes into the Central City tunnel system is likely contributing the flooding at all locations except Second Avenue S. between Tenth Street S. and Thirteenth Street S. (connected by drop shaft to the main tunnel system). Areas where drill-hole capacity contributes to the flooding include:

- Third Street S. between Hennepin Avenue S. and Second Avenue S.
- Washington Avenue S. at Fifth Avenue S. and Third Avenue S.

- Second Avenue S. at Fifth Street S.
- Nicollet Avenue S. at Ninth Street S.

Considering that the storm sewer system and tunnel system are directly connected by drop shafts, flooding in the Chicago and Eleventh Avenue tunnel systems is likely caused by storm sewer pipe capacity.

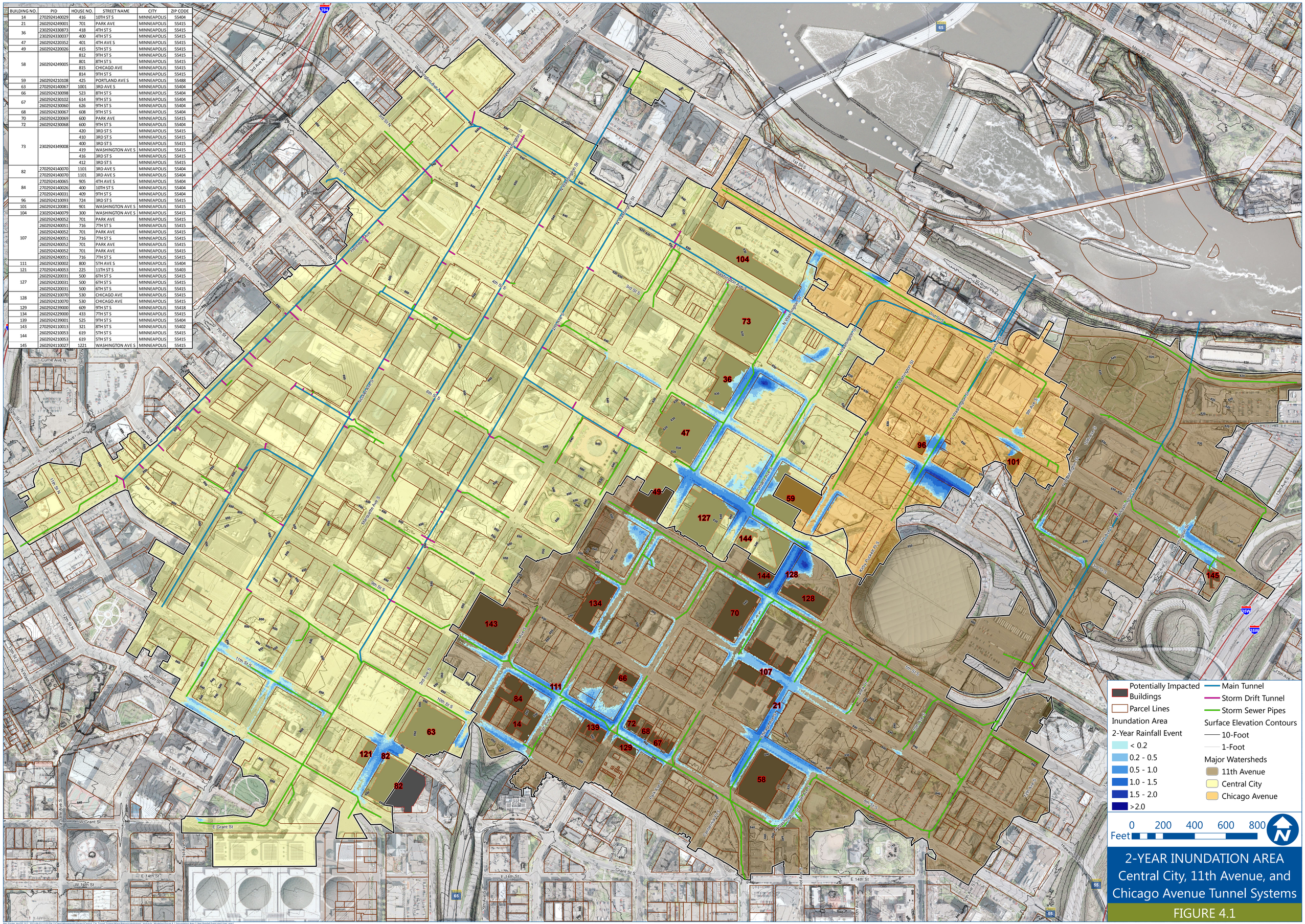
Potentially impacted buildings for each design event were determined by intersecting building outlines from the city with each inundation layer. Tables imbedded in Figure 4.1 for the 2-year design storm, Figure 4.2 for the 10-year design storm and Figure 4.3 for the 100-year design storm detail potentially impacted buildings.

For all three modeled design events negative flow is present in the Central City tunnel system, showing restricted tunnel capacity along Washington Avenue S., Hennepin Avenue S., Nicollet Avenue S., and Marquette Avenue S. Flows in the Second Avenue S. tunnel section remain positive throughout all three design storms. The negative flow in the tunnel system could be contributing to inundation in these systems, especially during the 100–year design storm.

In the Eleventh Avenue tunnel system a connector pipe to the I-35W tunnel system is present at Chicago Avenue S. and Ninth Street S. This pipe was modeled as a free outflow from the system. Including water elevations for the 35W system could impact the inundation results for the Eleventh Avenue tunnel system.

Based on the results of the design event models we would recommend placing additional pressure-monitoring stations in the Chicago Avenue and Eleventh Avenue tunnel systems. The 14 monitoring locations in the Central City tunnel system provide sufficient coverage for model calibration. Monitoring was not conducted in the Chicago Avenue or the Eleventh Avenue tunnel systems, limiting calibration of those systems. Placing pressure monitoring probes in the tunnel at the intersection of Eleventh Avenue S. and Third Street S. and at the intersection of Washington Avenue S. and Chicago Avenue S. would provide enough coverage to determine if the calibration assumptions used in the Central City tunnel system apply to the Chicago and Eleventh Avenue systems. Additional monitoring locations in the Central City tunnel system could include monitoring at drill-hole locations. Such locations could include the intersection of Fourth and Fifth Avenue S. with Washington Avenue S. Pressure monitors could be placed at the top of the drill holes where the storm sewer section enters to gain an understanding of how water is building up at these locations and to assist in model calibration.

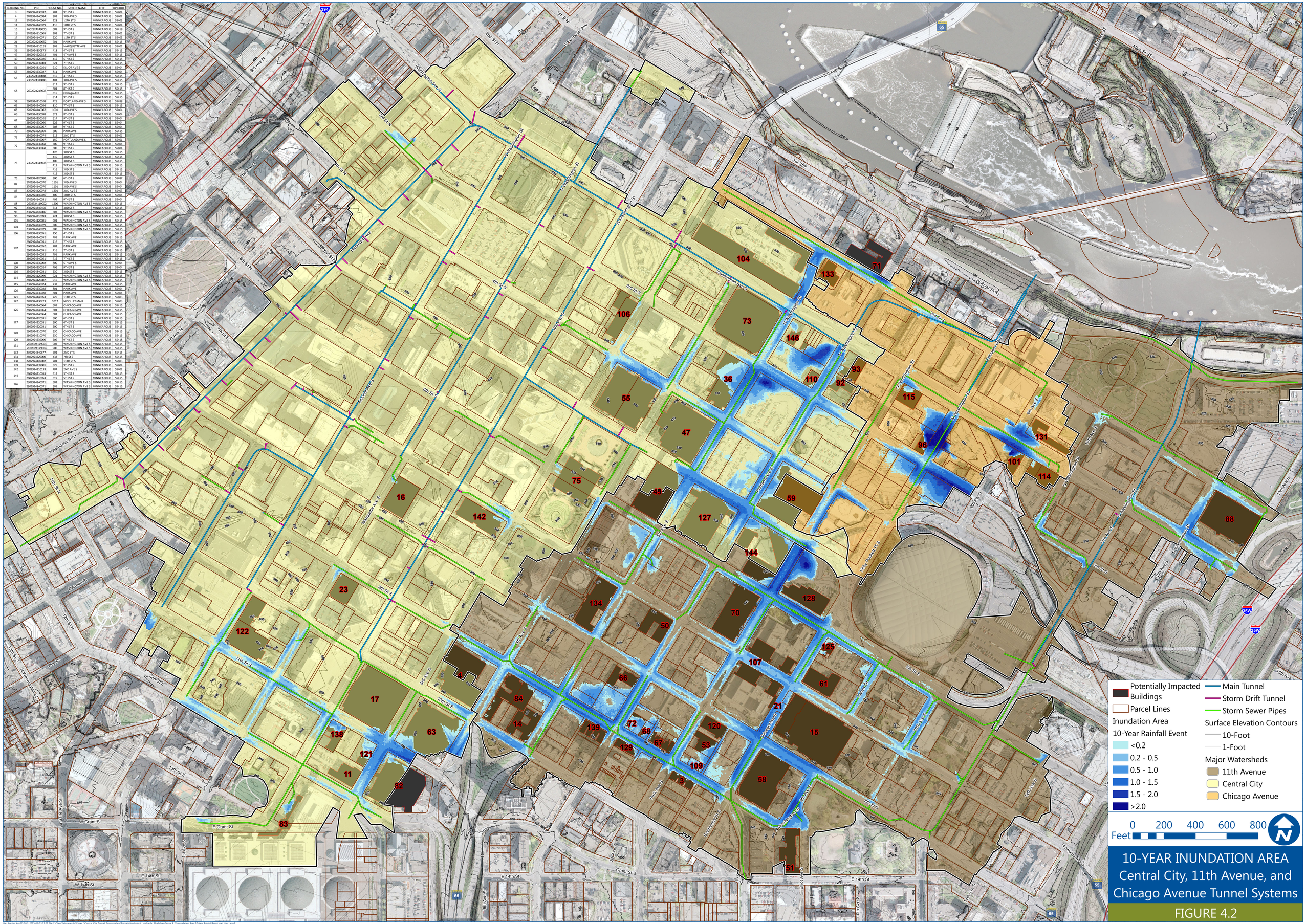
BUILDING NO.	PID	HOUSE NO.	STREET NAME	CITY	ZIP CODE
14	2702924140029	416	10TH ST S	MINNEAPOLIS	55404
21	2602924249001	701	PARK AVE	MINNEAPOLIS	55415
36	2302924330873	418	4TH ST S	MINNEAPOLIS	55415
	2302924330037	400	4TH ST S	MINNEAPOLIS	55415
47	2602924220352	401	4TH AVE S	MINNEAPOLIS	55415
49	2602924220026	415	5TH ST S	MINNEAPOLIS	55415
58	2602924249005	812	9TH ST S	MINNEAPOLIS	55415
		801	8TH ST S	MINNEAPOLIS	55415
		815	CHICAGO AVE	MINNEAPOLIS	55415
		814	9TH ST S	MINNEAPOLIS	55415
59	2602924210108	425	PORTLAND AVE S	MINNEAPOLIS	55488
63	2702924140067	1001	3RD AVE S	MINNEAPOLIS	55404
66	2602924230098	523	8TH ST S	MINNEAPOLIS	55404
67	2602924230102	614	9TH ST S	MINNEAPOLIS	55404
	2602924230060	626	9TH ST S	MINNEAPOLIS	55404
68	2602924230067	608	9TH ST S	MINNEAPOLIS	55404
70	2602924220069	600	PARK AVE	MINNEAPOLIS	55415
72	2602924230068	600	9TH ST S	MINNEAPOLIS	55404
73	2302924349008	420	3RD ST S	MINNEAPOLIS	55415
		410	3RD ST S	MINNEAPOLIS	55415
		400	3RD ST S	MINNEAPOLIS	55415
		419	WASHINGTON AVE S	MINNEAPOLIS	55415
		416	3RD ST S	MINNEAPOLIS	55415
		412	3RD ST S	MINNEAPOLIS	55415
82	2702924140070	1101	3RD AVE S	MINNEAPOLIS	55404
	2702924140070	1101	3RD AVE S	MINNEAPOLIS	55404
84	2702924140065	905	4TH AVE S	MINNEAPOLIS	55404
	2702924140026	400	10TH ST S	MINNEAPOLIS	55404
	2702924140031	409	9TH ST S	MINNEAPOLIS	55404
96	2602924210093	724	3RD ST S	MINNEAPOLIS	55415
101	2602924120081	901	WASHINGTON AVE S	MINNEAPOLIS	55415
104	2302924340079	300	WASHINGTON AVE S	MINNEAPOLIS	55415
107	2602924240052	701	PARK AVE	MINNEAPOLIS	55415
	2602924240051	716	7TH ST S	MINNEAPOLIS	55415
	2602924240052	701	PARK AVE	MINNEAPOLIS	55415
	2602924240051	716	7TH ST S	MINNEAPOLIS	55415
	2602924240052	701	PARK AVE	MINNEAPOLIS	55415
	2602924240052	701	PARK AVE	MINNEAPOLIS	55415
	2602924240051	716	7TH ST S	MINNEAPOLIS	55415
111	2602924230002	800	5TH AVE S	MINNEAPOLIS	55404
121	2702924140053	225	11TH ST S	MINNEAPOLIS	55403
127	2602924220031	500	6TH ST S	MINNEAPOLIS	55415
	2602924220031	500	6TH ST S	MINNEAPOLIS	55415
	2602924220031	500	6TH ST S	MINNEAPOLIS	55415
128	2602924210070	530	CHICAGO AVE	MINNEAPOLIS	55415
	2602924210070	530	CHICAGO AVE	MINNEAPOLIS	55415
129	2602924239000	609	9TH ST S	MINNEAPOLIS	55418
134	2602924229000	433	7TH ST S	MINNEAPOLIS	55415
139	2602924239001	525	9TH ST S	MINNEAPOLIS	55404
143	2702924110013	321	8TH ST S	MINNEAPOLIS	55402
144	2602924210053	619	5TH ST S	MINNEAPOLIS	55415
	2602924210053	619	5TH ST S	MINNEAPOLIS	55415
145	2602924110027	1221	WASHINGTON AVE S	MINNEAPOLIS	55415



2-YEAR INUNDATION AREA
Central City, 11th Avenue, and Chicago Avenue Tunnel Systems

FIGURE 4.1

BUILDING NO.	PID	HOUSE NO.	STREET NAME	CITY	ZIP CODE
3	2602924230037	701	9TH ST S	MINNEAPOLIS	55404
4	2702924140084	901	3RD AVE S	MINNEAPOLIS	55402
11	2702924140064	228	12TH ST S	MINNEAPOLIS	55403
14	2702924140029	416	10TH ST S	MINNEAPOLIS	55404
15	2602924249000	609	7TH ST S	MINNEAPOLIS	55418
16	2702924110005	109	7TH ST S	MINNEAPOLIS	55402
17	2702924140071	220	11TH ST S	MINNEAPOLIS	55403
21	2602924240052	701	PARK AVE	MINNEAPOLIS	55415
23	2702924110128	901	MARQUETTE AVE	MINNEAPOLIS	55402
36	2302924330871	418	4TH ST S	MINNEAPOLIS	55415
47	2602924220052	401	4TH AVE S	MINNEAPOLIS	55415
49	2602924220026	415	5TH ST S	MINNEAPOLIS	55415
50	2602924230003	521	7TH ST S	MINNEAPOLIS	55415
51	2602924310101	910	ELIOT AVE S	MINNEAPOLIS	55404
53	2602924230027	811	PARK AVE	MINNEAPOLIS	55404
55	2302924330044	315	4TH ST S	MINNEAPOLIS	55415
	2302924330043	401	3RD AVE S	MINNEAPOLIS	55415
58	2602924249005	812	9TH ST S	MINNEAPOLIS	55415
		801	8TH ST S	MINNEAPOLIS	55415
		815	Chicago Ave	MINNEAPOLIS	55415
		814	9TH ST S	MINNEAPOLIS	55415
59	2602924210108	425	PORTLAND AVE S	MINNEAPOLIS	55488
61	2602924240056	810	7TH ST S	MINNEAPOLIS	55415
63	2702924140067	1001	3RD AVE S	MINNEAPOLIS	55404
66	2602924230098	523	8TH ST S	MINNEAPOLIS	55404
67	2602924230102	614	9TH ST S	MINNEAPOLIS	55404
	2602924230060	626	9TH ST S	MINNEAPOLIS	55404
68	2602924230067	608	9TH ST S	MINNEAPOLIS	55404
70	2602924230069	600	PARK AVE	MINNEAPOLIS	55415
71	2302924340074	512	2ND ST S	MINNEAPOLIS	55401
	2302924340027	150	PORTLAND AVE S	MINNEAPOLIS	55415
72	2602924230068	600	7TH ST S	MINNEAPOLIS	55404
	2602924230068	600	9TH ST S	MINNEAPOLIS	55404
73	2302924349002	420	3RD ST S	MINNEAPOLIS	55415
		410	3RD ST S	MINNEAPOLIS	55415
		400	3RD ST S	MINNEAPOLIS	55415
		419	WASHINGTON AVE S	MINNEAPOLIS	55415
		416	3RD ST S	MINNEAPOLIS	55415
		412	3RD ST S	MINNEAPOLIS	55415
75	2602924220080	300	6TH ST S	MINNEAPOLIS	55487
82	2702924140070	1101	3RD AVE S	MINNEAPOLIS	55404
	2702924140070	1101	3RD AVE S	MINNEAPOLIS	55404
83	2702924220078	1301	2ND AVE S	MINNEAPOLIS	55403
84	2702924140044	400	10TH ST S	MINNEAPOLIS	55404
	2702924140031	409	9TH ST S	MINNEAPOLIS	55404
88	2302924119002	1300	WASHINGTON AVE S	MINNEAPOLIS	55415
92	2302924340450	614	3RD ST S	MINNEAPOLIS	55415
93	2302924349006	607	WASHINGTON AVE S	MINNEAPOLIS	55415
96	2602924210091	724	3RD ST S	MINNEAPOLIS	55415
101	2602924120081	901	WASHINGTON AVE S	MINNEAPOLIS	55415
104	2302924340079	300	WASHINGTON AVE S	MINNEAPOLIS	55415
	2302924340079	300	WASHINGTON AVE S	MINNEAPOLIS	55415
106	2302924330051	250	4TH ST S	MINNEAPOLIS	55415
107	2602924240052	701	PARK AVE	MINNEAPOLIS	55415
	2602924240053	716	7TH ST S	MINNEAPOLIS	55415
	2602924240052	701	PARK AVE	MINNEAPOLIS	55415
	2602924240053	716	7TH ST S	MINNEAPOLIS	55415
	2602924240052	701	PARK AVE	MINNEAPOLIS	55415
	2602924240051	716	7TH ST S	MINNEAPOLIS	55415
108	2602924230002	800	5TH AVE S	MINNEAPOLIS	55404
109	2602923010014	706	9TH ST S	MINNEAPOLIS	55404
110	2302924340031	530	3RD ST S	MINNEAPOLIS	55415
114	2302924119040	921	WASHINGTON AVE S	MINNEAPOLIS	55415
	2302924120087	915	WASHINGTON AVE S	MINNEAPOLIS	55415
115	2302924340024	233	PARK AVE	MINNEAPOLIS	55415
120	2602924230028	801	PARK AVE	MINNEAPOLIS	55404
	2602924230028	801	PARK AVE	MINNEAPOLIS	55404
121	2702924140053	225	11TH ST S	MINNEAPOLIS	55403
122	2702924130223	1017	NICOLLET MALL	MINNEAPOLIS	55403
125	2602924240064	601	CHICAGO AVE	MINNEAPOLIS	55415
	2602924240064	601	CHICAGO AVE	MINNEAPOLIS	55415
	2602924240064	601	CHICAGO AVE	MINNEAPOLIS	55415
127	2602922030031	500	6TH ST S	MINNEAPOLIS	55415
	2602922030031	500	6TH ST S	MINNEAPOLIS	55415
	2602922030031	500	6TH ST S	MINNEAPOLIS	55415
128	2602922010070	530	CHICAGO AVE	MINNEAPOLIS	55415
	2602922010070	530	CHICAGO AVE	MINNEAPOLIS	55415
129	2602923230000	609	7TH ST S	MINNEAPOLIS	55418
131	2302924129004	902	WASHINGTON AVE S	MINNEAPOLIS	55415
	2302924129004	900	WASHINGTON AVE S	MINNEAPOLIS	55415
133	2302924340077	501	2ND ST S	MINNEAPOLIS	55415
134	2602924229000	433	7th St S	MINNEAPOLIS	55415
138	2702924140002	201	11TH ST S	MINNEAPOLIS	55403
139	2602924239021	525	9TH ST S	MINNEAPOLIS	55404
142	2702924110133	707	2ND AVE S	MINNEAPOLIS	55402
144	2602924210053	619	5TH ST S	MINNEAPOLIS	55415
	2602924210053	619	5TH ST S	MINNEAPOLIS	55415
146	2302924340071	501	WASHINGTON AVE S	MINNEAPOLIS	55415
	2302924340071	501	WASHINGTON AVE S	MINNEAPOLIS	55415



10-YEAR INUNDATION AREA
Central City, 11th Avenue, and Chicago Avenue Tunnel Systems

FIGURE 4.2

Bar Footer: ArcGIS 10.3, 2015-06-03 11:07 File: I:\Client\Minneapolis\Project\Central_City_Tunnel_System\Maps\Reports\Hydrologic_Hydraulic_Modeling\Figure 4_2 Inundation Area 10-Year Rainfall Event.mxd User: arm2

BUILDING NO.	PID	HOUSE NO.	FRAC_HOUSE	STREET NAME	CITY	ZIP CODE	BUILDING NO.	PID	HOUSE NO.	FRAC_HOUSE	STREET NAME	CITY	ZIP CODE
1	2302924340071	501		WASHINGTON AVE S	MINNEAPOLIS	55415	63	2702924140067	1001		3RD AVE S	MINNEAPOLIS	55404
	2302924340035	515		WASHINGTON AVE S	MINNEAPOLIS	55415	64	2602924230068	600		9TH ST S	MINNEAPOLIS	55404
2	2602924230037	701		9TH ST S	MINNEAPOLIS	55404	65	2302924330046	255		2ND AVE S	MINNEAPOLIS	55401
3	2602924230036	905		PARK AVE	MINNEAPOLIS	55404	66	2602924230098	523		8TH ST S	MINNEAPOLIS	55404
	2602924230037	701		9TH ST S	MINNEAPOLIS	55404	67	2602924230102	614		9TH ST S	MINNEAPOLIS	55404
4	2702924140084	901		3RD AVE S	MINNEAPOLIS	55402		2602924230060	626		9TH ST S	MINNEAPOLIS	55404
5	2602924130096	1010		7TH ST S	MINNEAPOLIS	55415	68	2602924230067	608		9TH ST S	MINNEAPOLIS	55404
	2602924240063	601		10TH AVE S	MINNEAPOLIS	55415	69	2602924240086	700		10TH AVE S	MINNEAPOLIS	55415
6	2602924130096	1010		7TH ST S	MINNEAPOLIS	55415	70	2602924220069	600		PARK AVE	MINNEAPOLIS	55415
	2602924240063	601		10TH AVE S	MINNEAPOLIS	55415	71	2302924340074	512		2ND ST S	MINNEAPOLIS	55401
7	2702924139002	1001		MARQUETTE AVE	MINNEAPOLIS	55403		2302924349007	150		PORTLAND AVE S	MINNEAPOLIS	55401
8	2702924110128	901		MARQUETTE AVE	MINNEAPOLIS	55402	72	2602924230068	600		9TH ST S	MINNEAPOLIS	55404
9	2702924110072	87		8TH ST S	MINNEAPOLIS	55402	73	2302924349008	420		3RD ST S	MINNEAPOLIS	55415
	2702924110073	83		8TH ST S	MINNEAPOLIS	55402			410		3RD ST S	MINNEAPOLIS	55415
	2702924110071	800	1/2	MARQUETTE AVE	MINNEAPOLIS	55402			400		3RD ST S	MINNEAPOLIS	55415
10	2702924110025	921		MARQUETTE AVE	MINNEAPOLIS	55402			419		WASHINGTON AVE S	MINNEAPOLIS	55415
	2702924110024	921		MARQUETTE AVE	MINNEAPOLIS	55402			416		3RD ST S	MINNEAPOLIS	55415
	2702924110160	900		2ND AVE S	MINNEAPOLIS	55402			412		3RD ST S	MINNEAPOLIS	55415
	2702924110128	901		MARQUETTE AVE	MINNEAPOLIS	55402	74	2602924240051	716		7TH ST S	MINNEAPOLIS	55415
	2702924140002	933		MARQUETTE AVE	MINNEAPOLIS	55402	75	2602924220080	300		6TH ST S	MINNEAPOLIS	55487
11	2702924140064	228		12TH ST S	MINNEAPOLIS	55403	76	2602924220031	500		6TH ST S	MINNEAPOLIS	55415
12	2702924130287	73		11TH ST S	MINNEAPOLIS	55403	77	2702924130267	1200		2ND AVE S	MINNEAPOLIS	55403
	2702924130293	1101		LASALLE AVE	MINNEAPOLIS	55403		2702924130281	117		12TH ST S	MINNEAPOLIS	55403
13	2702924139002	1001		MARQUETTE AVE	MINNEAPOLIS	55403	78	2702924140068	207		9TH ST S	MINNEAPOLIS	55402
14	2702924140029	416		10TH ST S	MINNEAPOLIS	55404	79	2702924140080	900		3RD AVE S	MINNEAPOLIS	55402
15	2602924249000	609		9TH ST S	MINNEAPOLIS	55418	80	2702924130293	1101		LASALLE AVE	MINNEAPOLIS	55403
	2602924249001	711		CHICAGO AVE	MINNEAPOLIS	55415	81	2702924140070	1101		3RD AVE S	MINNEAPOLIS	55404
16	2702924110006	717		MARQUETTE AVE	MINNEAPOLIS	55402	82	2702924140070	1101		3RD AVE S	MINNEAPOLIS	55404
17	2702924140071	220		11TH ST S	MINNEAPOLIS	55403	83	2702924420078	1301		2ND AVE S	MINNEAPOLIS	55403
18	2702924120139	800		NICOLLET MALL	MINNEAPOLIS	55402	84	2702924140065	905		4TH AVE S	MINNEAPOLIS	55404
19	2602924240052	701		PARK AVE	MINNEAPOLIS	55415		2702924140026	400		10TH ST S	MINNEAPOLIS	55404
	2602924240051	716		7TH ST S	MINNEAPOLIS	55415		2702924140031	409		9TH ST S	MINNEAPOLIS	55404
20	2602924240052	701		PARK AVE	MINNEAPOLIS	55415	85	2202924410090	24		3RD ST N	MINNEAPOLIS	55401
	2602924240051	716		7TH ST S	MINNEAPOLIS	55415	86	2702924130027	1016		MARQUETTE AVE	MINNEAPOLIS	55403
21	2602924240052	701		PARK AVE	MINNEAPOLIS	55415	87	2602924119002	1200		WASHINGTON AVE S	MINNEAPOLIS	55415
22	2602924210070	530		CHICAGO AVE	MINNEAPOLIS	55415	88	2602924119002	1200		WASHINGTON AVE S	MINNEAPOLIS	55415
23	2702924110160	900		2ND AVE S	MINNEAPOLIS	55402	89		1102	1/2	WASHINGTON AVE S	MINNEAPOLIS	55415
	2702924140069	120		10TH ST S	MINNEAPOLIS	55403		2602924119003	1100		WASHINGTON AVE S	MINNEAPOLIS	55415
	2702924110128	901		MARQUETTE AVE	MINNEAPOLIS	55402	90	2602924110024	200		12TH AVE S	MINNEAPOLIS	55415
	2702924140002	933		MARQUETTE AVE	MINNEAPOLIS	55402			1102	1/2	WASHINGTON AVE S	MINNEAPOLIS	55415
24	2702924110014	825		2ND AVE S	MINNEAPOLIS	55402		2602924119003	1100		WASHINGTON AVE S	MINNEAPOLIS	55415
25	2702924110085	805		2ND AVE S	MINNEAPOLIS	55402	91	2602924249006	626		10TH AVE S	MINNEAPOLIS	55415
26	2702924110015	819		2ND AVE S	MINNEAPOLIS	55402		2602924240122	616		10TH AVE S	MINNEAPOLIS	55415
27	2702924110093	222		9TH ST S	MINNEAPOLIS	55402	92	2302924340450	614		3RD ST S	MINNEAPOLIS	55415
	2702924110085	805		2ND AVE S	MINNEAPOLIS	55402	93	2302924349006	607		WASHINGTON AVE S	MINNEAPOLIS	55415
28	2702924110031	625		2ND AVE S	MINNEAPOLIS	55402	94	2602924120077	312		11TH AVE S	MINNEAPOLIS	55415
29	2702924120102	88		10TH ST S	MINNEAPOLIS	55403	95	2302924340024	233		PARK AVE	MINNEAPOLIS	55415
	2702924120096	84		10TH ST S	MINNEAPOLIS	55403	96	2602924210093	724		3RD ST S	MINNEAPOLIS	55415
	2702924120101	94		10TH ST S	MINNEAPOLIS	55403	97	2602924130042	601		11TH AVE S	MINNEAPOLIS	55415
30	2702924140001	815		4TH AVE S	MINNEAPOLIS	55404	98	2602924110006	1205		WASHINGTON AVE S	MINNEAPOLIS	55415
	2602924230002	800		5TH AVE S	MINNEAPOLIS	55404		2602924110086	1203		WASHINGTON AVE S	MINNEAPOLIS	55415
	2602924230001	405		8TH ST S	MINNEAPOLIS	55404		2602924110008	1201		WASHINGTON AVE S	MINNEAPOLIS	55415
31	2202924410012	250		MARQUETTE AVE	MINNEAPOLIS	55401	99	2602924110086	1203		WASHINGTON AVE S	MINNEAPOLIS	55415
32	2702924120096	84		10TH ST S	MINNEAPOLIS	55403		2602924110005	1207		WASHINGTON AVE S	MINNEAPOLIS	55415
33	2702924110084	523		2ND AVE S	MINNEAPOLIS	55402	100	2702924110080	120		9TH ST S	MINNEAPOLIS	55402
34	2302924340071	501		WASHINGTON AVE S	MINNEAPOLIS	55415		2702924110082	825		MARQUETTE AVE	MINNEAPOLIS	55402
	2302924340035	515		WASHINGTON AVE S	MINNEAPOLIS	55415	101	2602924120081	901		WASHINGTON AVE S	MINNEAPOLIS	55415
35	2302924330873	418		4TH ST S	MINNEAPOLIS	55415	102	2702924149002	201		11TH ST S	MINNEAPOLIS	55403
	2302924330041	301		4TH AVE S	MINNEAPOLIS	55415	103	2602924210053	619		5TH ST S	MINNEAPOLIS	55415
36	2302924330873	418		4TH ST S	MINNEAPOLIS	55415	104	2302924340079	300		WASHINGTON AVE S	MINNEAPOLIS	55415
	2302924330037	400		4TH ST S	MINNEAPOLIS	55415	105	2302924330051	250		4TH ST S	MINNEAPOLIS	55415
37	2302924340071	501		WASHINGTON AVE S	MINNEAPOLIS	55415	106	2302924330051	250		4TH ST S	MINNEAPOLIS	55415
38	2302924340035	515		WASHINGTON AVE S	MINNEAPOLIS	55415	107	2602924240052	701		PARK AVE	MINNEAPOLIS	55415
39	2302924330016	416		3RD AVE S	MINNEAPOLIS	55415		2602924240051	716		7TH ST S	MINNEAPOLIS	55415
40	2302924340079	300		WASHINGTON AVE S	MINNEAPOLIS	55415	108	2602924230002	800		5TH AVE S	MINNEAPOLIS	55404
41	2302924349005	535		2ND ST S	MINNEAPOLIS	55415	109	2602924230024	706		9TH ST S	MINNEAPOLIS	55404
		537		2ND ST S	MINNEAPOLIS	55415	110	2302924340031	530		3RD ST S	MINNEAPOLIS	55415
		539		2ND ST S	MINNEAPOLIS	55415	111	2702924140001	815		4TH AVE S	MINNEAPOLIS	55404
		541		2ND ST S	MINNEAPOLIS	55415		2602924230002	800		5TH AVE S	MINNEAPOLIS	55404
		543		2ND ST S	MINNEAPOLIS	55415	112	2702924130088	1000		MARQUETTE AVE	MINNEAPOLIS	55403
		204		PORTLAND AVE S	MINNEAPOLIS	55415		2702924120197	1001		NICOLLET MALL	MINNEAPOLIS	55403
		208		PORTLAND AVE S	MINNEAPOLIS	55415	113	2602924210071	401		CHICAGO AVE	MINNEAPOLIS	55415
		210		PORTLAND AVE S	MINNEAPOLIS	55415	114	2602924120090	921		WASHINGTON AVE S	MINNEAPOLIS	55415
		212		PORTLAND AVE S	MINNEAPOLIS	55415		2602924120087	915		WASHINGTON AVE S	MINNEAPOLIS	55415
		214		PORTLAND AVE S	MINNEAPOLIS	55415	115	2302924340024	233		PARK AVE	MINNEAPOLIS	55415
		216		PORTLAND AVE S	MINNEAPOLIS	55415	116	2602924220343	625		4TH AVE S	MINNEAPOLIS	55415
		545		2ND ST S	MINNEAPOLIS	55415	117	2602924210085	700		4TH ST S	MINNEAPOLIS	55415
42	2302924339001	200		5TH ST S	MINNEAPOLIS	55402		2602924210086	716		4TH ST S	MINNEAPOLIS	55415
		220		5TH ST S	MINNEAPOLIS	55402	118	2302924330009	309		2ND AVE S	MINNEAPOLIS	55401
43	2202924440012	300		NICOLLET MALL	MINNEAPOLIS	55401	119	2302924339000	121		WASHINGTON AVE S	MINNEAPOLIS	55401
44	2302924330012	330		2ND AVE S	MINNEAPOLIS	55401	120	2602924230028	801		PARK AVE	MINNEAPOLIS	55404
45	2602924220080	300		6TH ST S	MINNEAPOLIS	55487	121	2702924140053	225		11TH ST S	MINNEAPOLIS	55403
46	2602924240051	716		7TH ST S	MINNEAPOLIS	55415	122	2702924130223	1017		NICOLLET MALL	MINNEAPOLIS	55403
47	2602924220352	401		4TH AVE S	MINNEAPOLIS	55415		2702924120197	1001		NICOLLET MALL	MINNEAPOLIS	55403
48	2602924220031	500		6TH ST S	MINNEAPOLIS	55415	123	2602924240064	601		CHICAGO AVE	MINNEAPOLIS	55415
49	2602924220026	415		5TH ST S	MINNEAPOLIS	55415	124	2602924240064	601		CHICAGO AVE	MINNEAPOLIS	55415
50	2602924239003	521		7TH ST S	MINNEAPOLIS	55415	125	2602924240064	601		CHICAGO AVE	MINNEAPOLIS	55415
51	2602924310101	910		ELLIOT AVE S	MINNEAPOLIS	55404	126	2602924210070	530		CHICAGO AVE	MINNEAPOLIS	55415
52	2602924210053	619		5TH ST S	MINNEAPOLIS	55415	127	2602924220031	500		6TH ST S	MINNEAPOLIS	55415
53	2602924230027	811		PARK AVE	MINNEAPOLIS	55404	128	2602924210070	530		CHICAGO AVE	MINNEAPOLIS	55415
	2602924230028	801		PARK AVE	MINNEAPOLIS	55404	129	2602924239000	609		9TH ST S	MINNEAPOLIS	55418
54	2702924219002	1100		HENNEPIN AVE	MINNEAPOLIS	55403	130	2302924439007	711		2ND ST S	MINNEAPOLIS	55415
	2702924219002	1126		HENNEPIN AVE	MINNEAPOLIS	55403		2302924340676	200		CHICAGO AVE	MINNEAPOLIS	55415
	2702924210183	1123		HAWTHORNE AVE	MINNEAPOLIS	55403	131	2602924129004	902		WASHINGTON AVE S	MINNEAPOLIS	55415
55	2302924330044	315		4TH ST S	MINNEAPOLIS	55415		2602924129004	900		WASHINGTON AVE S	MINNEAPOLIS	55415
	2302924330043	401		3RD AVE S	MINNEAPOLIS	55415	132	2302924340389	500		WASHINGTON AVE S	MINNEAPOLIS	55415
56	2602924249005	812		9TH ST S	MINNEAPOLIS	55415	133	2302924340677	501		2ND ST S	MINNEAPOLIS	55415
		801		8TH ST S	MINNEAPOLIS	55415	134	2602924229000	433		7th St S	MINNEAPOLIS	55415
		815		CHICAGO AVE	MINNEAPOLIS	55415	135	2302924349001	200		PARK AVE	MINNEAPOLIS	55415
		814		9TH ST S	MINNEAPOLIS	55415	136	2302924330876	300		4TH ST S	MINNEAPOLIS	55415
57	2602924240112	826		9TH ST S	MINNEAPOLIS	55404		2302924330035	310		4TH AVE S	MINNEAPOLIS	55415
	2602924249005	812		9TH ST S	MINNEAPOLIS	55415	137	2702924129003	900		NICOLLET MALL	MINNEAPOLIS	55402
		801		8TH ST S	MINNEAPOLIS	55415	138	2702924149002	201		11TH ST S	MINNEAPOLIS	55403
		815		CHICAGO AVE	MINNEAPOLIS	55415	139	2602924239001	525		9TH ST S	MINNEAPOLIS	55404
		814		9TH ST S	MINNEAPOLIS	55415	140	2202924440101	150		5TH ST S	MINNEAPOLIS	55402
	2602924240113	825		8TH ST S	MINNEAPOLIS	55404	141	2702924110127	201		6TH ST S	MINNEAPOLIS	55402
58	2602924249005	812		9TH ST S	MINNEAPOLIS	55415	142	2702924110133	707		2ND AVE S	MINNEAPOLIS	55402
		801		8TH ST S	MINNEAPOLIS	55415	143	2702924110013	321		8TH ST S	MINNEAPOLIS	55402
		815		CHICAGO AVE	MINNEAPOLIS	55415	144	2602924210053	619		5TH ST S	MINNEAPOLIS	55415
		814		9TH ST S	MINNEAPOLIS	55415	145	2602924110027	1221		WASHINGTON AVE S	MINNEAPOLIS	55415
59	2602924210108	425		PORTLAND AVE S	MINNEAPOLIS	55488	146	2302924340071	501		WASHINGTON AVE S	MINNEAPOLIS	55415
60	2602924230039	900		CENTENNIAL PL	MINNEAPOLIS	55404	147	2602924249008	906		7TH ST S	MINNEAPOLIS	55415
61	2602924240056	810		7TH ST S	MINNEAPOLIS	55415		2602924249006	626		10TH AVE S	MINNEAPOLIS	55415
62	2602924240064	601		CHICAGO AVE	MINNEAPOLIS	55415		2602924249007	626		10TH AVE S	MINNEAPOLIS	55415

5.0 Conclusions and Recommendations

During the hydraulic analysis conducted and presented in this report:

- A calibrated model was created to simulate flow in the Central City (west of Chicago/Eighth Avenue), Chicago Avenue (along Eighth Avenue), and Eleventh Avenue tunnel systems for two separate storm events and validated using a third storm event. This calibrated model will help City staff investigate the hydraulic capacity of the stormwater tunnel systems, as well as design and implement flood mitigation measures throughout the downtown area of Minneapolis
- Pressure measurements collected in the Central City tunnel system were converted to water surface elevation for three rainfall events and were simulated with the model.
- Model calibration was evaluated based on a visual comparison to measured data, calculation of the Nash-Sutcliff coefficient, and comparison of peak water surface elevations.
- Design storms were modeled using the calibrated model for the 2-, 10- and 100-year, 24-hour Atlas 14 rainfall events using the NRCS MSE3 rainfall distribution.
- Inundation maps were created for each of the three design storms showing areas of flooding and potentially impacted buildings.
- Most of the inundation is occurring in storm sewer sections of the study area. Drill hole capacity is likely contributing to flooding as the storm sewer sections enter the main tunnel in the Central City tunnel system. Flooding in the Chicago and Eleventh Ave tunnel systems are likely caused by storm sewer pipe capacity as the larger drop shafts are used in these systems to connect to the main tunnel system.

The following recommendations are provided to the City of Minneapolis for consideration when using this model to evaluate storm sewer and tunnel systems within the study area:

- Add pressure monitoring stations at the intersection of Eleventh Avenue S. and Third Street S. and at the intersection of Washington Avenue S. and Chicago Avenue S. to determine whether the calibration assumptions used in the Central City tunnel system apply to the Chicago and Eleventh Avenue systems. An additional monitoring station could be placed at drill-hole locations (i.e., intersection of Fourth or Fifth Avenue S. and Washington Avenue S.) to assist in the calibration of these systems.
- Completing an as-built drawing of the stormwater cavern located downstream of the intersection of Washington and Portland Avenues.
- Prior to using model results for design or permitting, evaluate how water surface elevations in the I-35W system impact surface inundation near the intersection of Ninth Street S. and Chicago Avenue S.
- If the City fills void spaces/caverns adjacent to the tunnel, the model calibration should be reviewed to determine the impact that filling the void spaces has on water surface elevations within the system.

6.0 References

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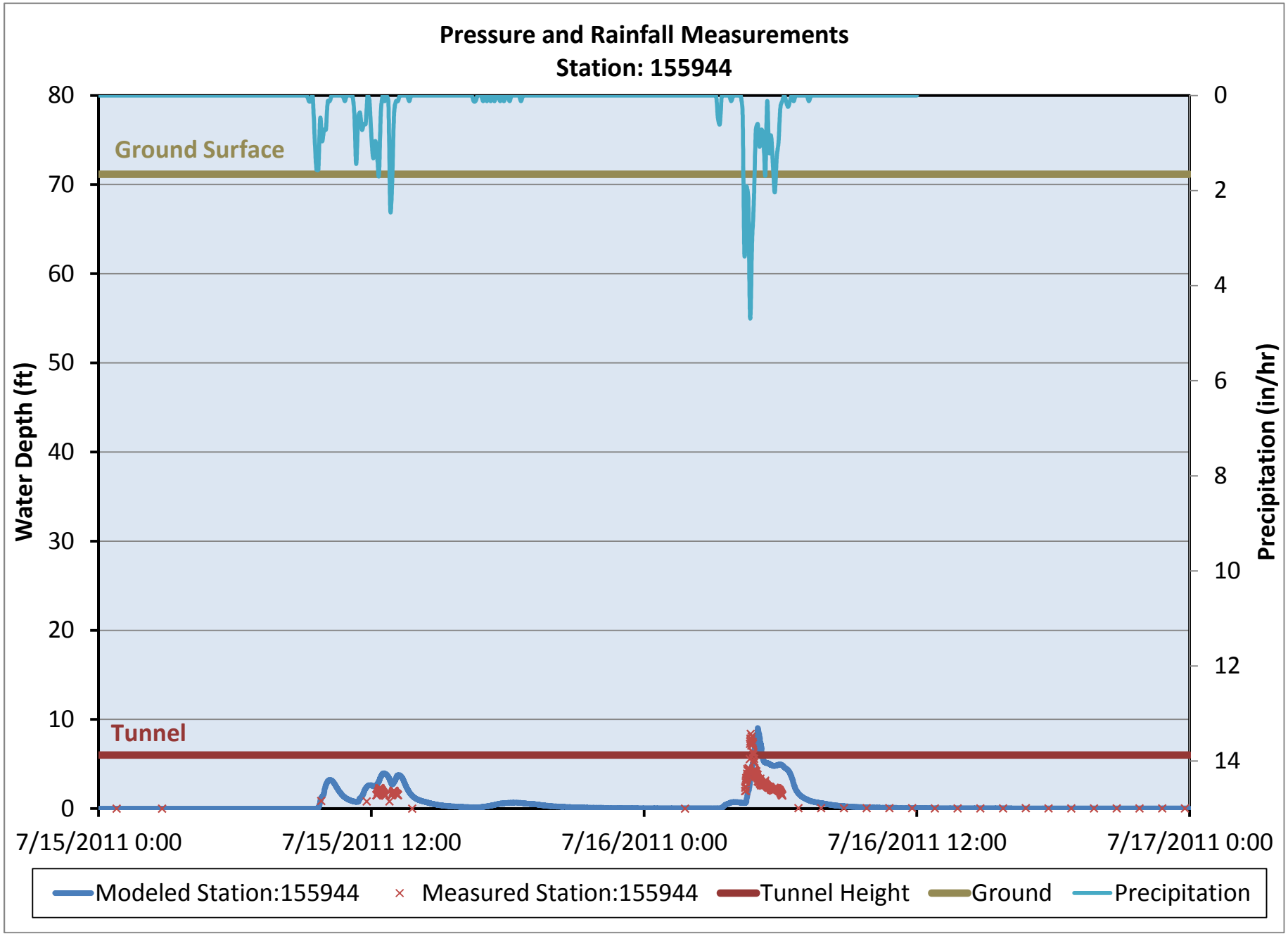
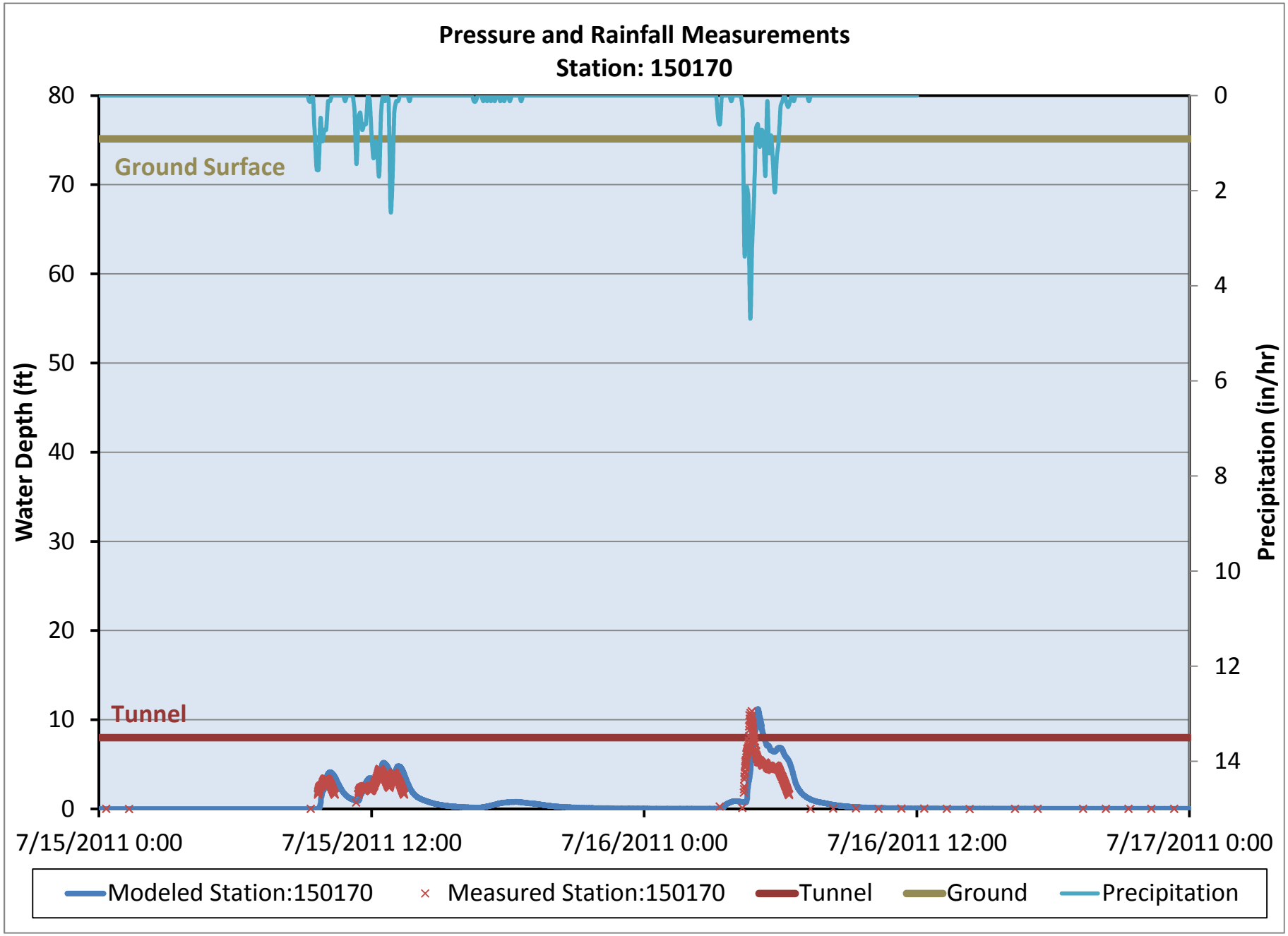
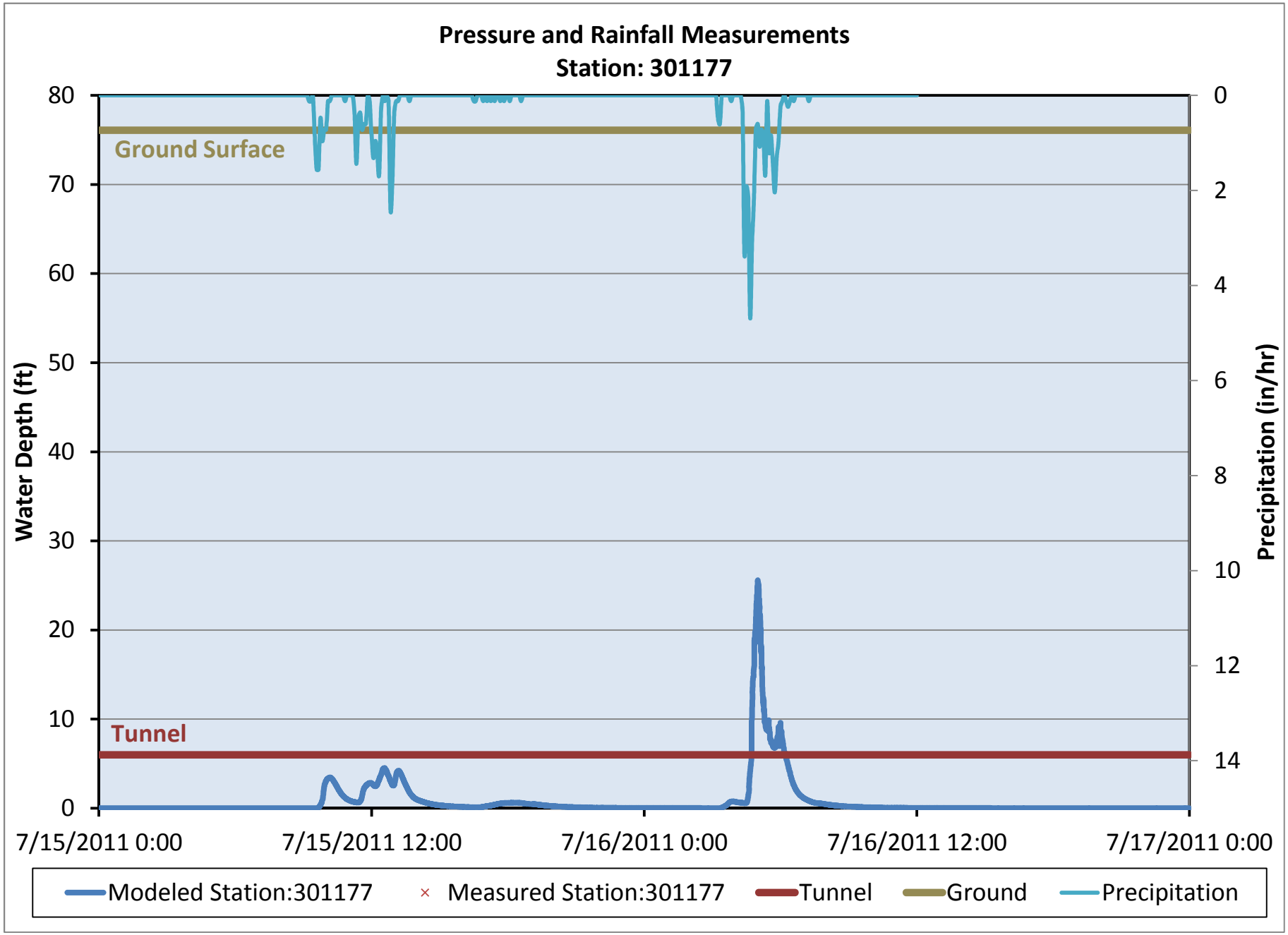
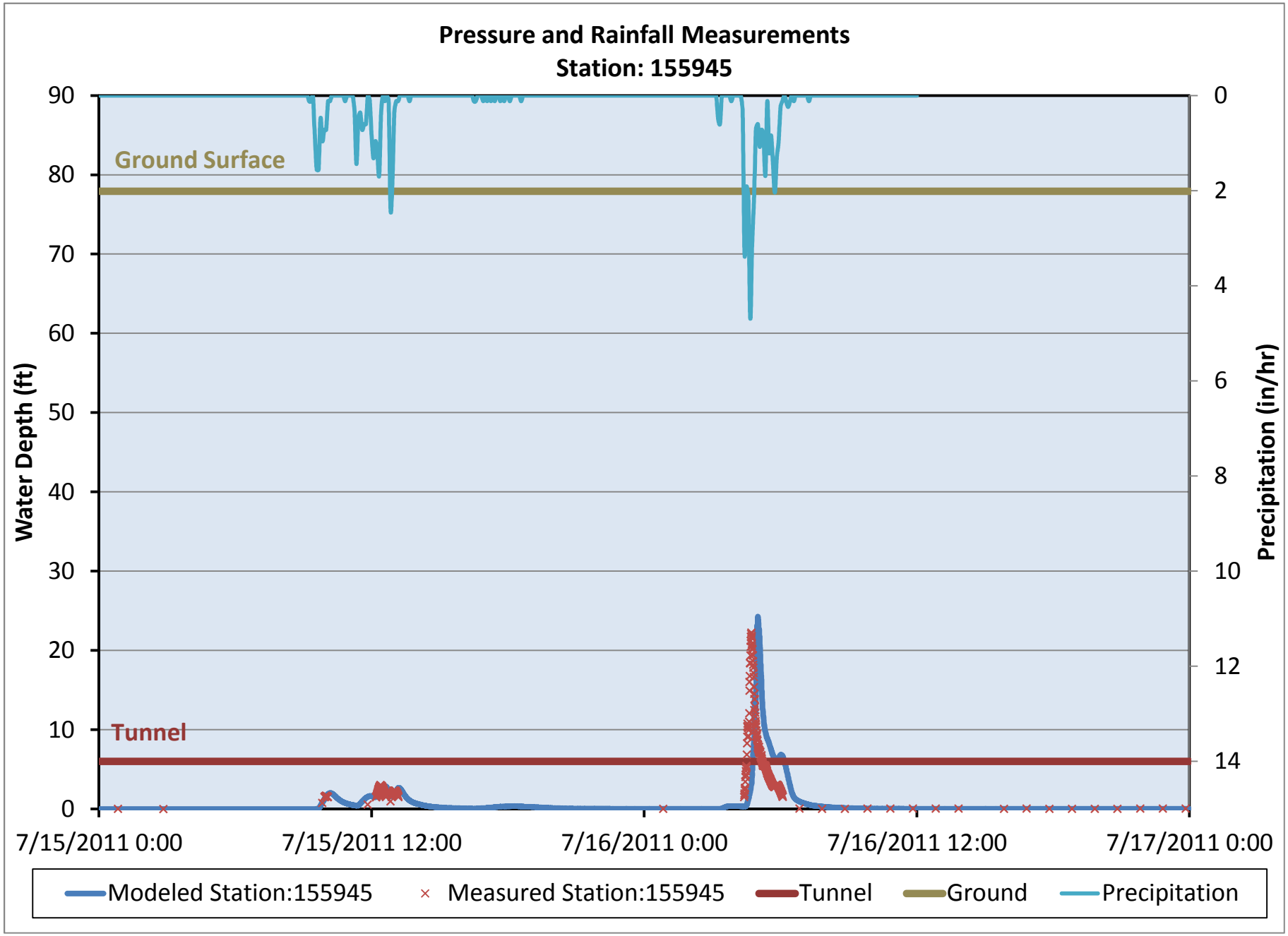
Appendix A

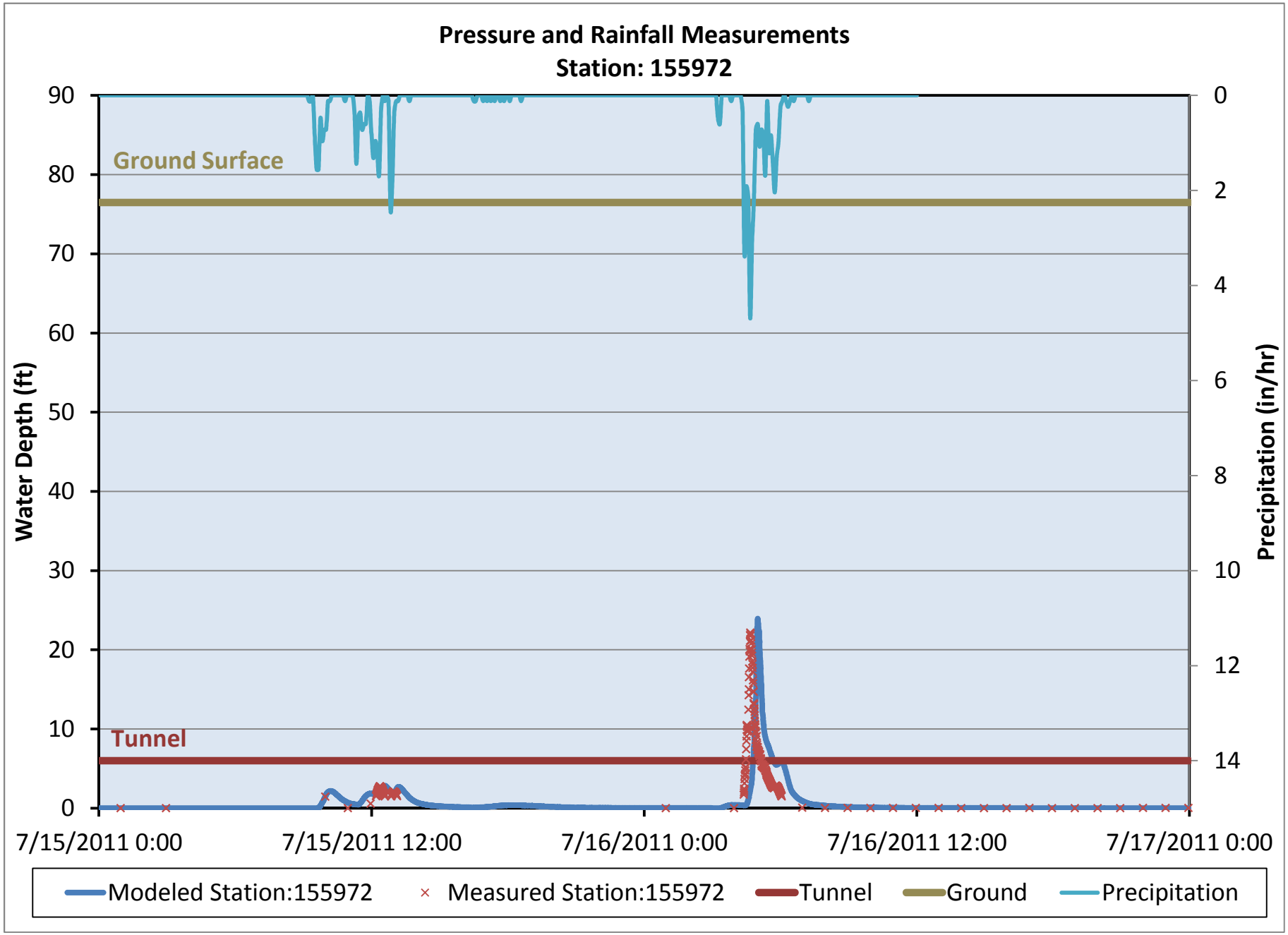
Model Calibration:
Comparison between Modeled and Monitored Results


Pressure and Rainfall Measurements
Station: 155944
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:155944
Measured Station:155944
Tunnel Height
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 150170
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:150170
Measured Station:150170
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301177
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:301177
Measured Station:301177
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155945
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:155945
Measured Station:155945
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155972
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
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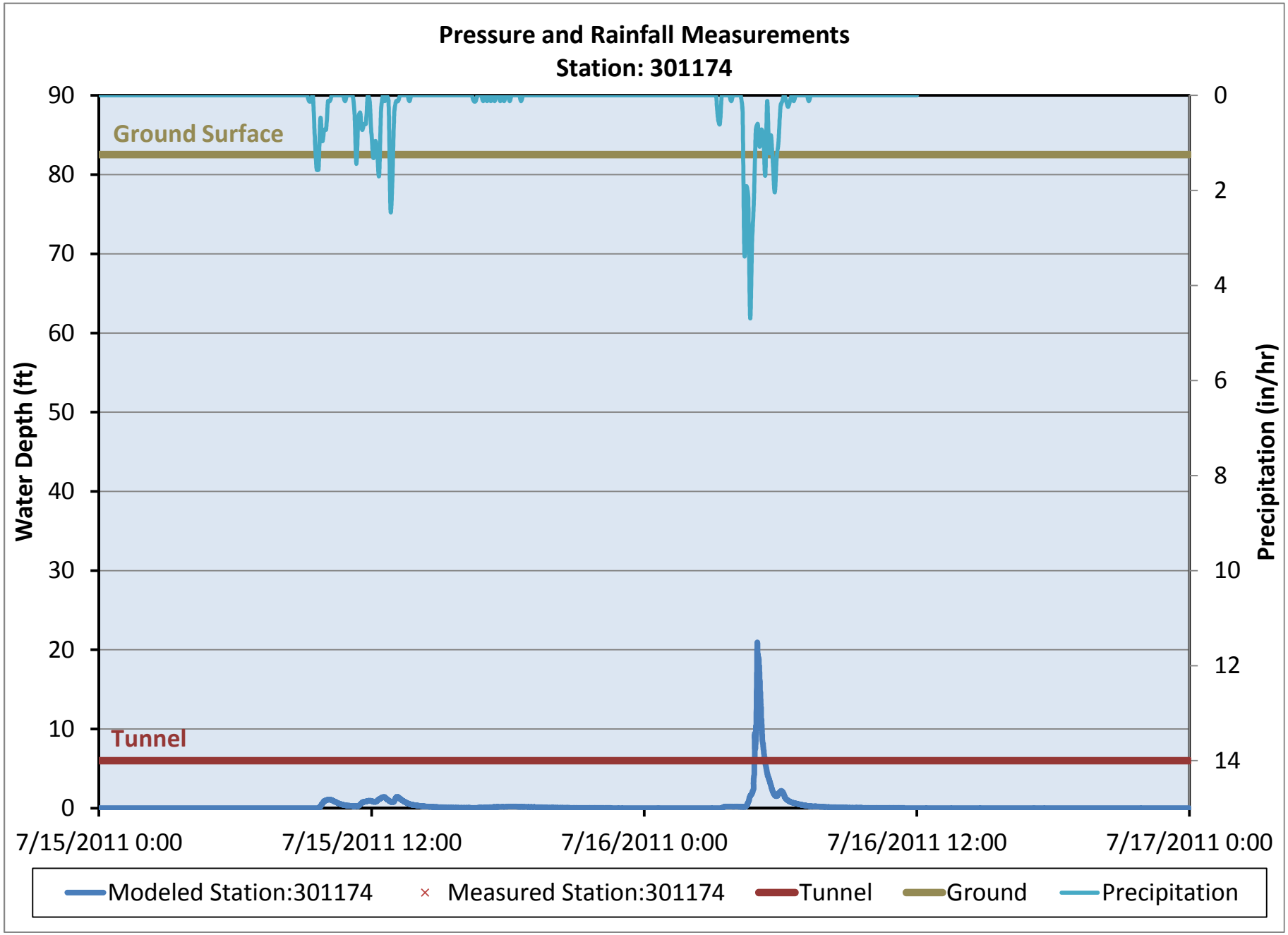
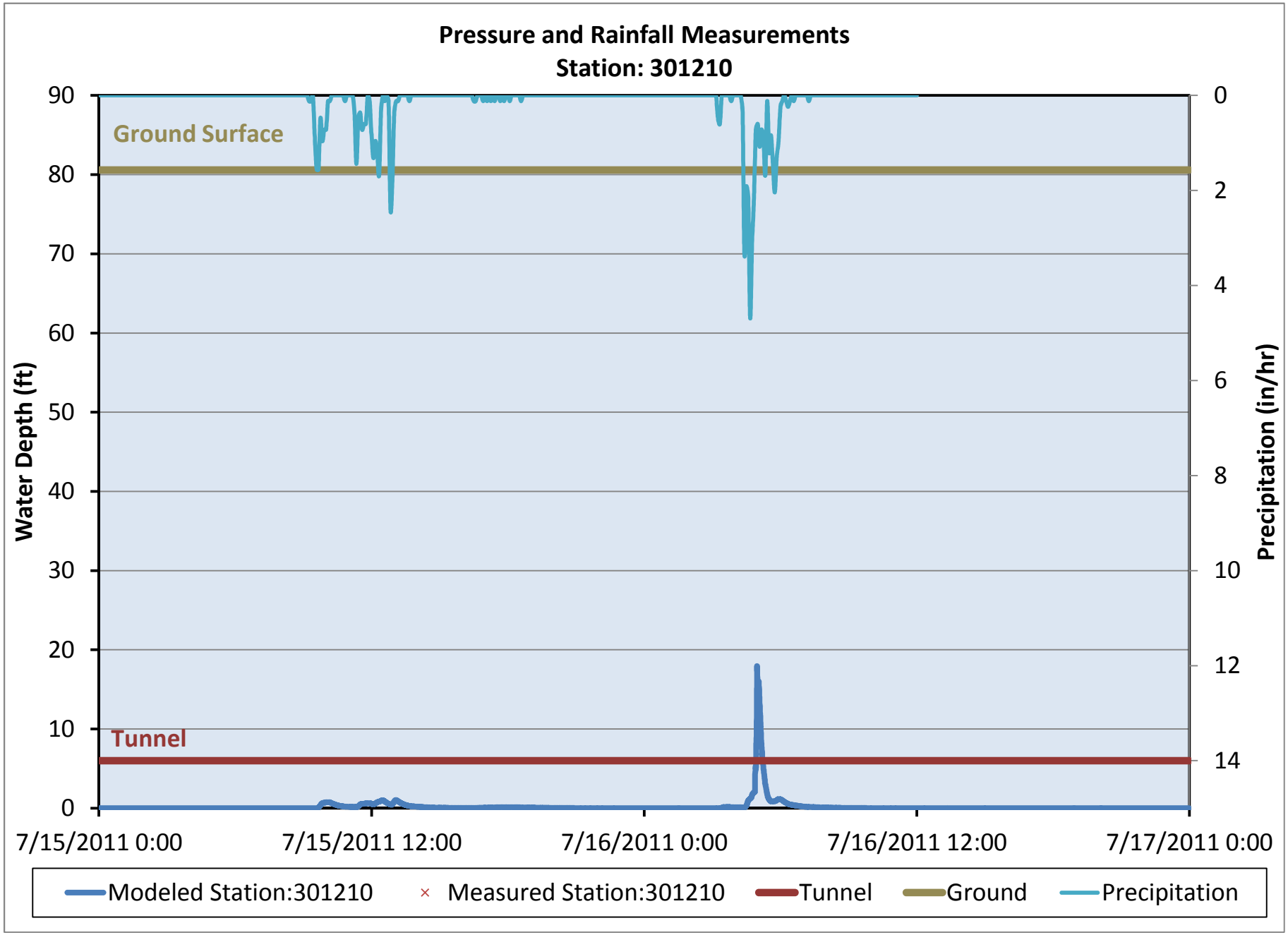
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:155972
Measured Station:155972
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301174
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:301174
Measured Station:301174
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301210
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
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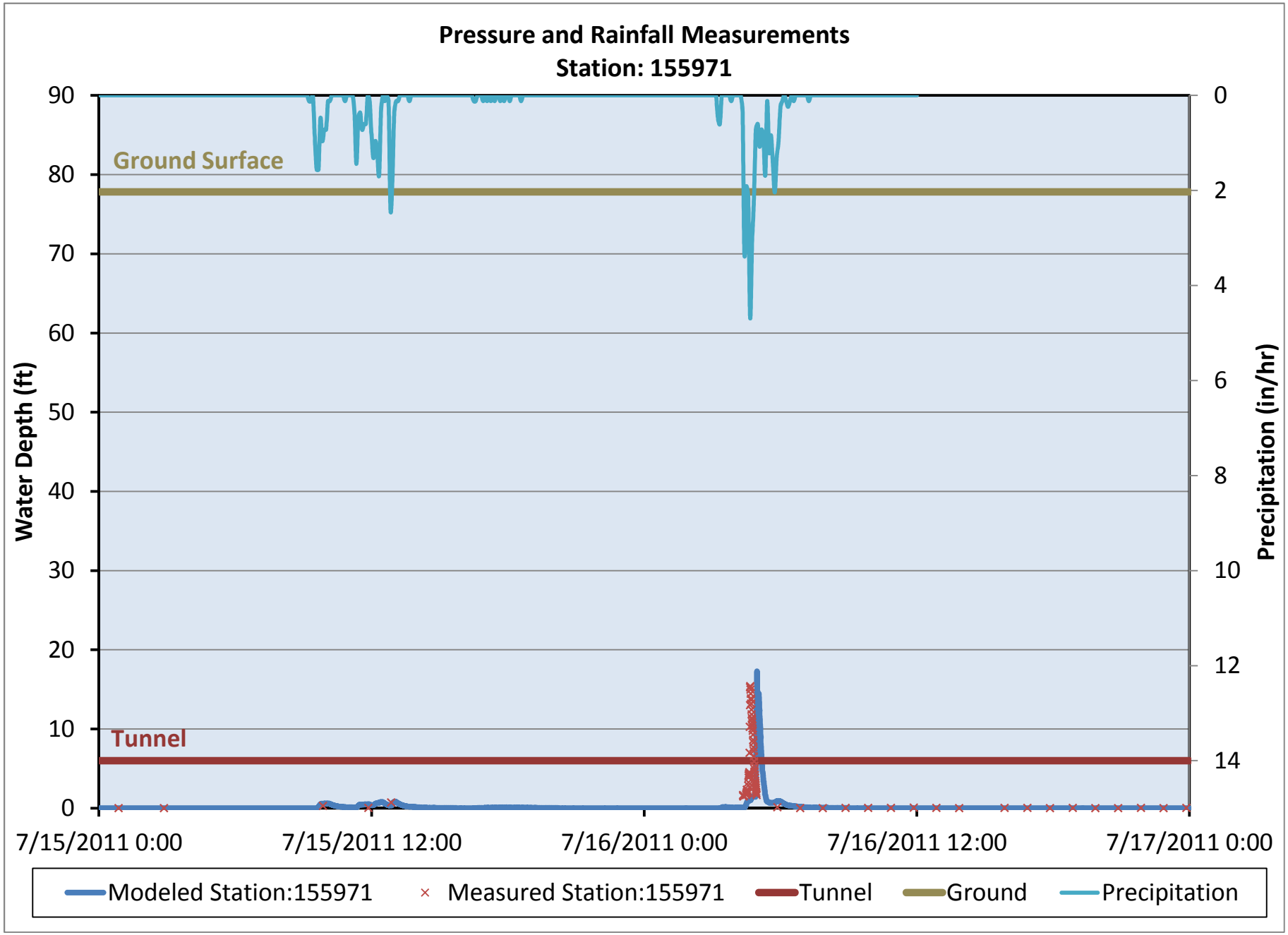
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:301210
Measured Station:301210
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155971
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
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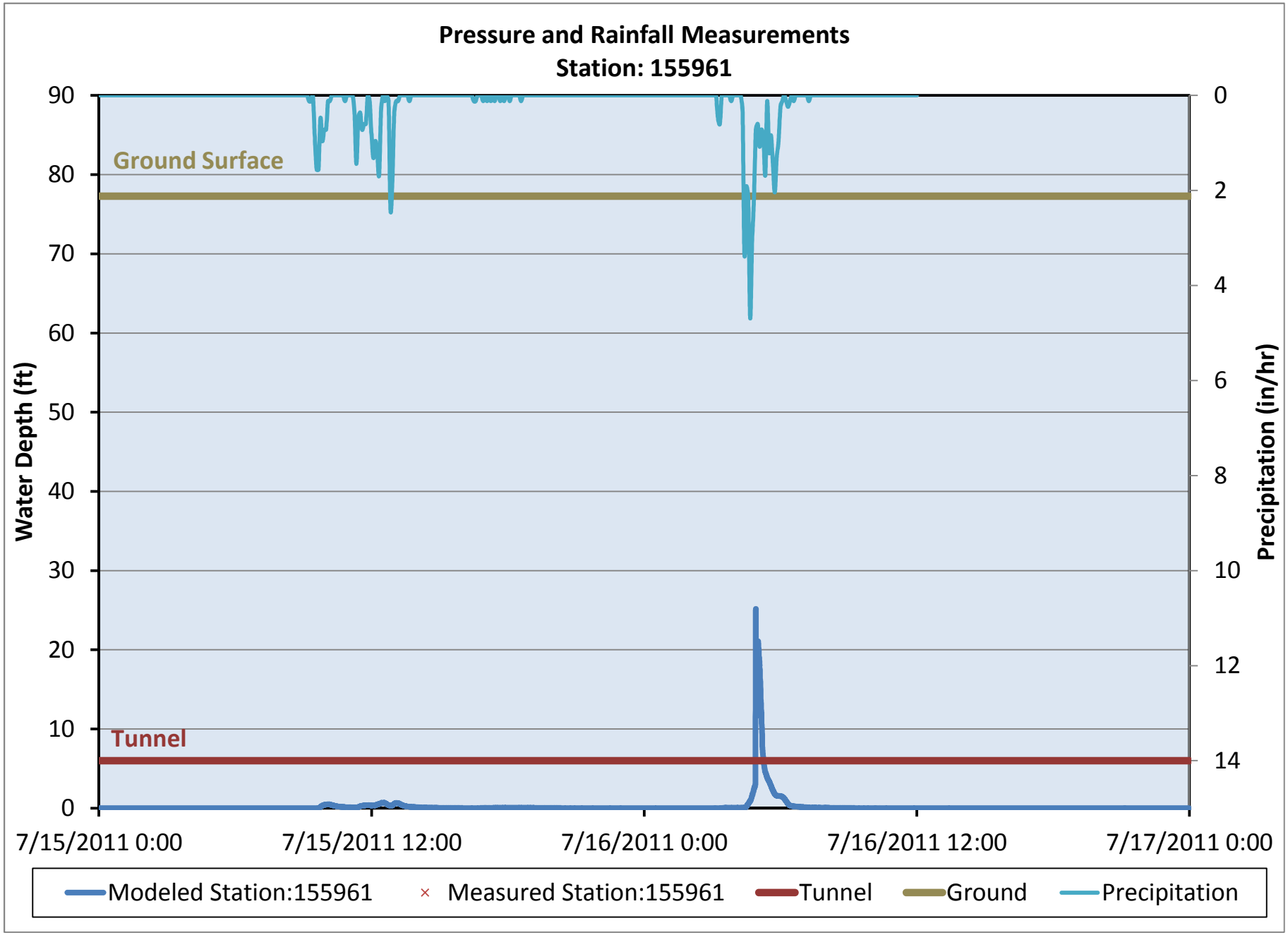
7/17/2011 0:00
Modeled Station:155971
Measured Station:155971
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155961
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
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60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
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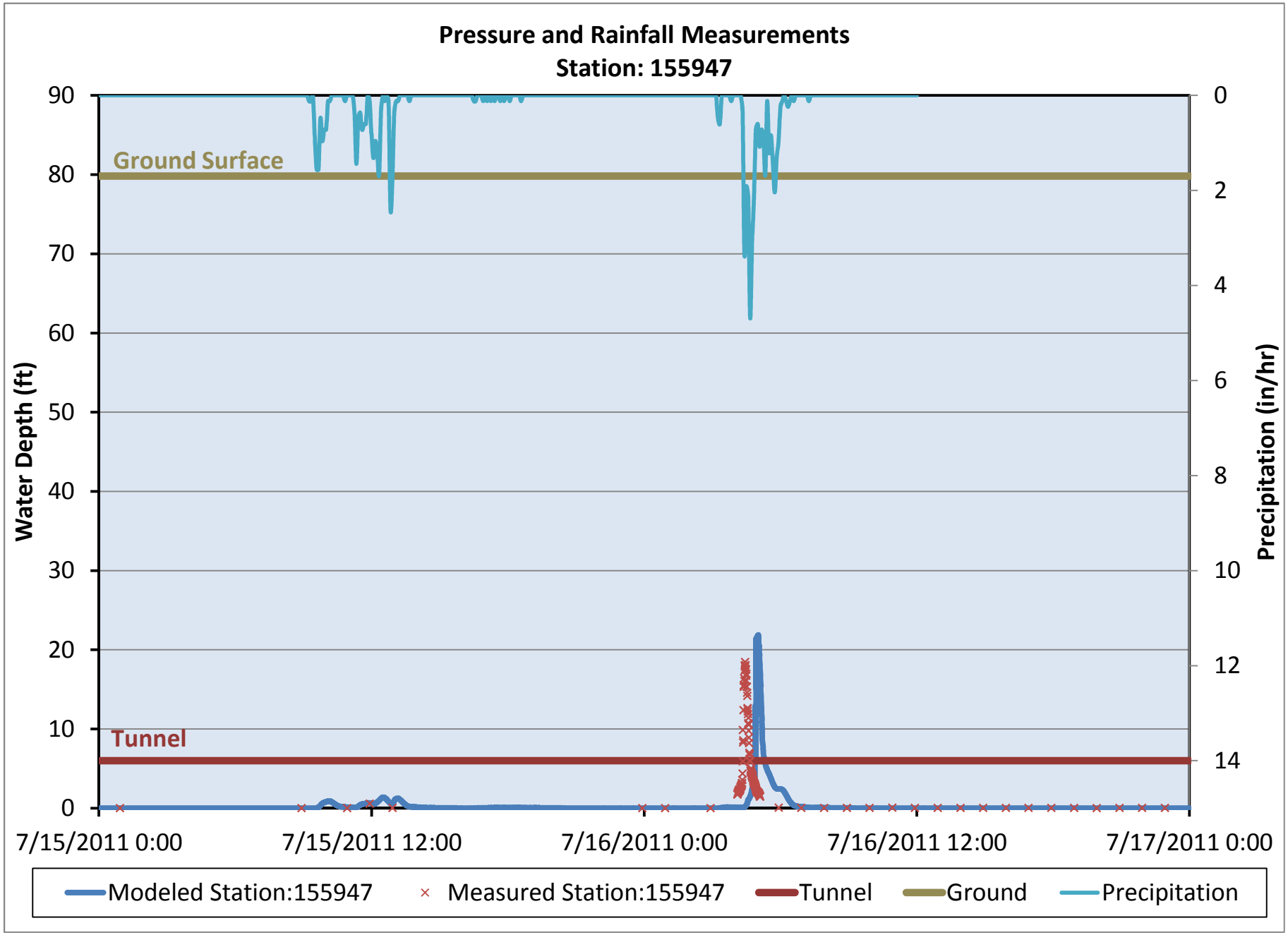
7/17/2011 0:00
Modeled Station:155961
Measured Station:155961
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155947
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
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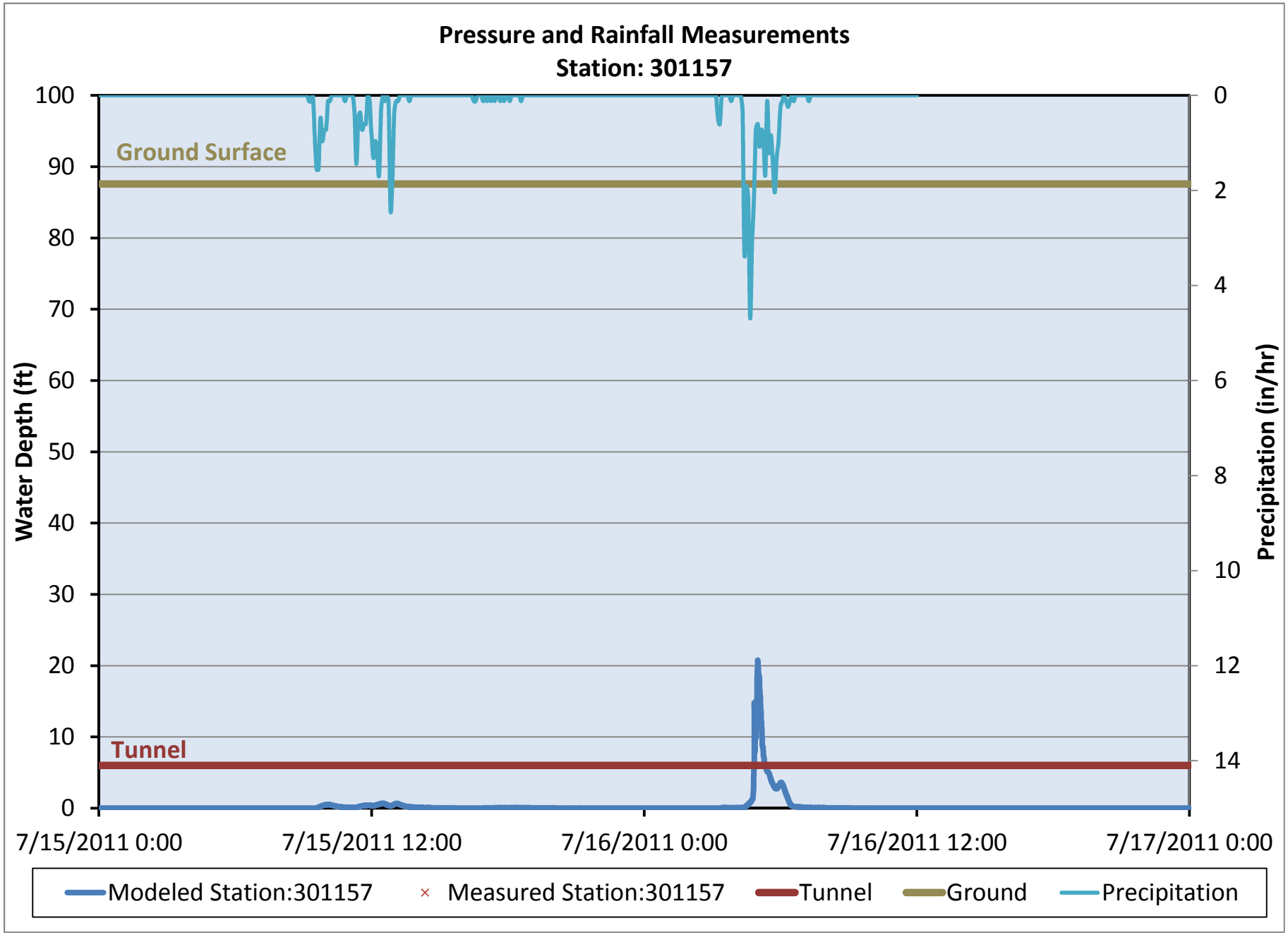
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:155947
Measured Station:155947
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301157
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
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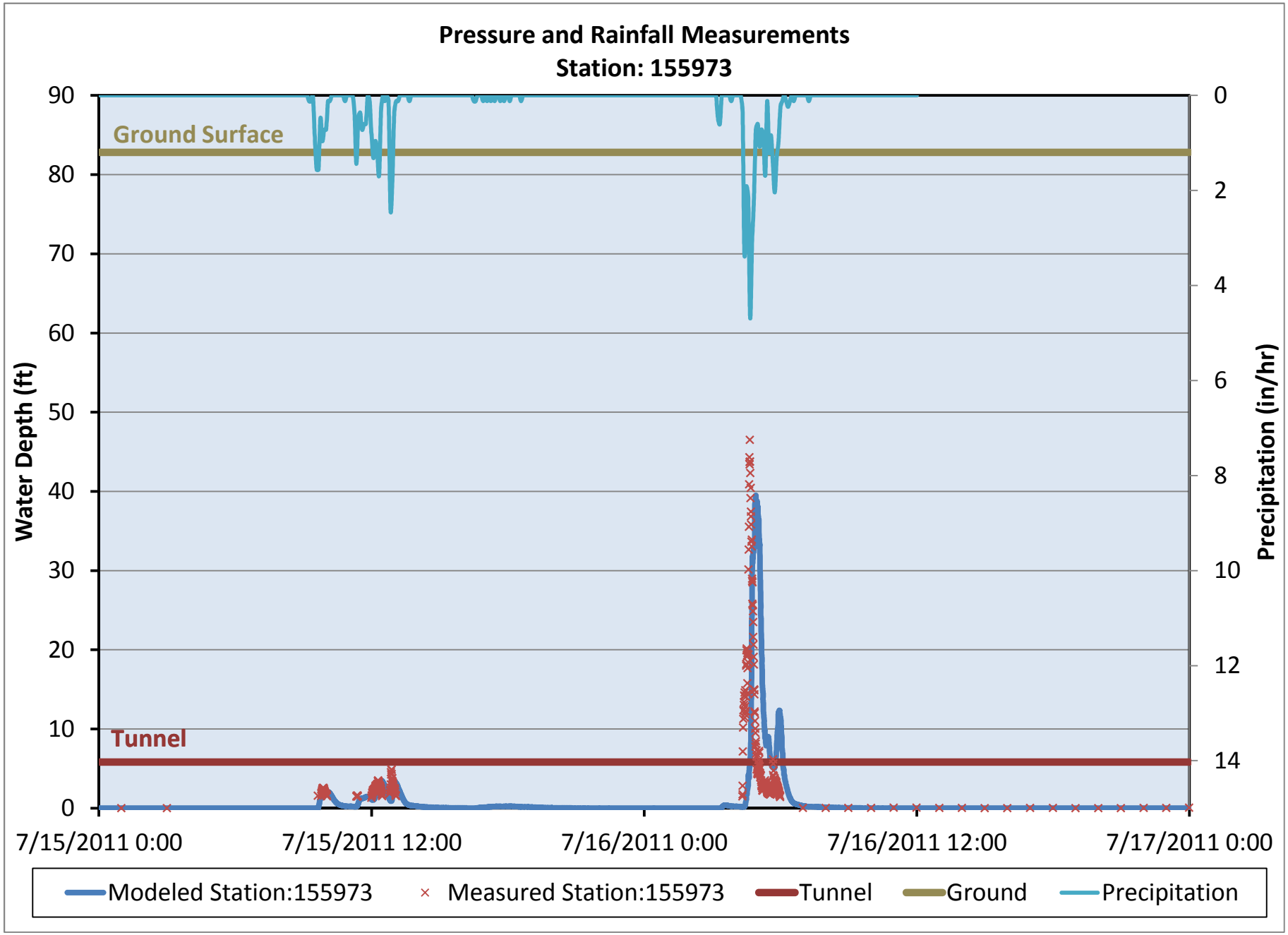
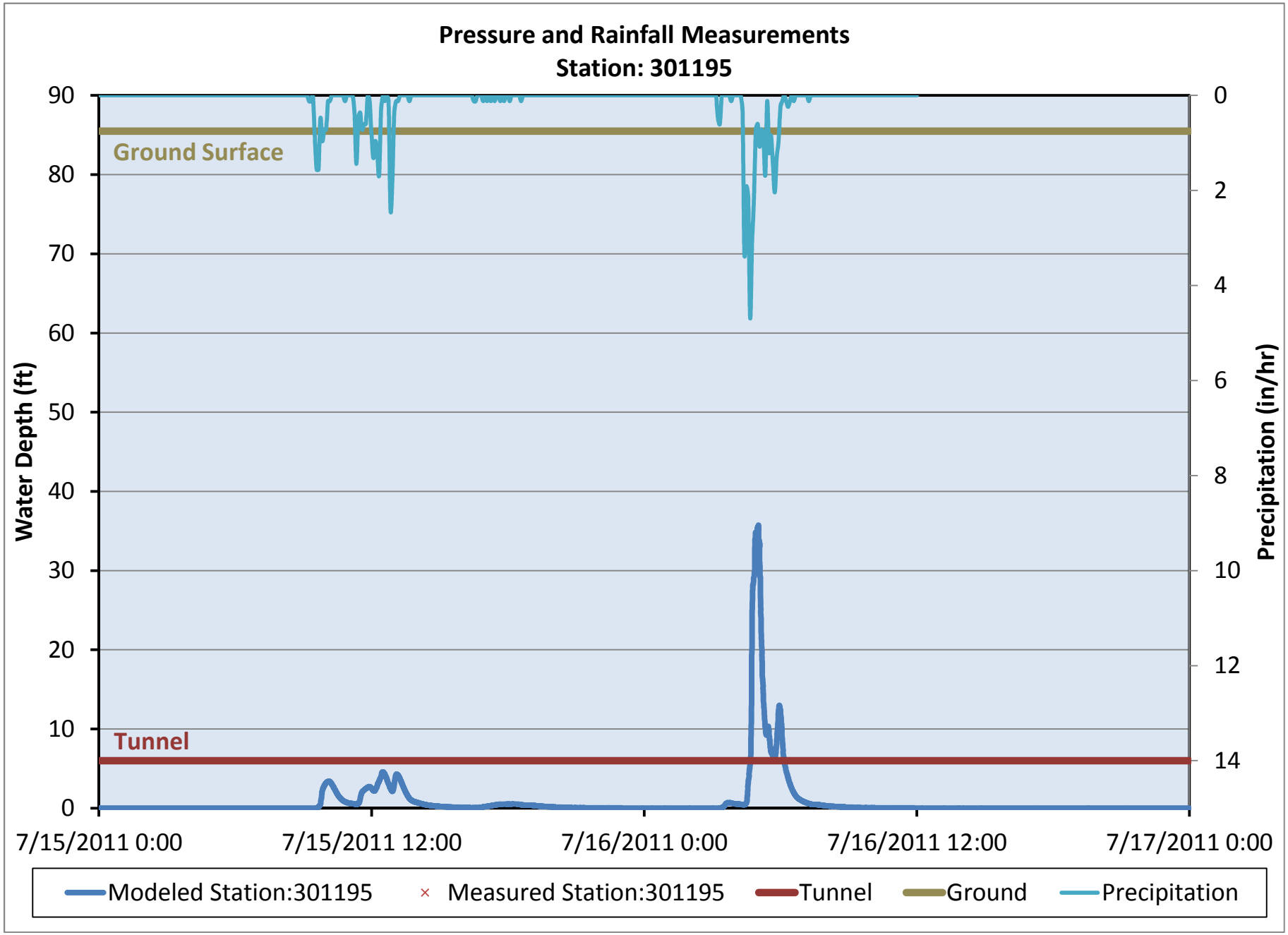
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:301157
Measured Station:301157
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155973
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:155973
Measured Station:155973
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301195
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
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80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
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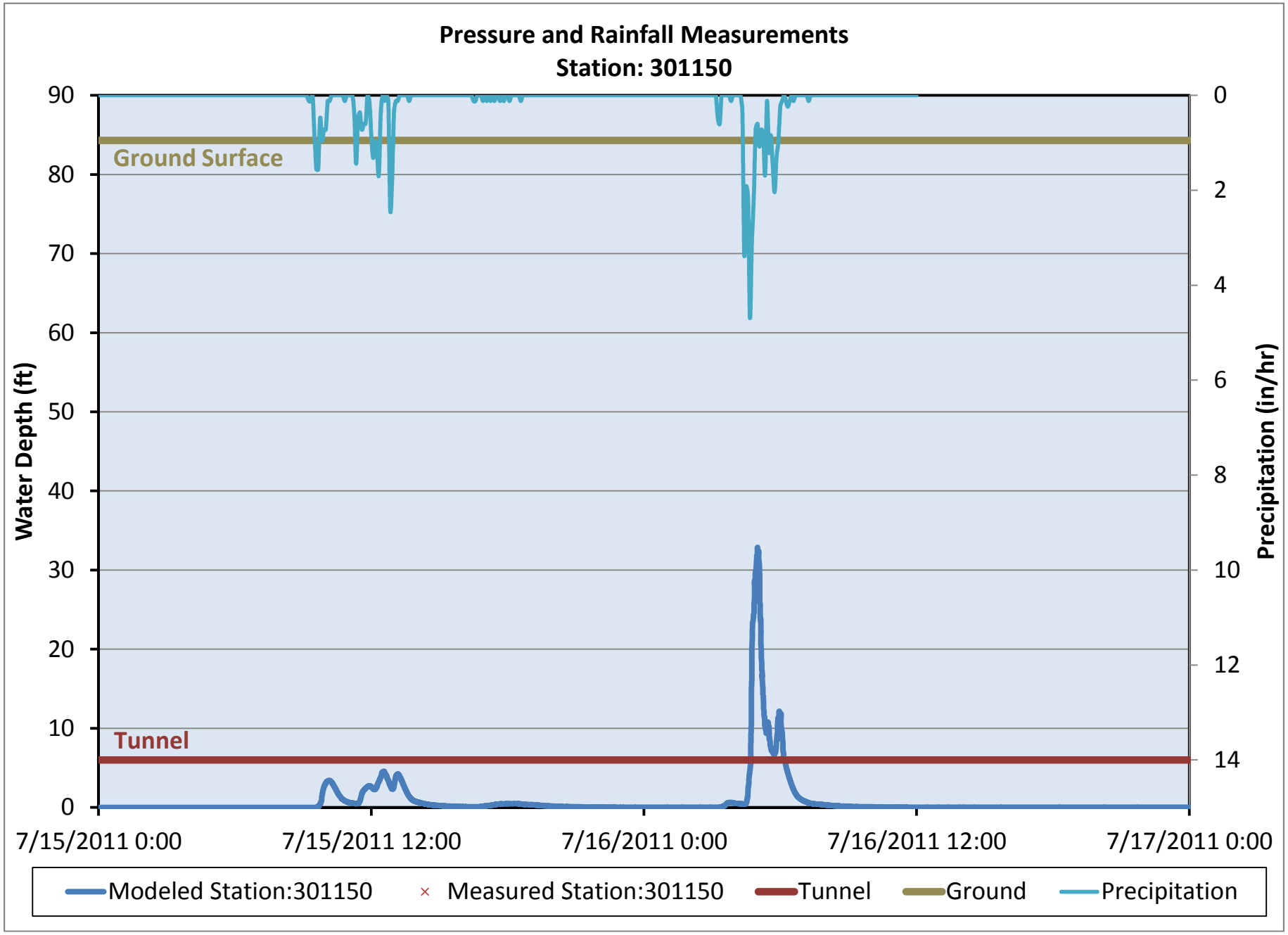
7/16/2011 12:00
7/17/2011 0:00
Modeled Station:301195
Measured Station:301195
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301150
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
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60
50
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30
20
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0
0
2
4
6
8
10
12
14
7/15/2011 0:00
7/15/2011 12:00
7/16/2011 0:00
7/16/2011 12:00
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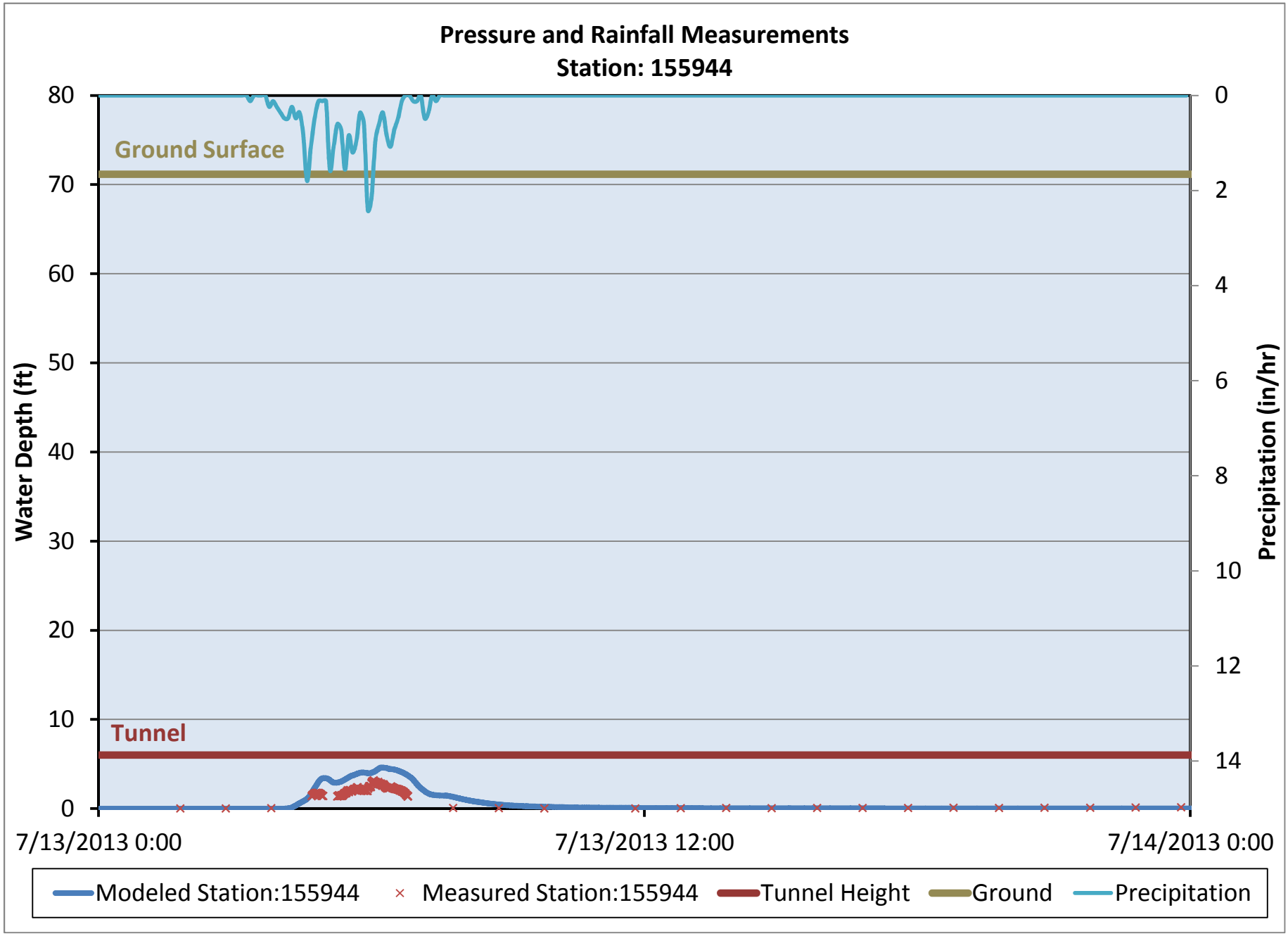
Modeled Station:301150
Measured Station:301150
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155944
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
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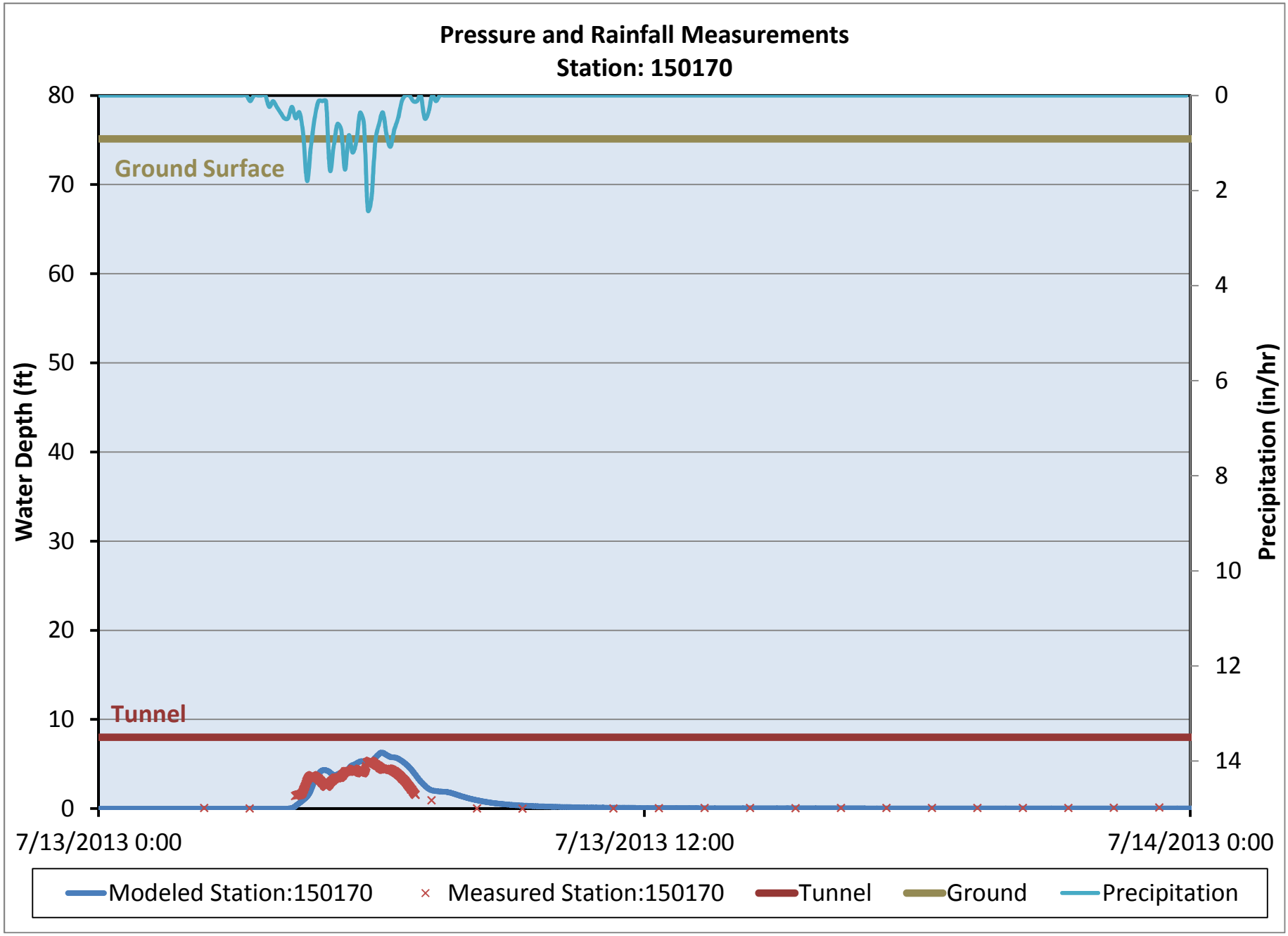
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:155944
Measured Station:155944
Tunnel Height
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 150170
Water Depth (ft)
Precipitation (in/hr)
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70
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50
40
30
20
10
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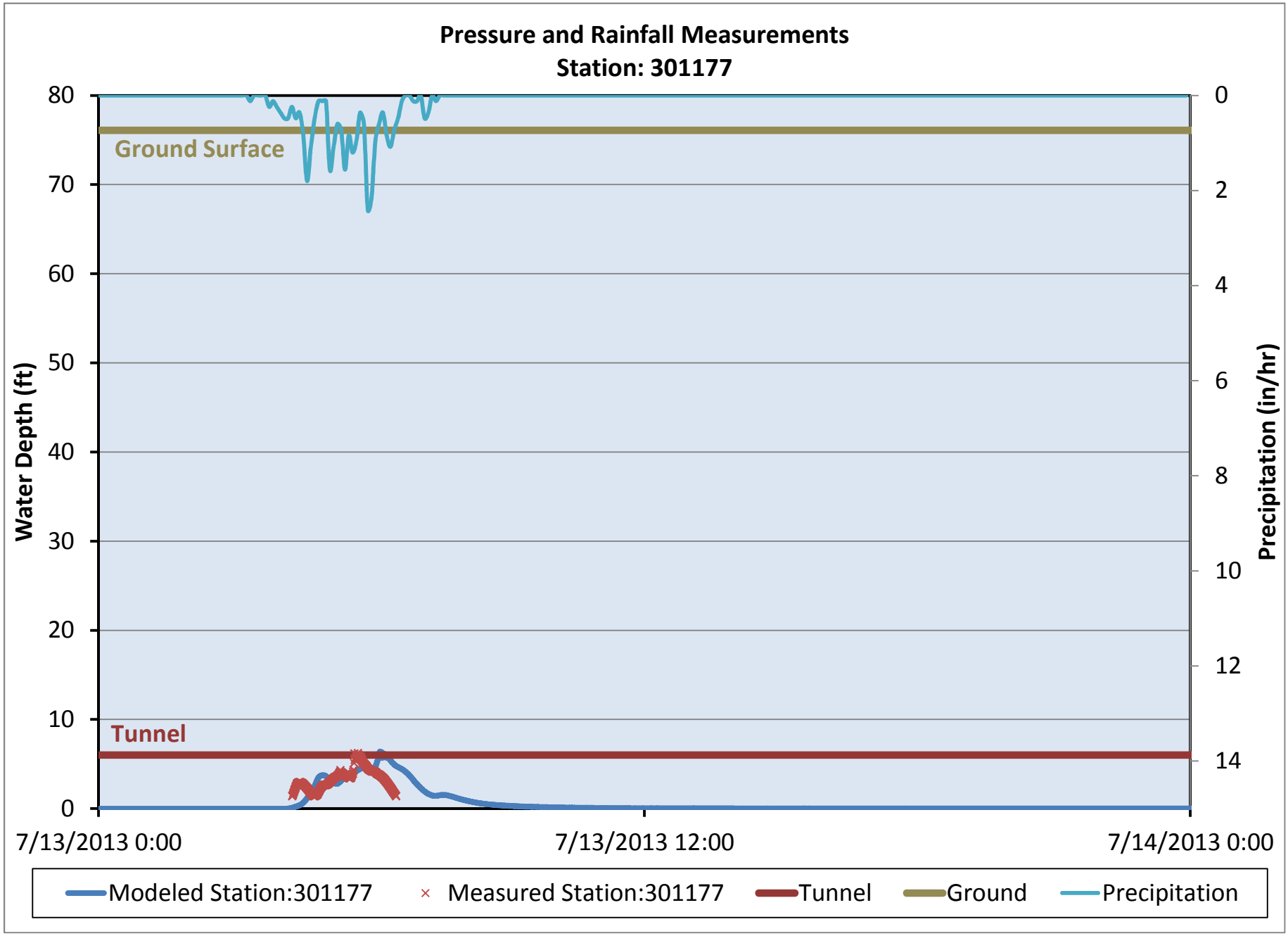
6
8
10
12
14
Ground Surface
Tunnel
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:150170
Measured Station:150170
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301177
Water Depth (ft)
Precipitation (in/hr)
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70
60
50
40
30
20
10
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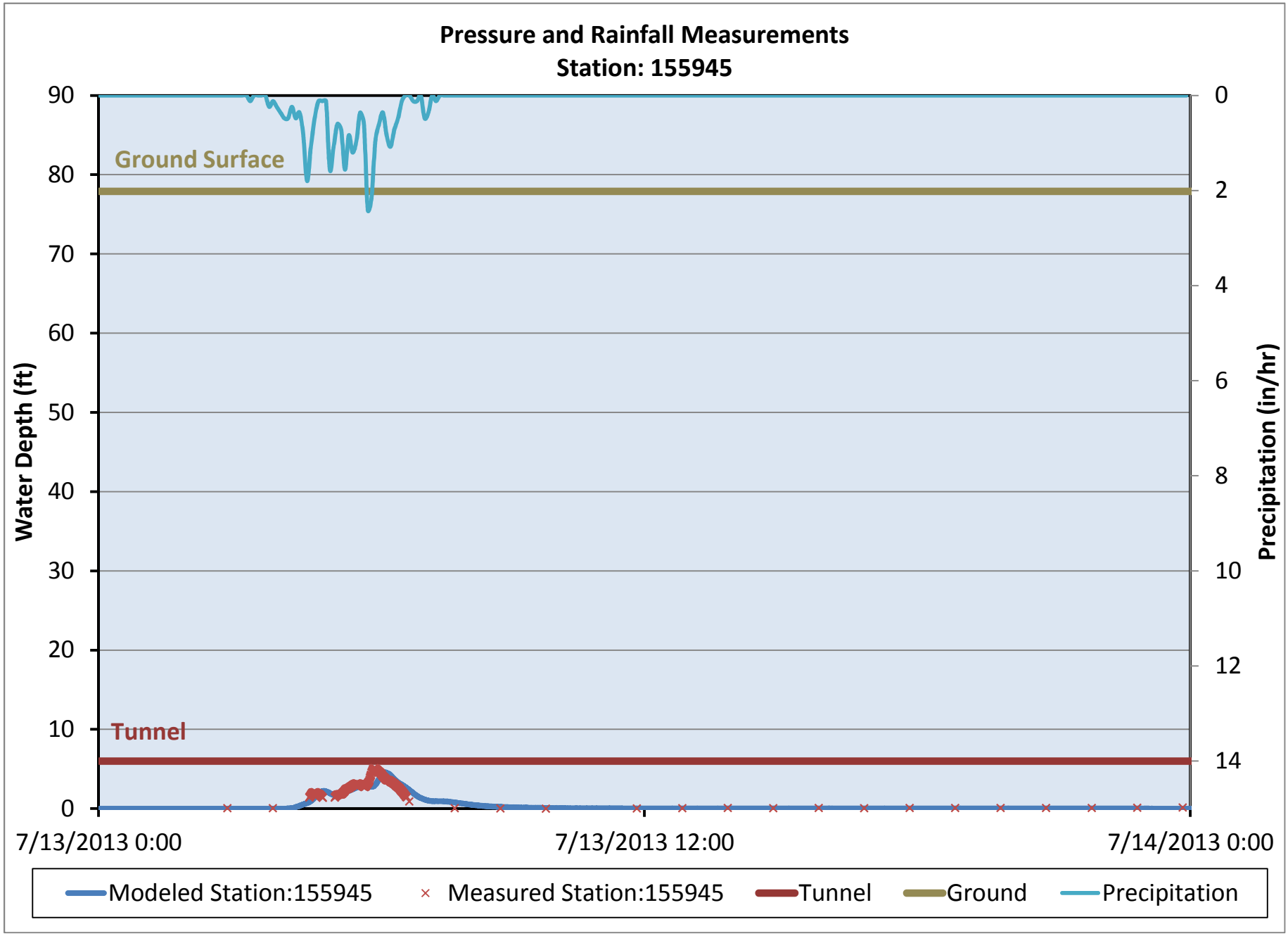
0
2
4
6
8
10
12
14
Ground Surface
Tunnel
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:301177
Measured Station:301177
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155945
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
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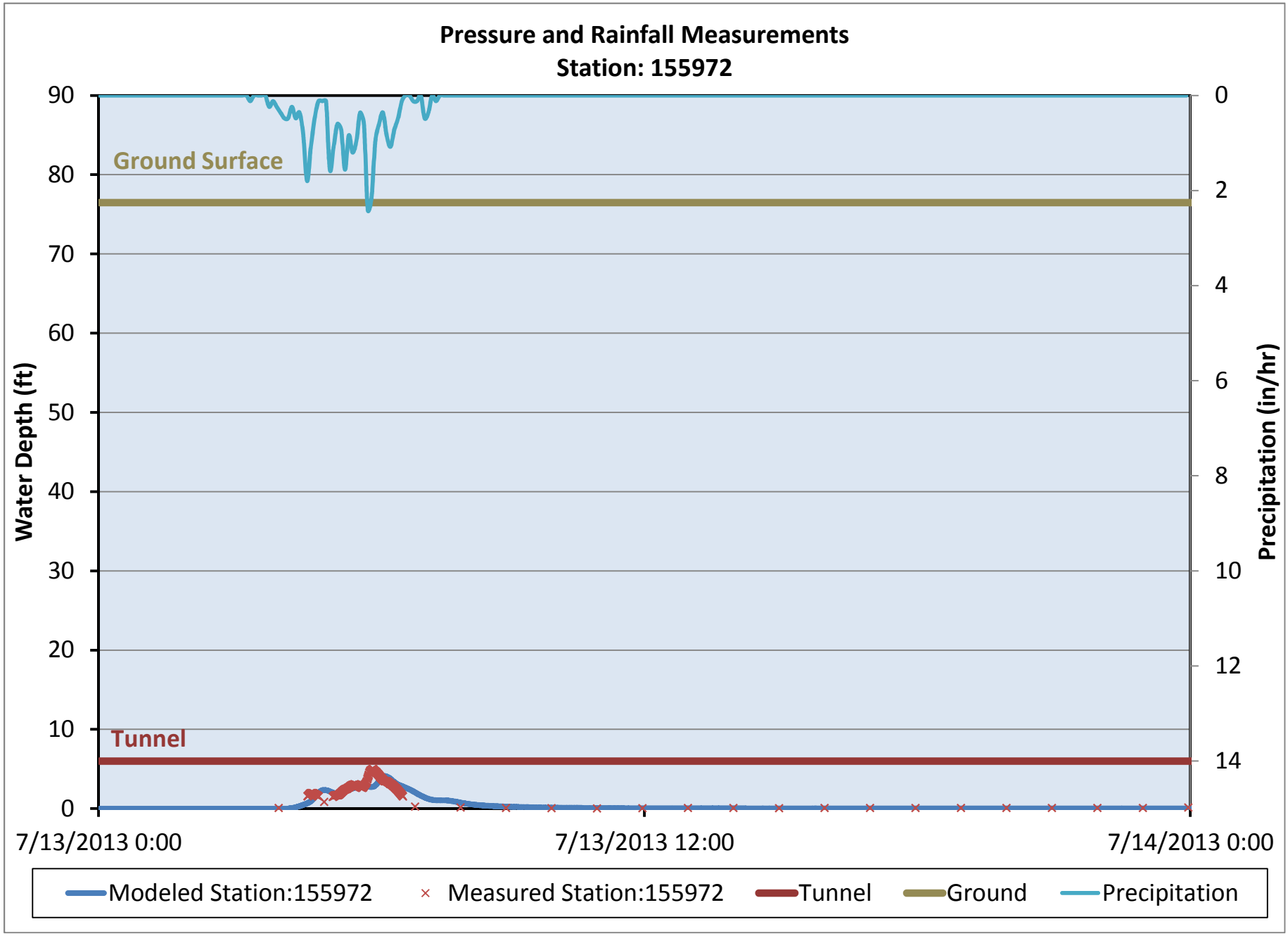
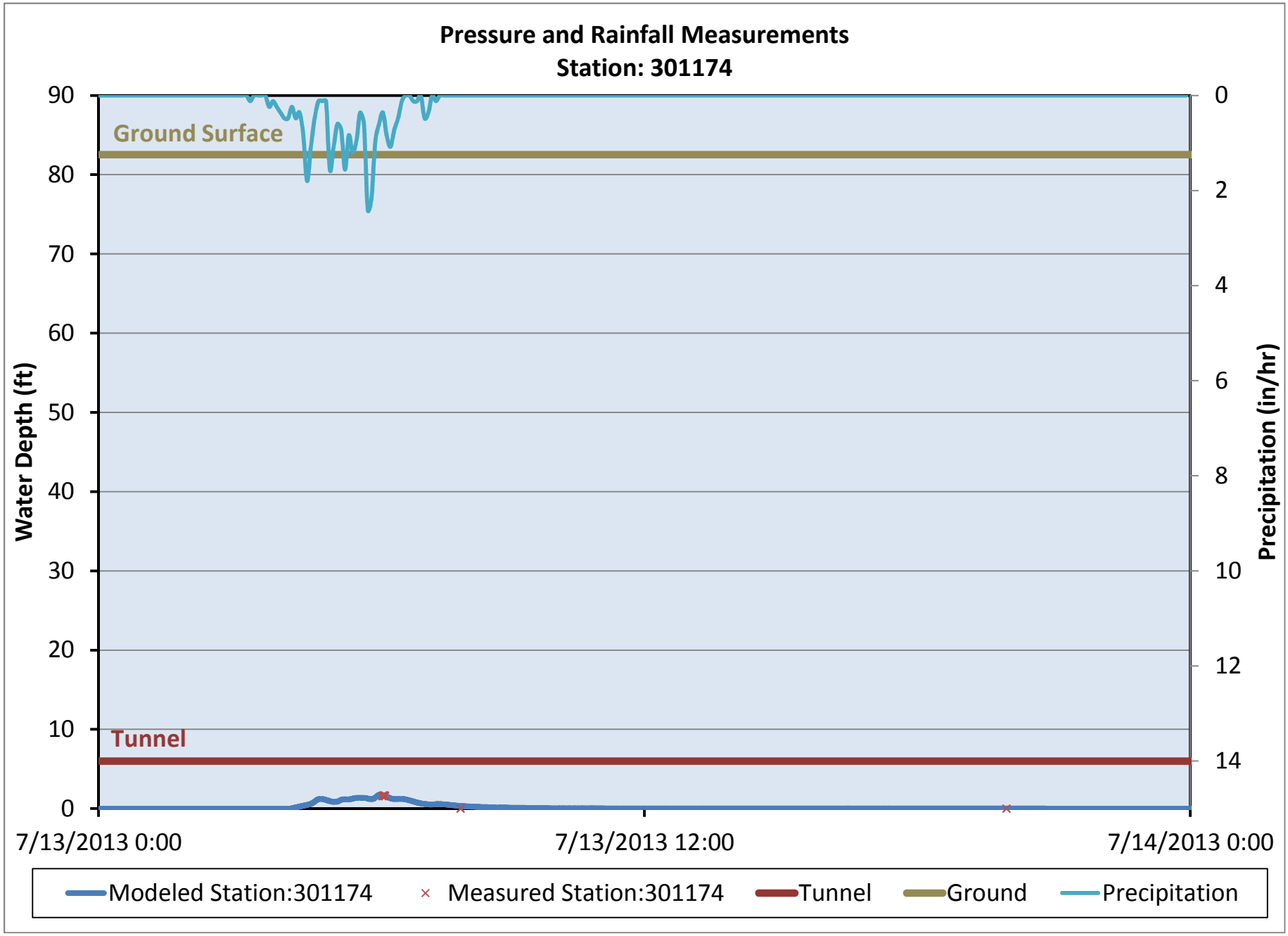
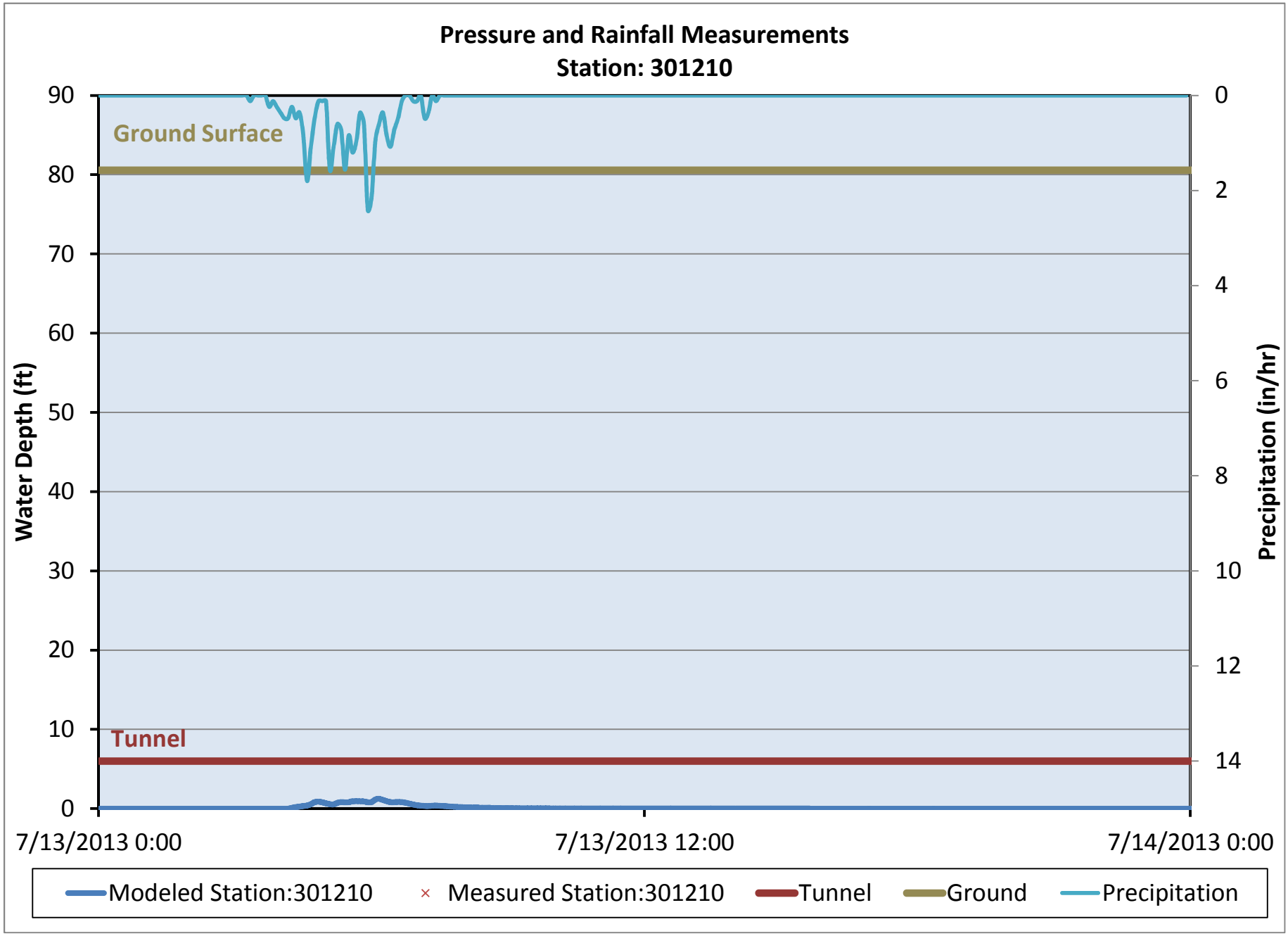
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:155945
Measured Station:155945
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155972
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
Ground Surface
Tunnel
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:155972
Measured Station:155972
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301174
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:301174
Measured Station:301174
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301210
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
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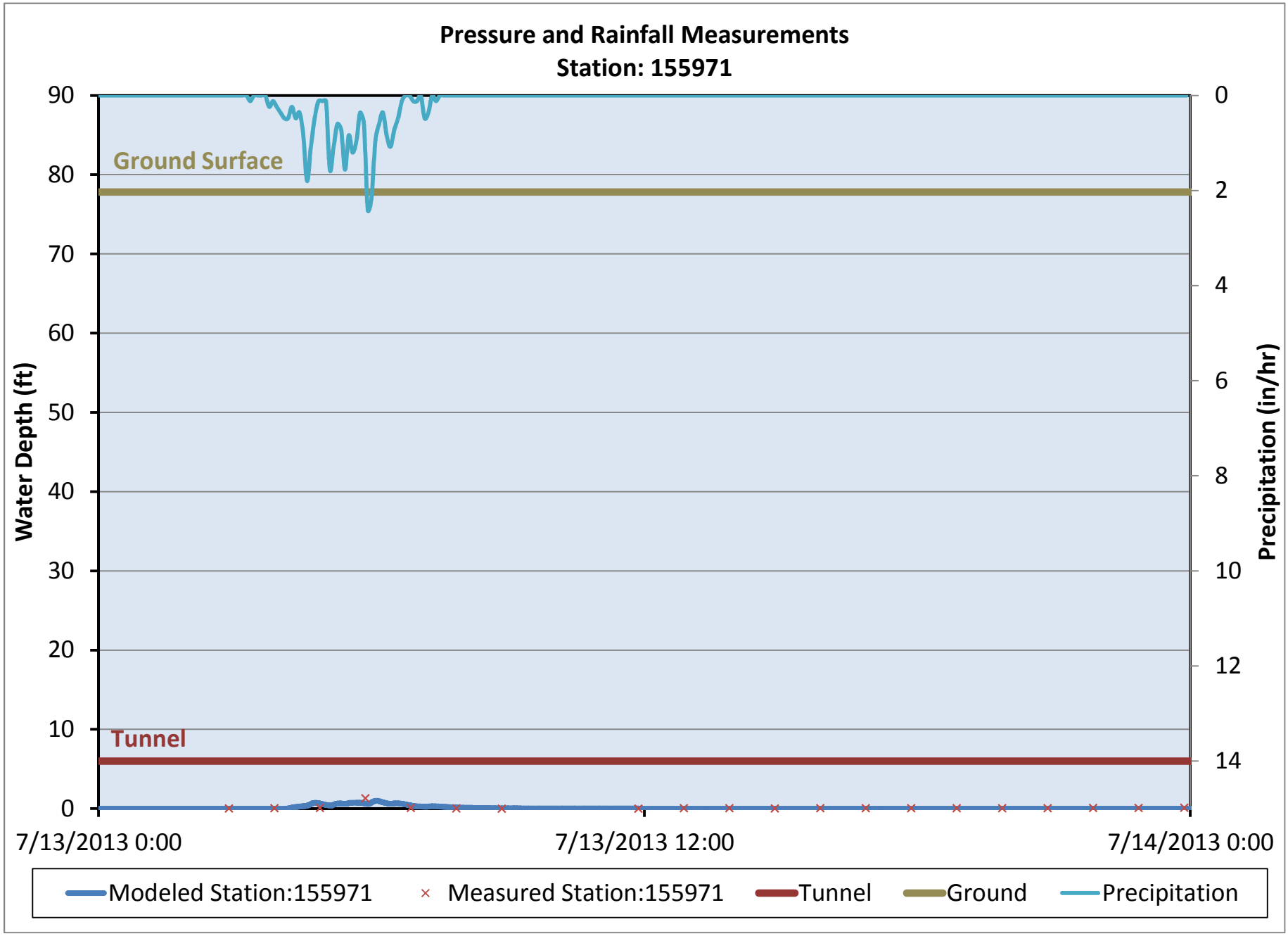
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:301210
Measured Station:301210
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
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Precipitation (in/hr)
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80
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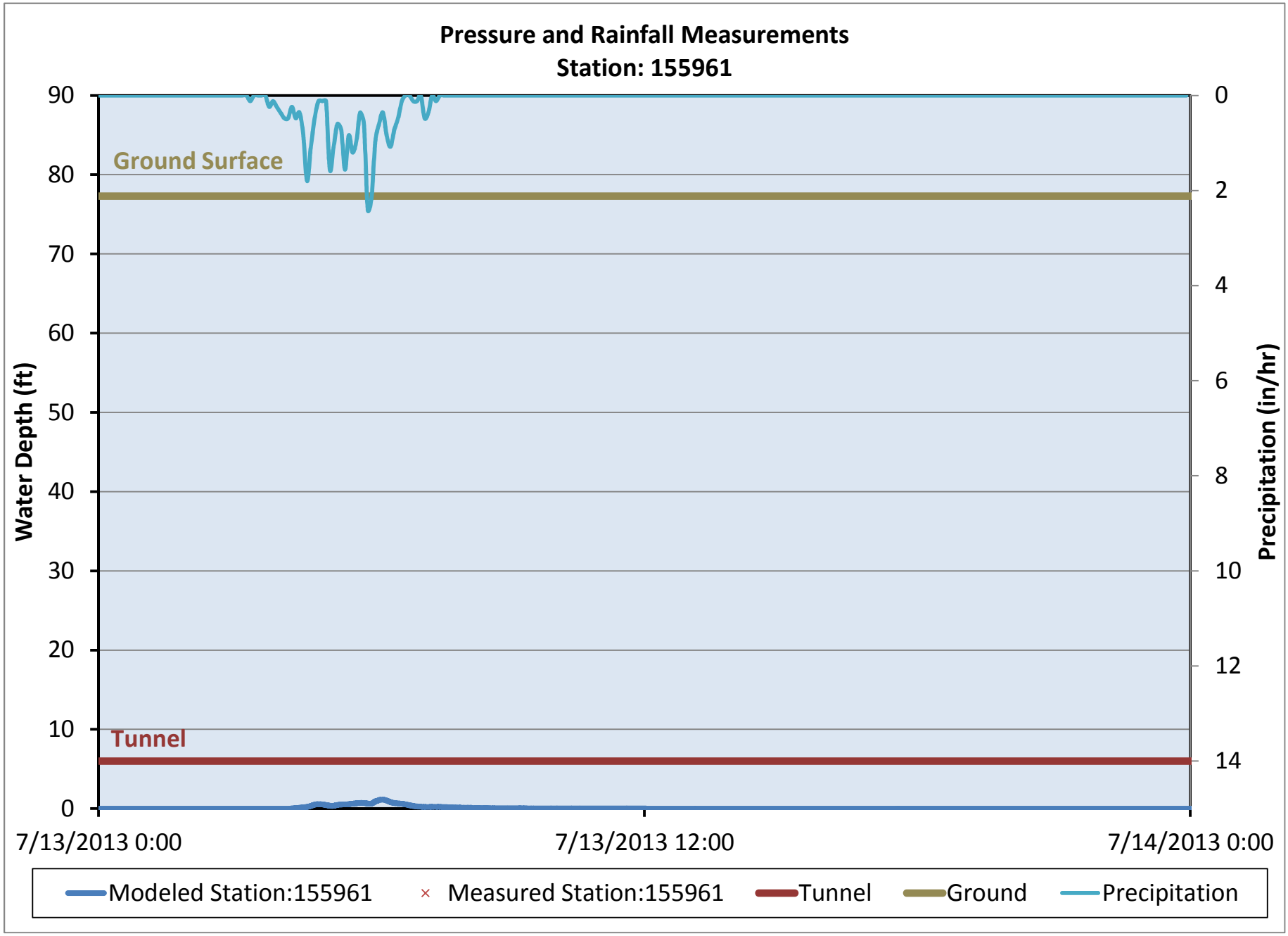
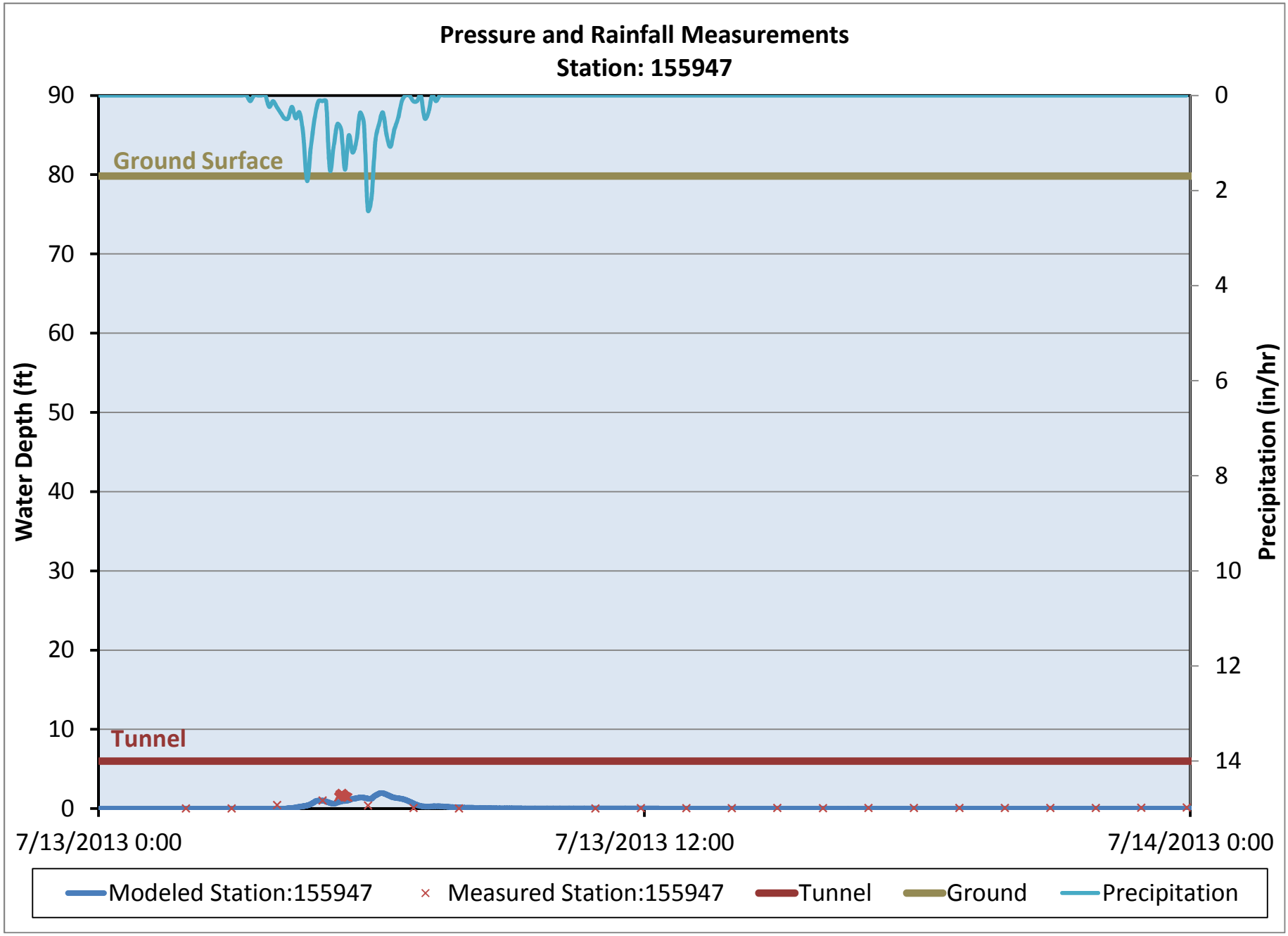
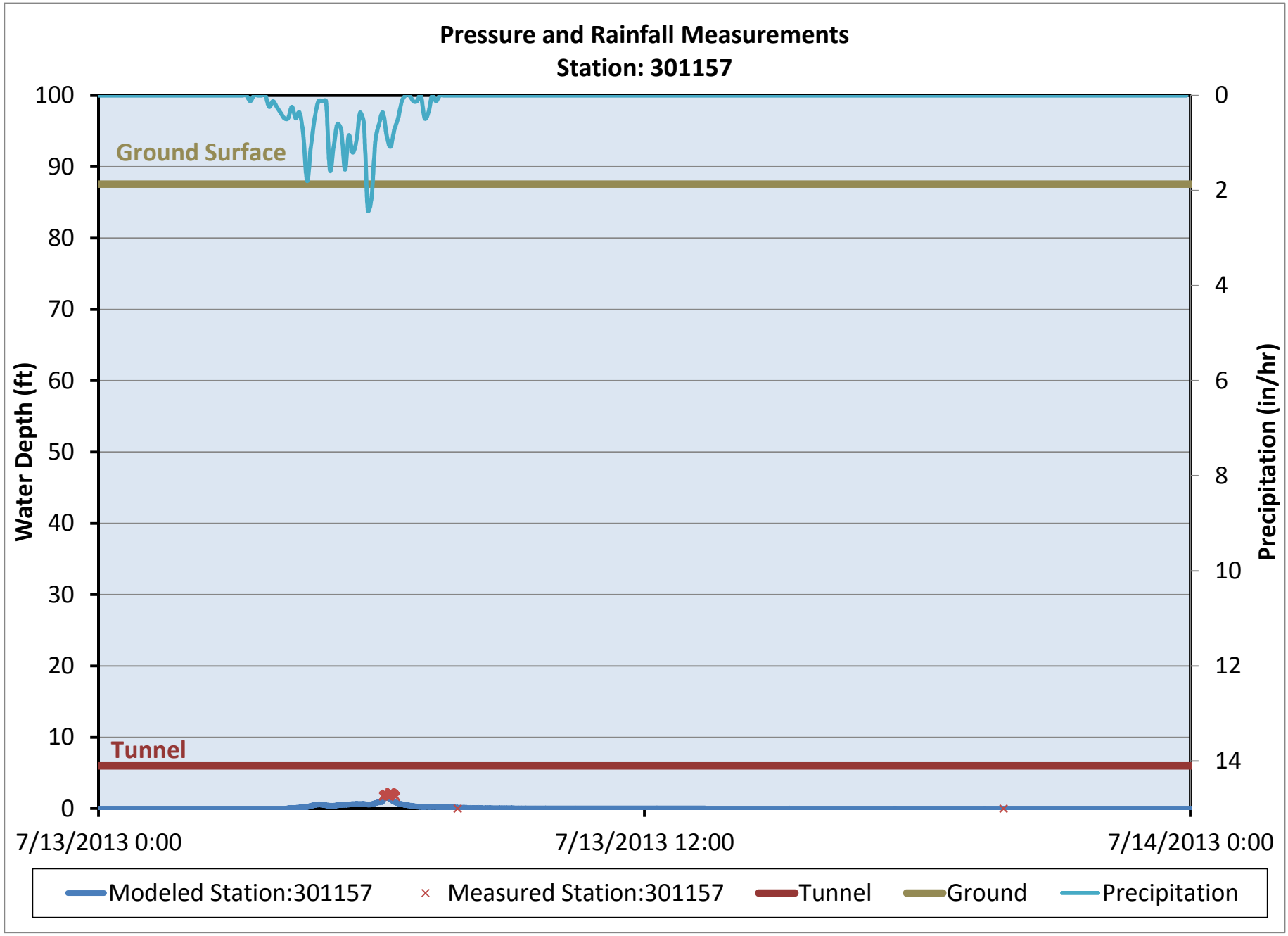
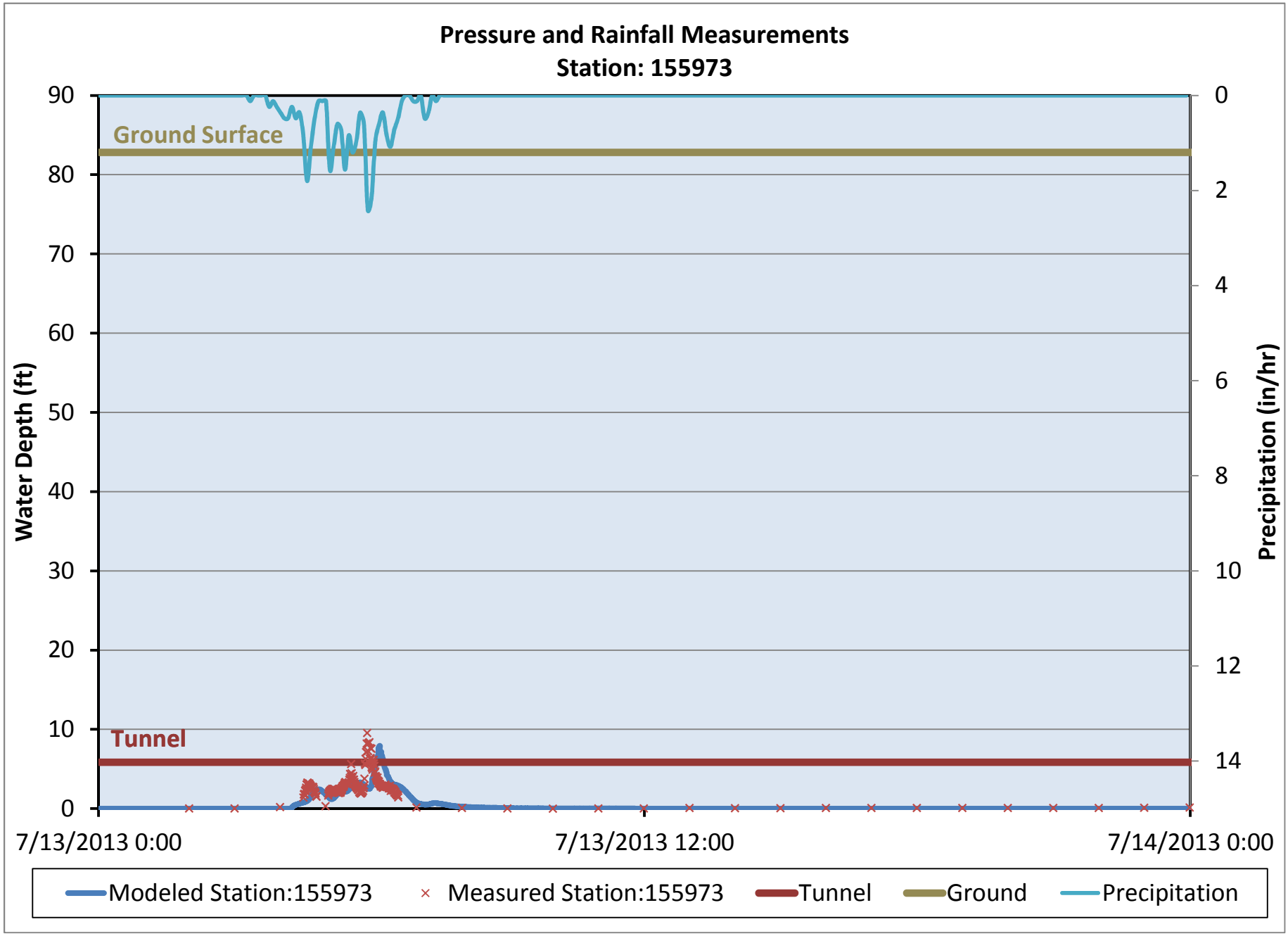
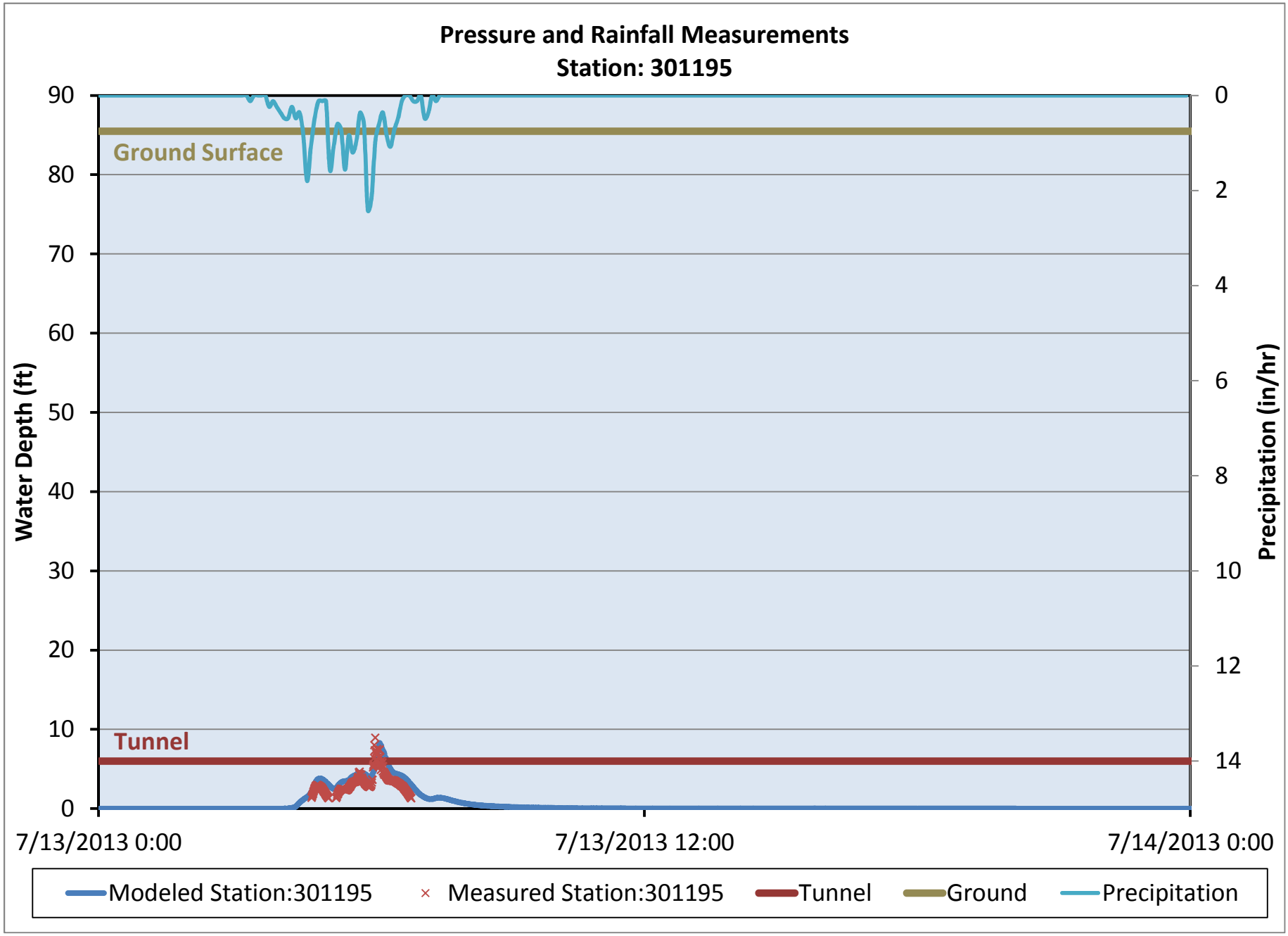
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
Ground Surface
Tunnel
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:155971
Measured Station:155971
Tunnel
Ground
Precipitation

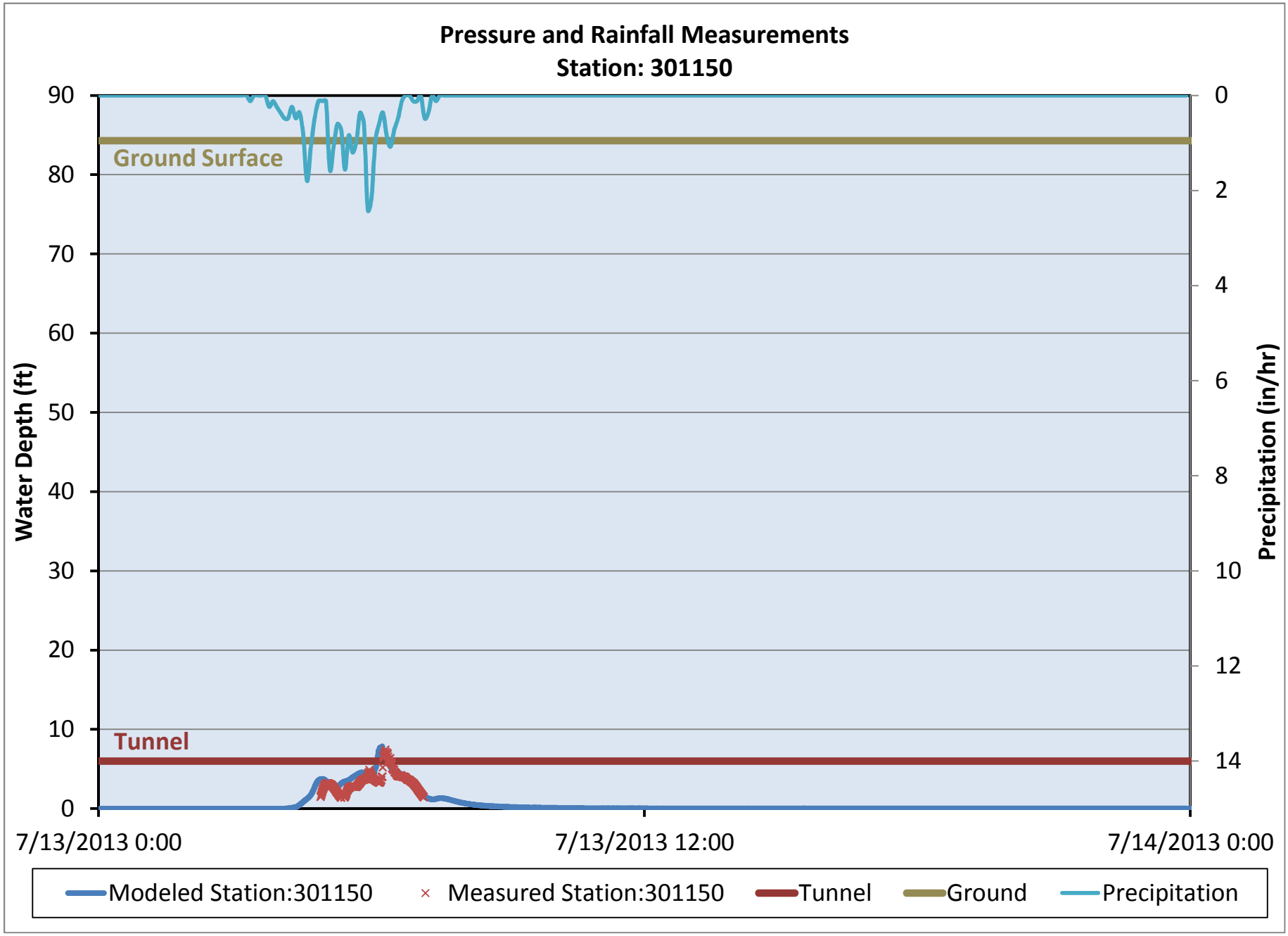

Pressure and Rainfall Measurements
Station: 155961
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
Ground Surface
Tunnel
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:155961
Measured Station:155961
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155947
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
Ground Surface
Tunnel
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:155947
Measured Station:155947
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301157
Water Depth (ft)
Precipitation (in/hr)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
Ground Surface
Tunnel
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:301157
Measured Station:301157
Tunnel
Ground
Precipitation

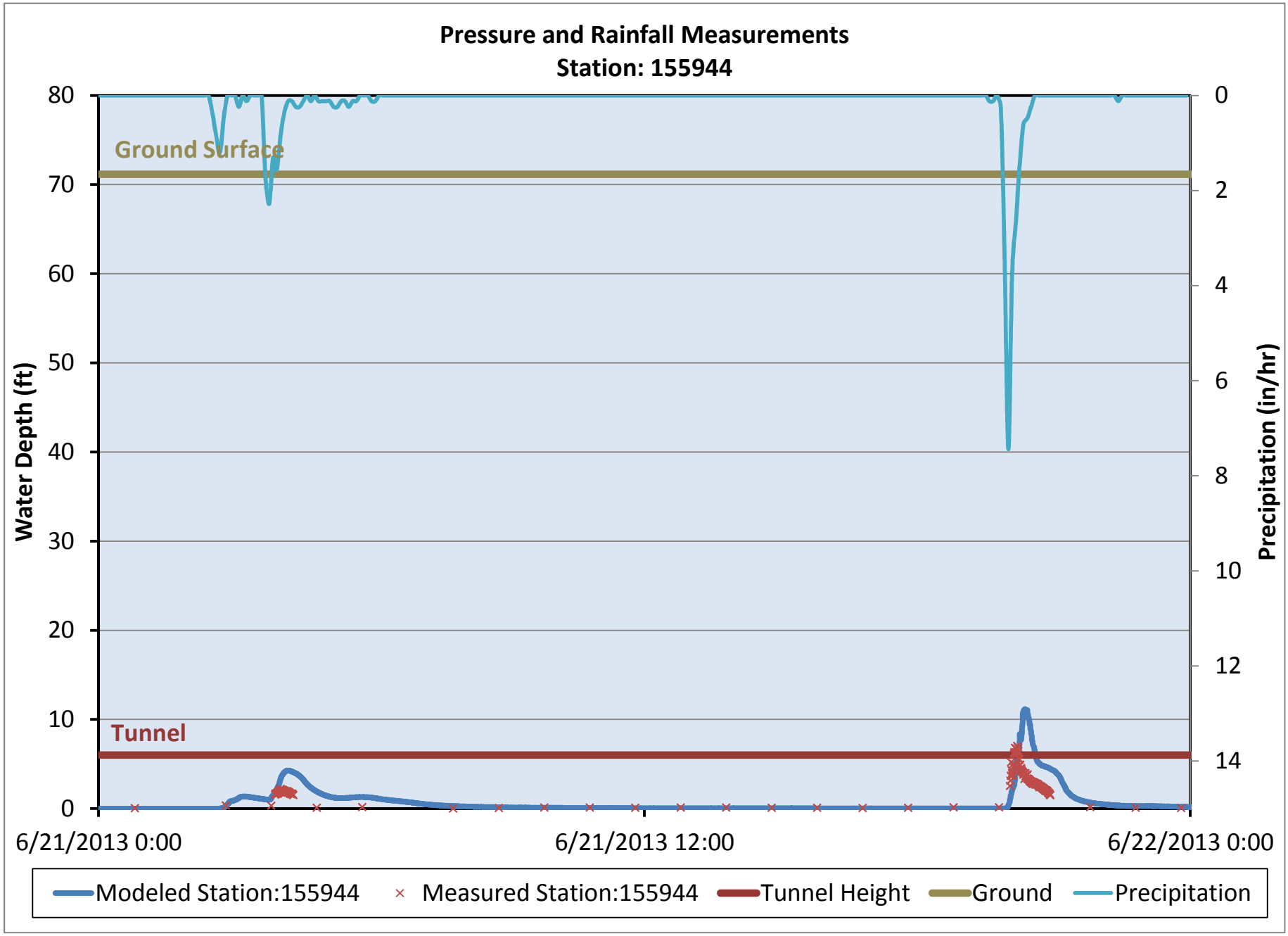

Pressure and Rainfall Measurements
Station: 155973
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:155973
Measured Station:155973
Tunnel
Ground
Precipitation

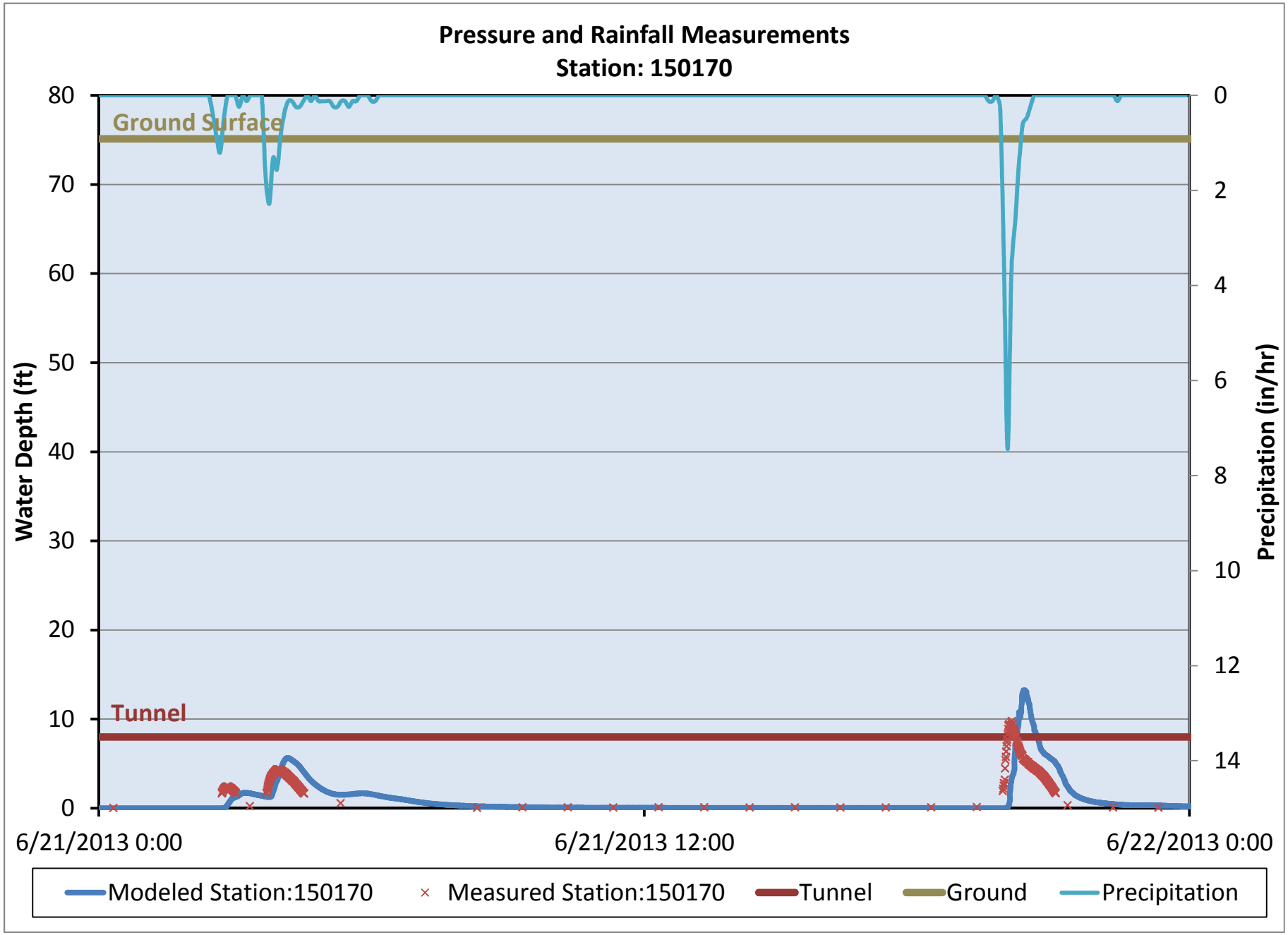

Pressure and Rainfall Measurements
Station: 301195
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:301195
Measured Station:301195
Tunnel
Ground
Precipitation

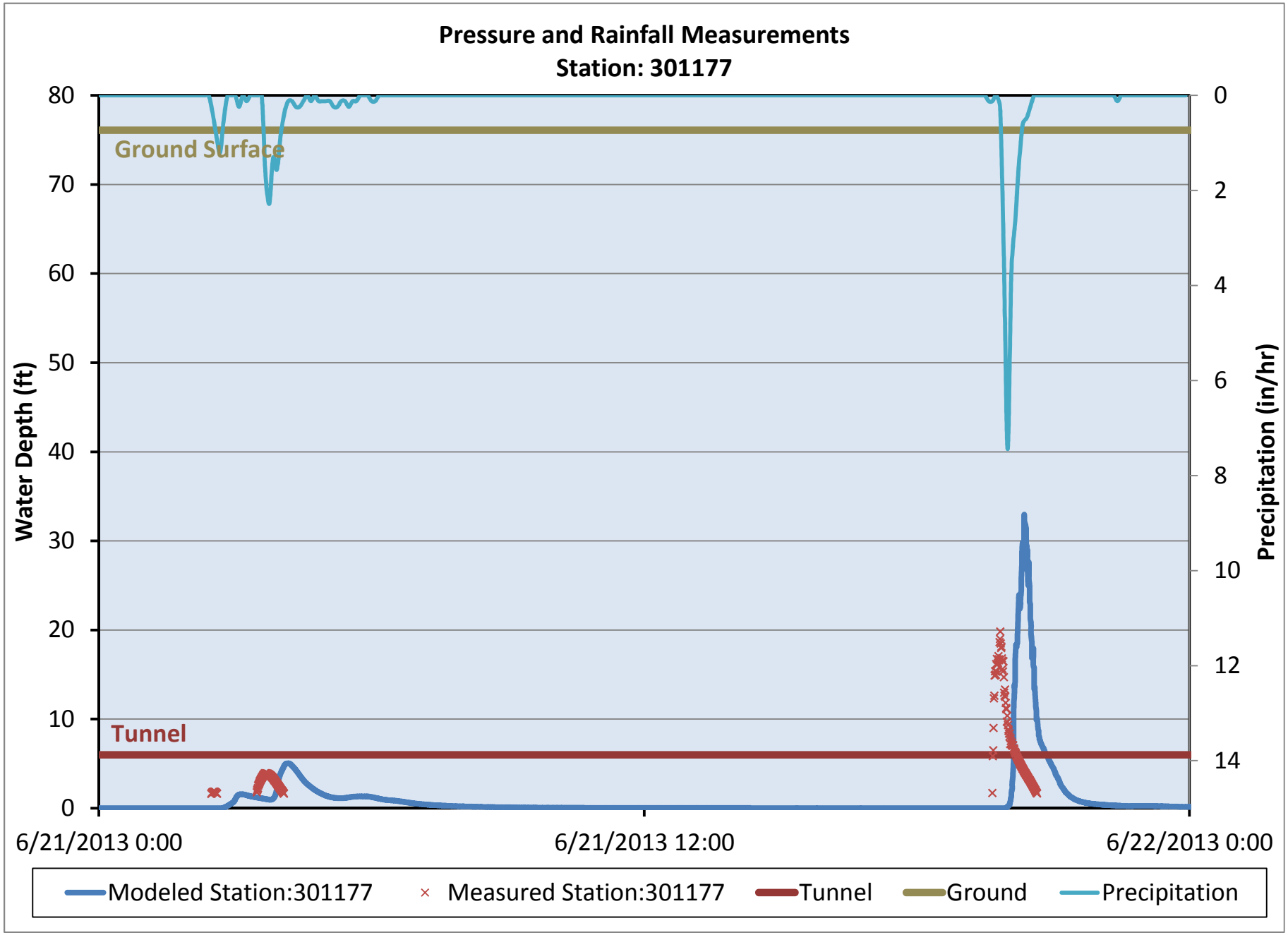

Pressure and Rainfall Measurements
Station: 301150
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
Ground Surface
Tunnel
7/13/2013 0:00
7/13/2013 12:00
7/14/2013 0:00
Modeled Station:301150
Measured Station:301150
Tunnel
Ground
Precipitation

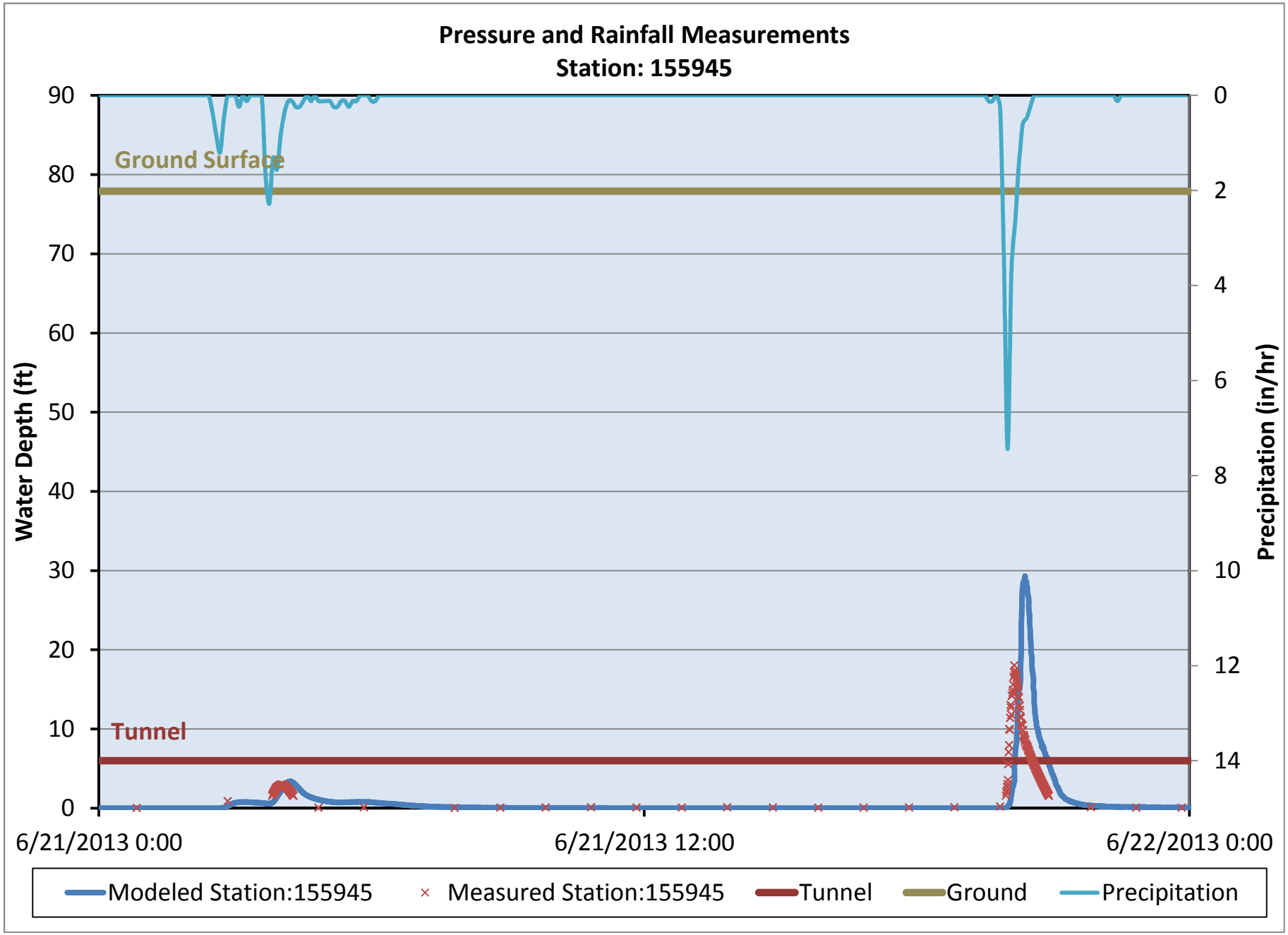
Appendix B

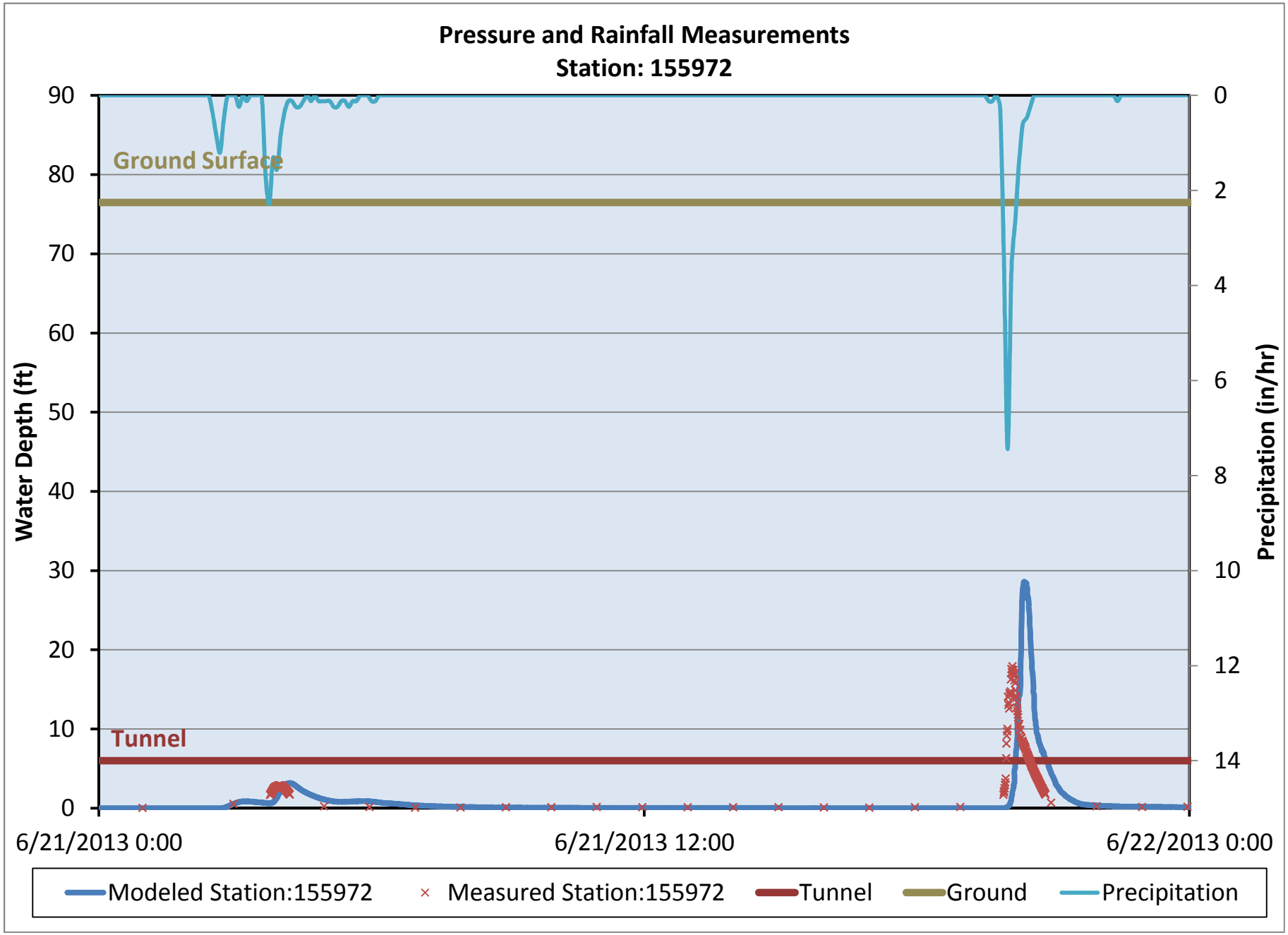
Model Validation:
Comparison between Modeled and Monitored Results

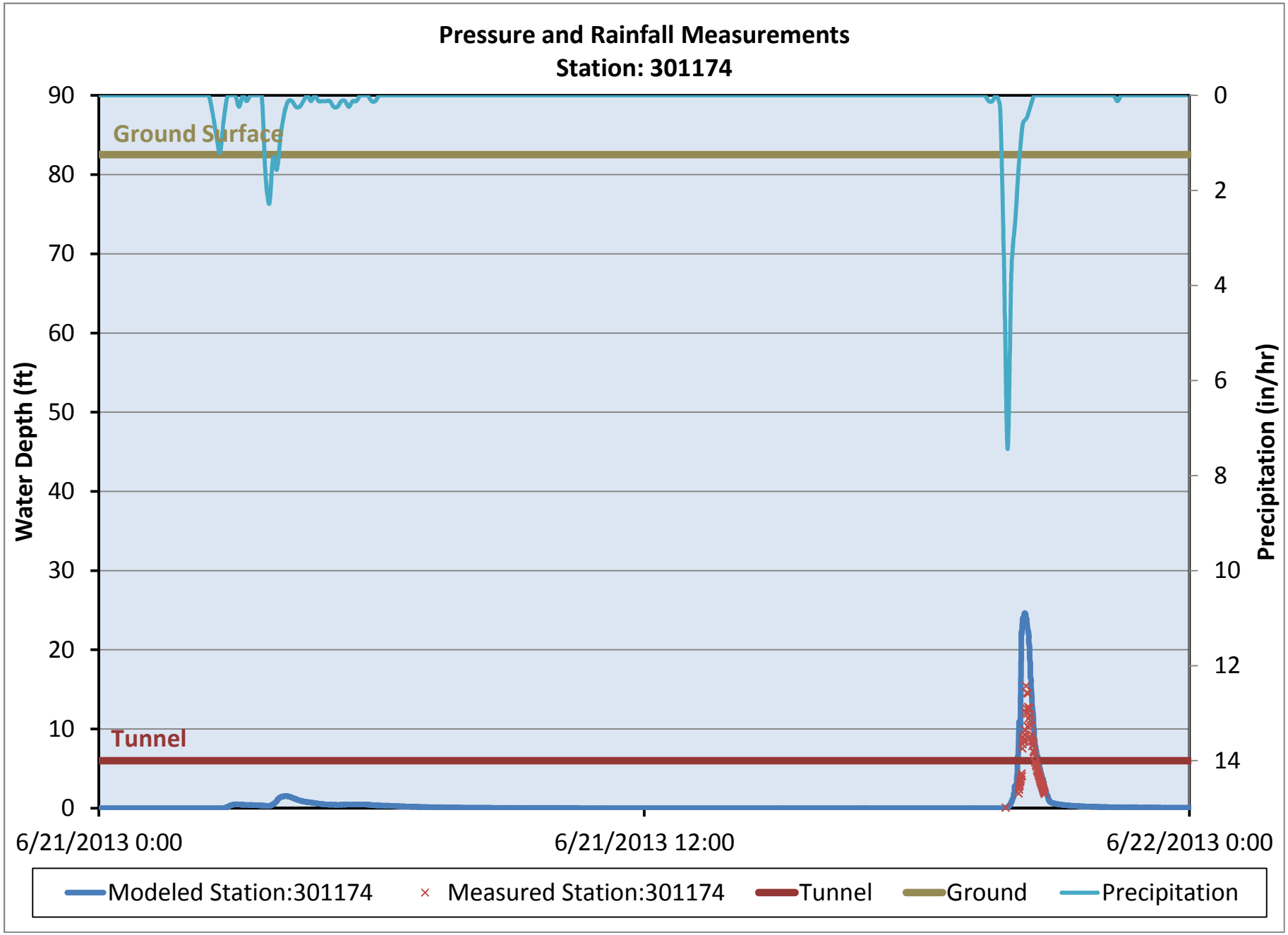

Pressure and Rainfall Measurements
Station: 155944
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:155944
Measured Station:155944
Tunnel Height
Ground
Precipitation

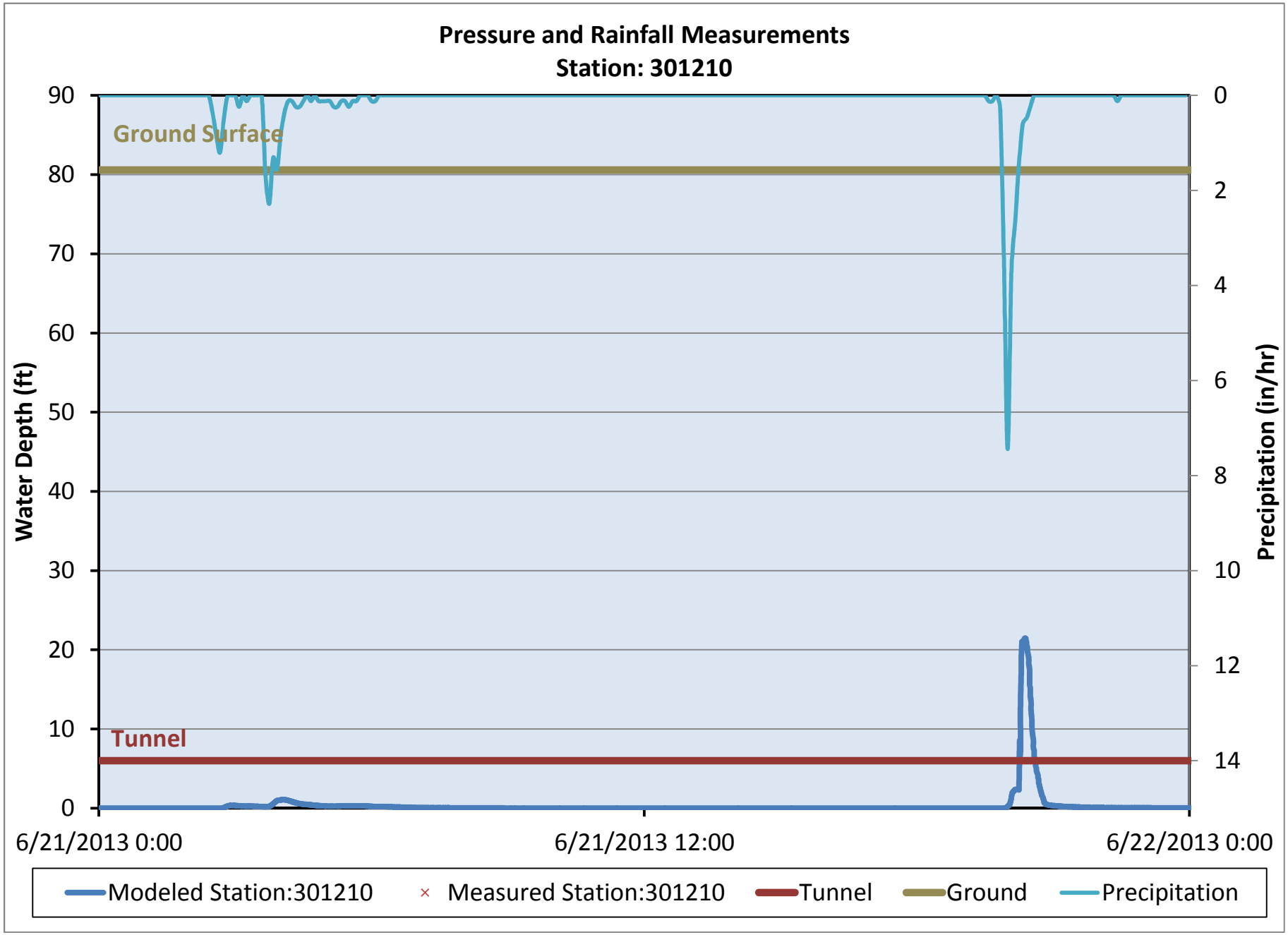

Pressure and Rainfall Measurements
Station: 150170
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:150170
Measured Station:150170
Tunnel
Ground
Precipitation

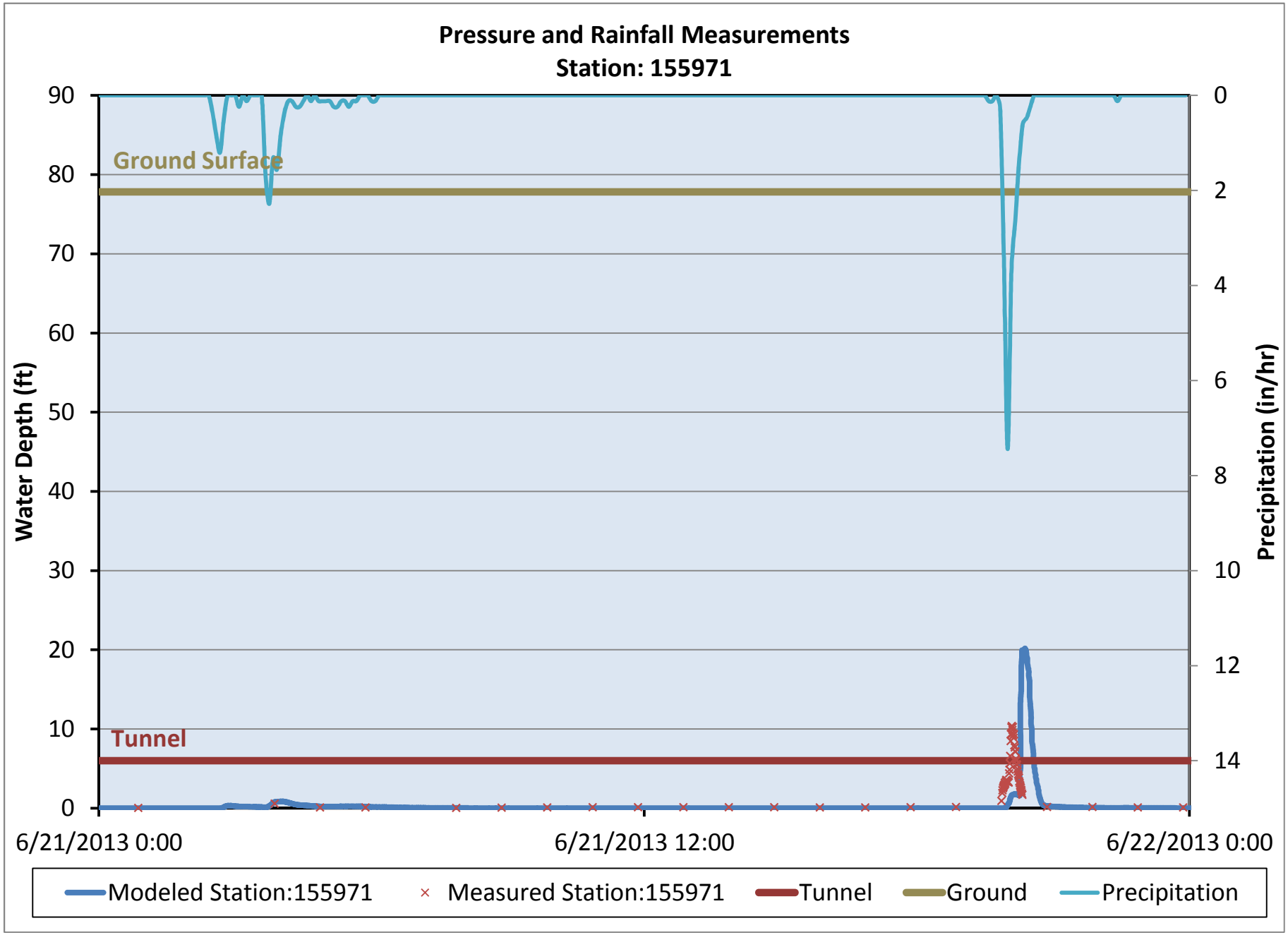

Pressure and Rainfall Measurements
Station: 301177
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:301177
Measured Station:301177
Tunnel
Ground
Precipitation

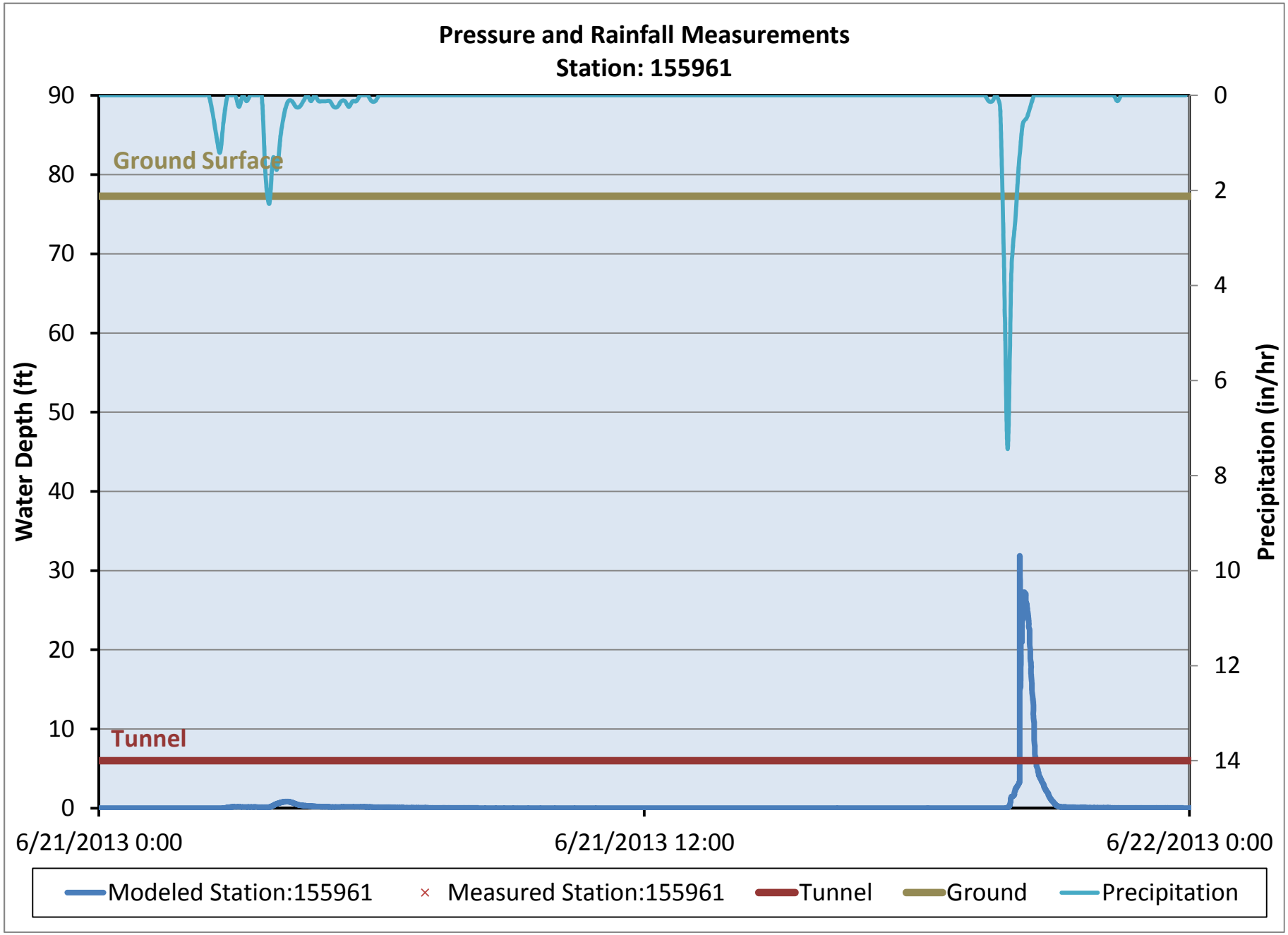

Pressure and Rainfall Measurements
Station: 155945
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:155945
Measured Station:155945
Tunnel
Ground
Precipitation

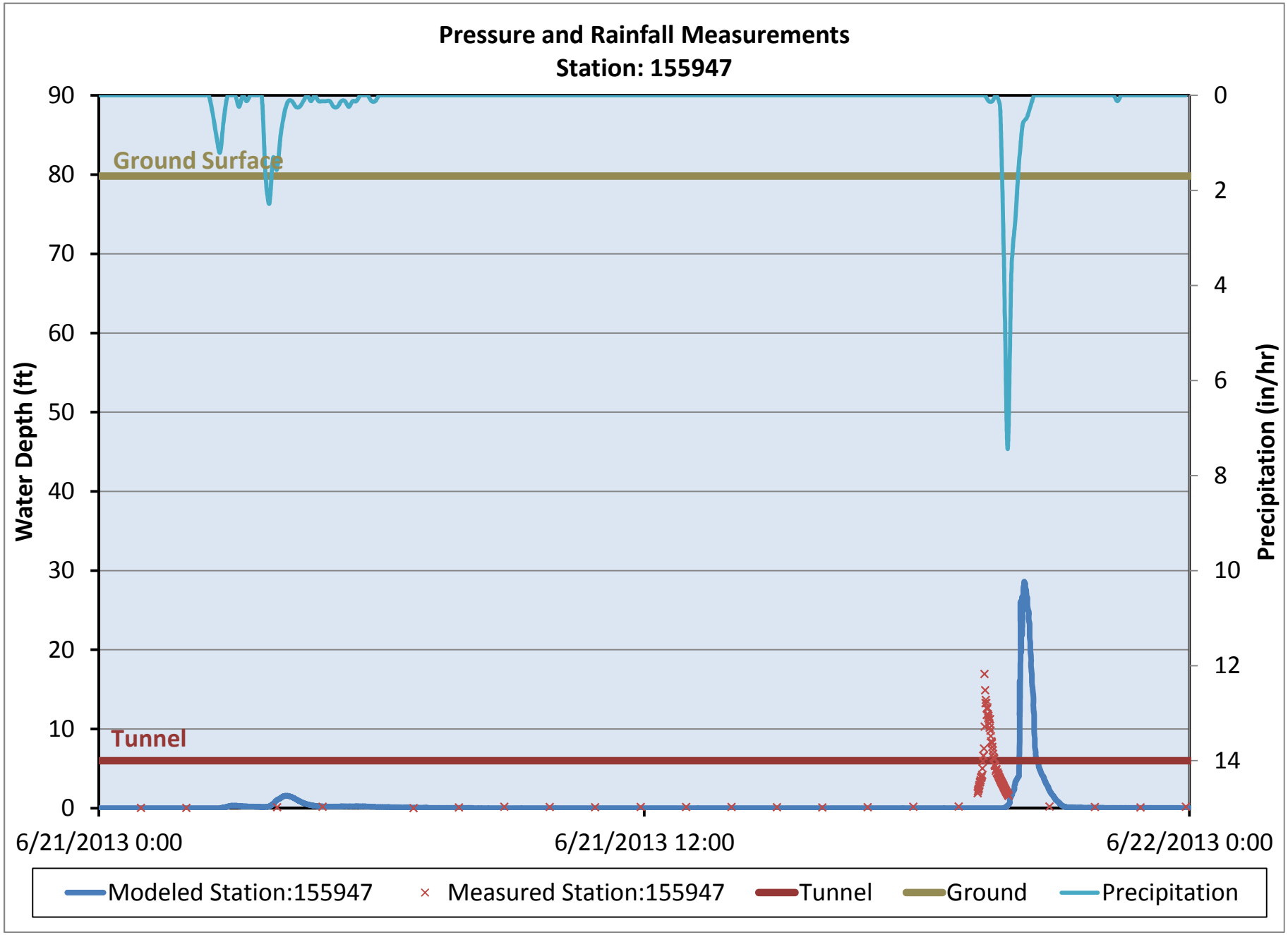

Pressure and Rainfall Measurements
Station: 155972
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:155972
Measured Station:155972
Tunnel
Ground
Precipitation

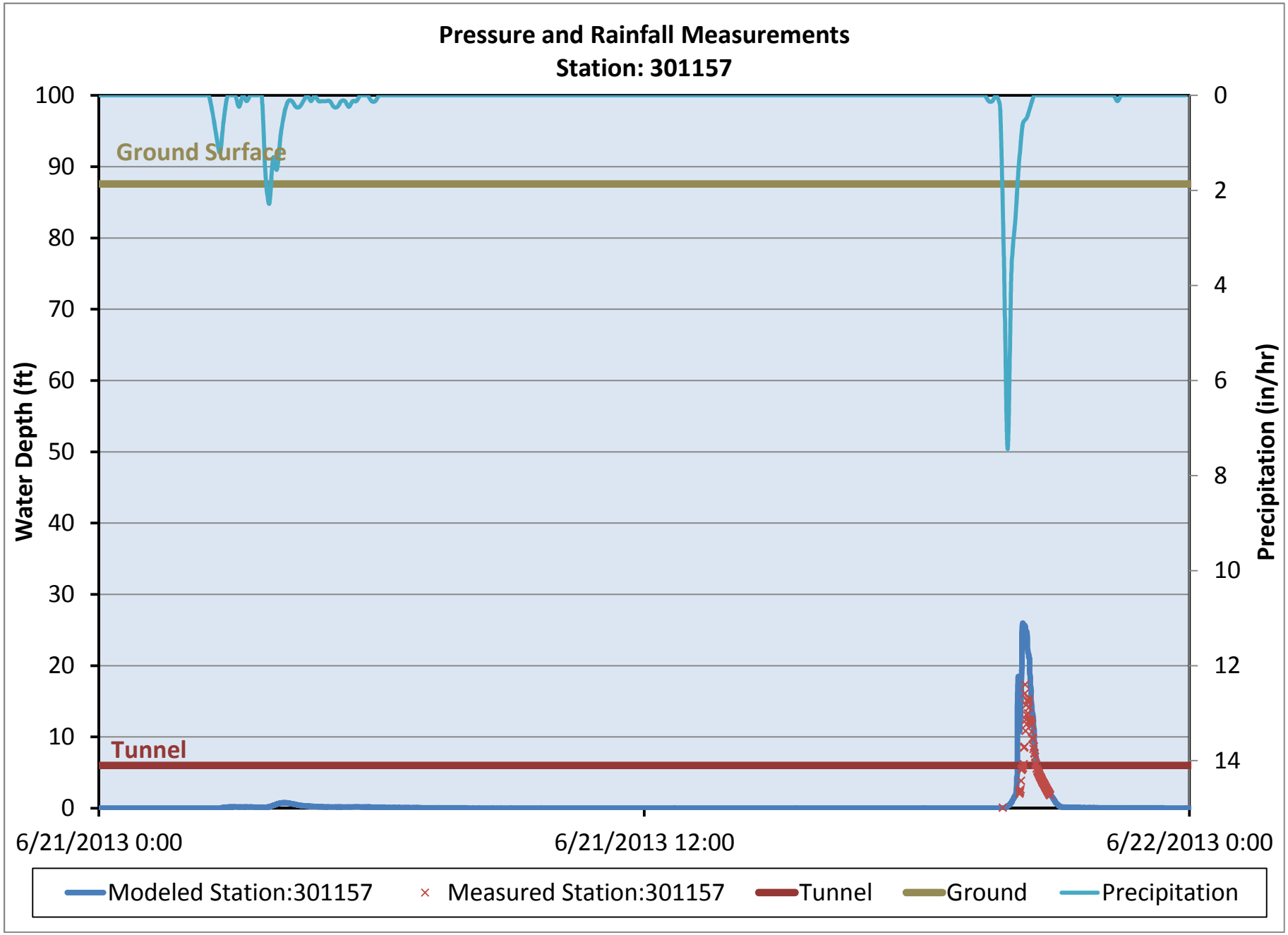

Pressure and Rainfall Measurements
Station: 301174
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:301174
Measured Station:301174
Tunnel
Ground
Precipitation

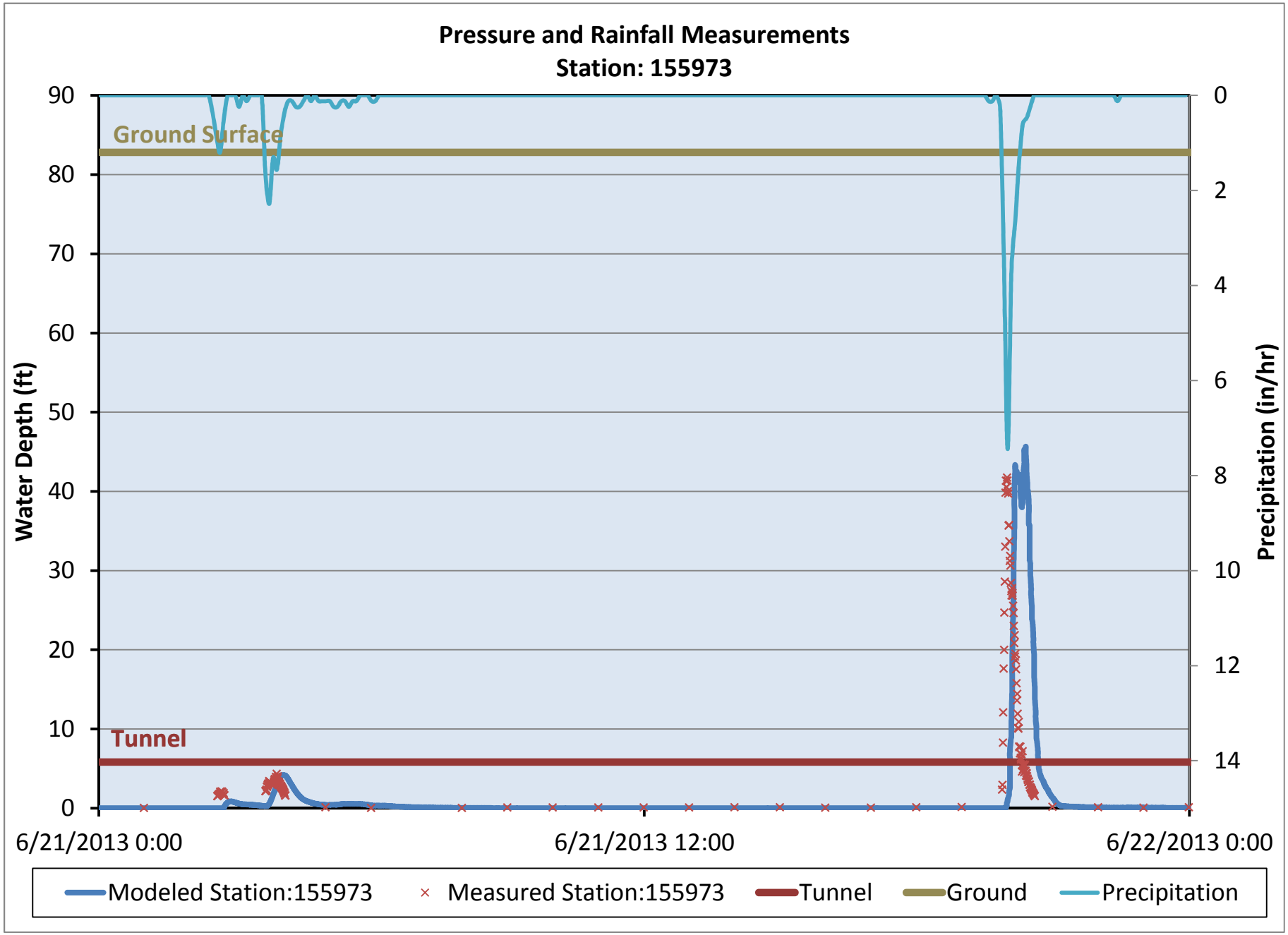

Pressure and Rainfall Measurements
Station: 301210
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:301210
Measured Station:301210
Tunnel
Ground
Precipitation

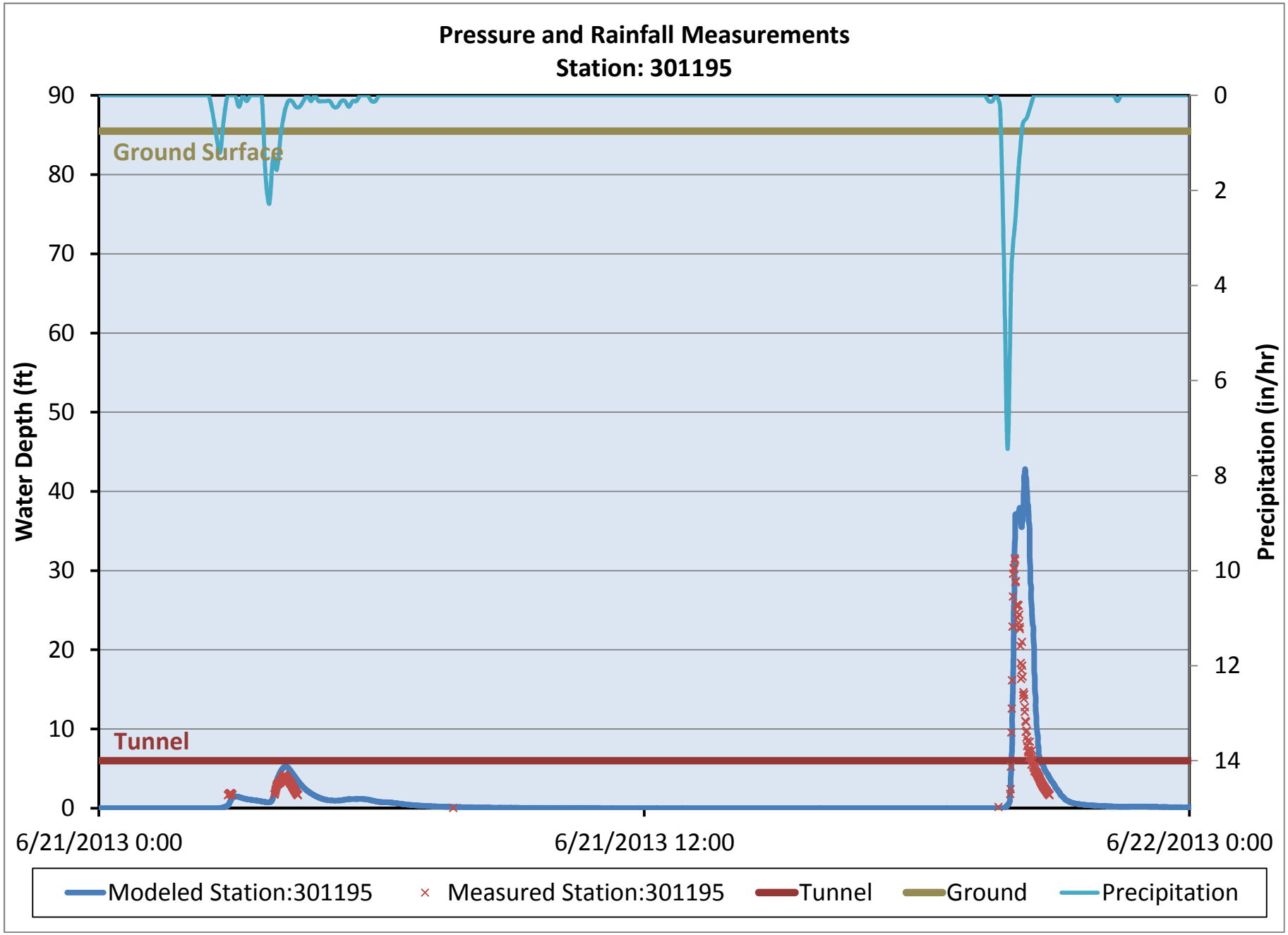

Pressure and Rainfall Measurements
Station: 155971
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:155971
Measured Station:155971
Tunnel
Ground
Precipitation

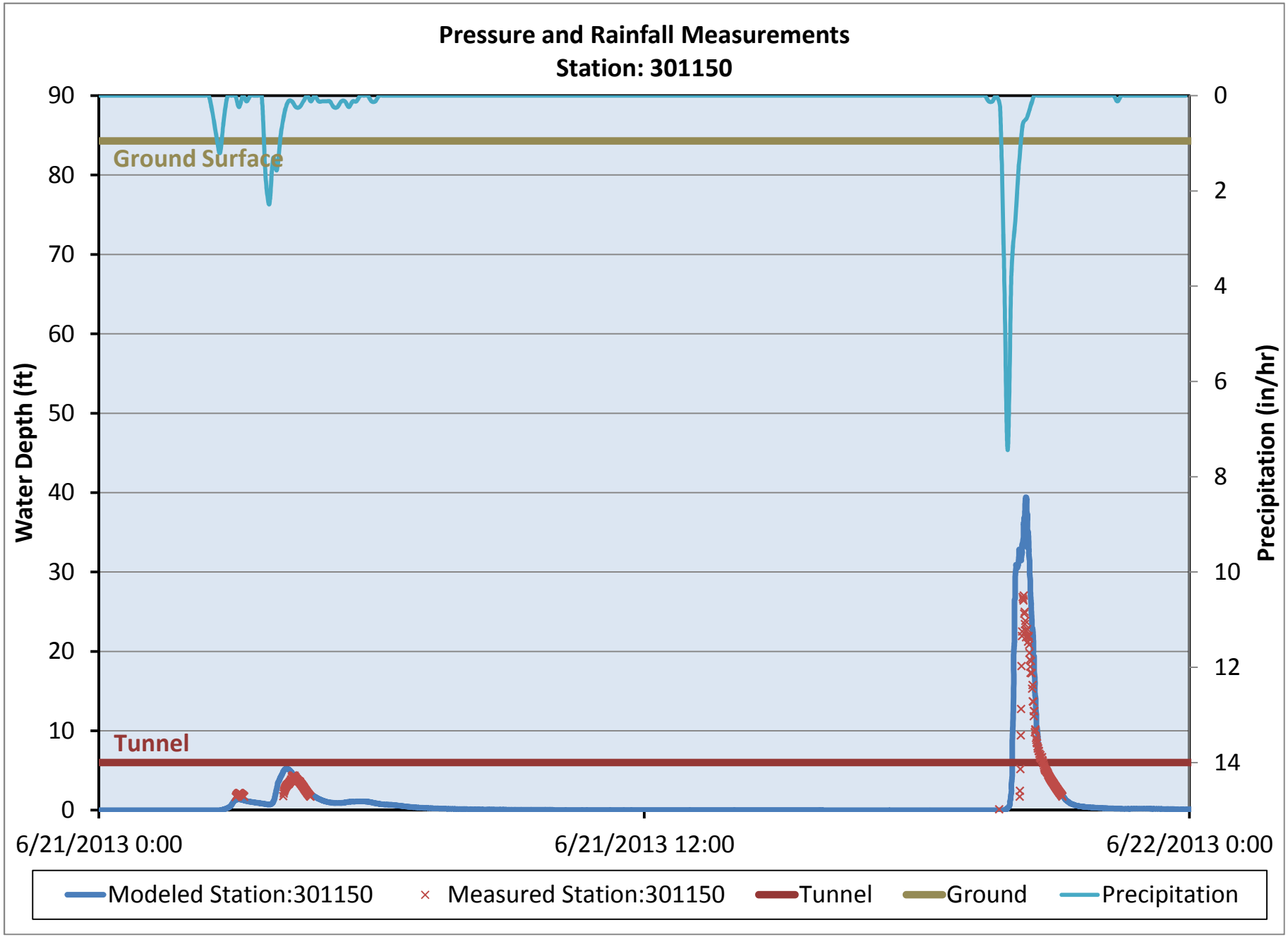

Pressure and Rainfall Measurements
Station: 155961
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:155961
Measured Station:155961
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155947
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:155947
Measured Station:155947
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301157
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:301157
Measured Station:301157
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 155973
Ground Surface
Tunnel
Water Depth (ft)
Precipitation (in/hr)
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:155973
Measured Station:155973
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301195
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:301195
Measured Station:301195
Tunnel
Ground
Precipitation


Pressure and Rainfall Measurements
Station: 301150
Water Depth (ft)
Precipitation (in/hr)
Ground Surface
Tunnel
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
6/21/2013 0:00
6/21/2013 12:00
6/22/2013 0:00
Modeled Station:301150
Measured Station:301150
Tunnel
Ground
Precipitation