REGULATORY, TECHNICAL AND MODELING CHALLENGES TO DEVELOPING A FREQUENCY BASED SSO CONTROL PROJECT IN WAYNE COUNTY, MICHIGAN

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ABSTRACT

Wayne County's North Huron Valley / Rouge Valley (NHVRV) interceptor system collects sewage from 15 communities located in Southeast Michigan and transports flows to the Detroit Water and Sewerage Department (DWSD) for treatment and discharge. The County is evaluating a regional approach to controlling wet weather sanitary sewer overflows (SSOs). A new methodology called the i3D antecedent moisture (AM) model, was used to perform the hydrologic modeling. The i3D model is a continuous model that produces a good match to observed flow data over time. The accuracy of the model resulted in a high level of confidence in the frequency analysis for SSOs and will serve as the basis for recommending improvements to control wet weather SSOs. The use of the AM model combined with a frequency analysis for sizing improvements eliminated the need to select a design storm event based on "average" conditions. This reduced many of the conservatisms that are frequently included in event models such as the capture coefficient and seasonal effects. The use of spatially varied rainfall also improved the accuracy of the analysis over the use of a point rain gauge. This paper presents the modeling and analysis innovations used and the preliminary development of a regional project.

KEYWORDS

SSO, Sanitary Collection System, Modeling, Antecedent Moisture, Frequency Analysis

INTRODUCTION

There were several regulatory and technical challenges during the development of the regional project to control SSOs for the NHVRV Interceptor System. These have included the adoption of a new wet weather SSO policy by the Michigan Department of Environmental Quality (MDEQ), the hydrologic behavior of the system that is highly affected by antecedent moisture conditions, and the complex hydraulic characteristics of the system, including the hydraulics of the downstream DWSD system.

Because wastewater system capacity is finite, it is unrealistic to expect that all wet weather SSOs can be eliminated. However, the State of Michigan has been very proactive in its SSO control policy. In December of 2002, the State established a formal wet weather SSO policy. This is one of the first SSO policies to be implemented in the Country and contains very aggressive standards for controlling SSOs. The policy calls for elimination of SSOs up to a 25-year, 24-hour design storm event during the growth season using average soil moisture conditions. The policy also allows for an alternative approach with a performance standard resulting in an SSO frequency of less than once in 10-years.

Previous event modeling had led to the conclusion that a relief/storage tunnel with an outlet to a CSO retention treatment basin would likely be the required SSO control project. Frequency of SSO events was explored by trying to use an event model, but the confidence in the results was not as high as desired for the anticipated magnitude of the capital investment involved. For this reason, the County elected to use the continuous antecedent moisture model to establish a frequency basis for developing their SSO control strategy.

A continuous antecedent moisture model was developed to identify system improvements to meet the 10-year frequency requirement. The continuous model was then used to perform a frequency of use analysis on the tunnel to size a preliminary tunnel volume. Continuous model simulations uncovered a potential hydraulic restriction in the system that had not been detected with previous modeling. This led to the conclusion that river inflow, system blockages, problems with downstream pump operations, and / or hydraulic gradients are likely contributors to the observed problems in addition to high flows during infrequent events. This paper explores these regulatory and technical challenges, presents the development of the NHVRV regional project to control SSOs and describes the innovations that were used to overcome the challenges facing the project.

METHODOLOGY

Several innovative techniques were utilized to perform the frequency analysis for the NHVRV SSO control project. An antecedent moisture model was developed to provide a highly accurate continuous estimate of system flows for a long period of record. A frequency analysis was used to analyze the statistical frequency of SSOs. A hydraulic process, called "null modeling", was used to isolate the hydraulic performance of the system. This process uncovered a potential hydraulic restriction in the interceptor system. The technical background and description of these innovative approaches is described in this section.

The Antecedent Moisture Model

Antecedent moisture is a term that describes the relative wetness or dryness of a sewershed, which is a function of the distribution of recent rainfall, temperature, seasonal variations and other dynamics. Because of the complex transport mechanisms of these flow sources, they are heavily dependent on variables that are not normally included in runoff models such as soil moisture conditions and seasonal effects. These variables continuously change during and in between storms in response to antecedent moisture conditions.

Figure 1 shows antecedent moisture effects from observations from the Novi subarea of the NHVRV system from the year 2000. The measured flow is comprised of a diurnal sanitary component and an I/I component. The I/I has been separated from the total flow by utilizing a time series extraction technique that does not alter the I/I information content within the data. This figure shows how antecedent moisture conditions cause a large variation in the observed capture coefficients (percentage of rainfall captured by the sewer system) from storm-to-storm. This effect is demonstrated by comparing the April 9, 2000 and May 31, 2000 storms. Both storms have rainfall volumes of approximately 1.0-inch, but have significantly different capture coefficients of 4.4% and 0.6%, respectively. This variation in capture coefficient is caused by the antecedent moisture conditions preceding each storm event. The May 31, 2000 storm occurs after a long dry period, whereas the April 9, 2000 storm occurs during the spring period, which is wet due to the cool, rainy spring season as well as the winter snowmelt. This demonstrates the significant impact that antecedent moisture has on system response to storm events.

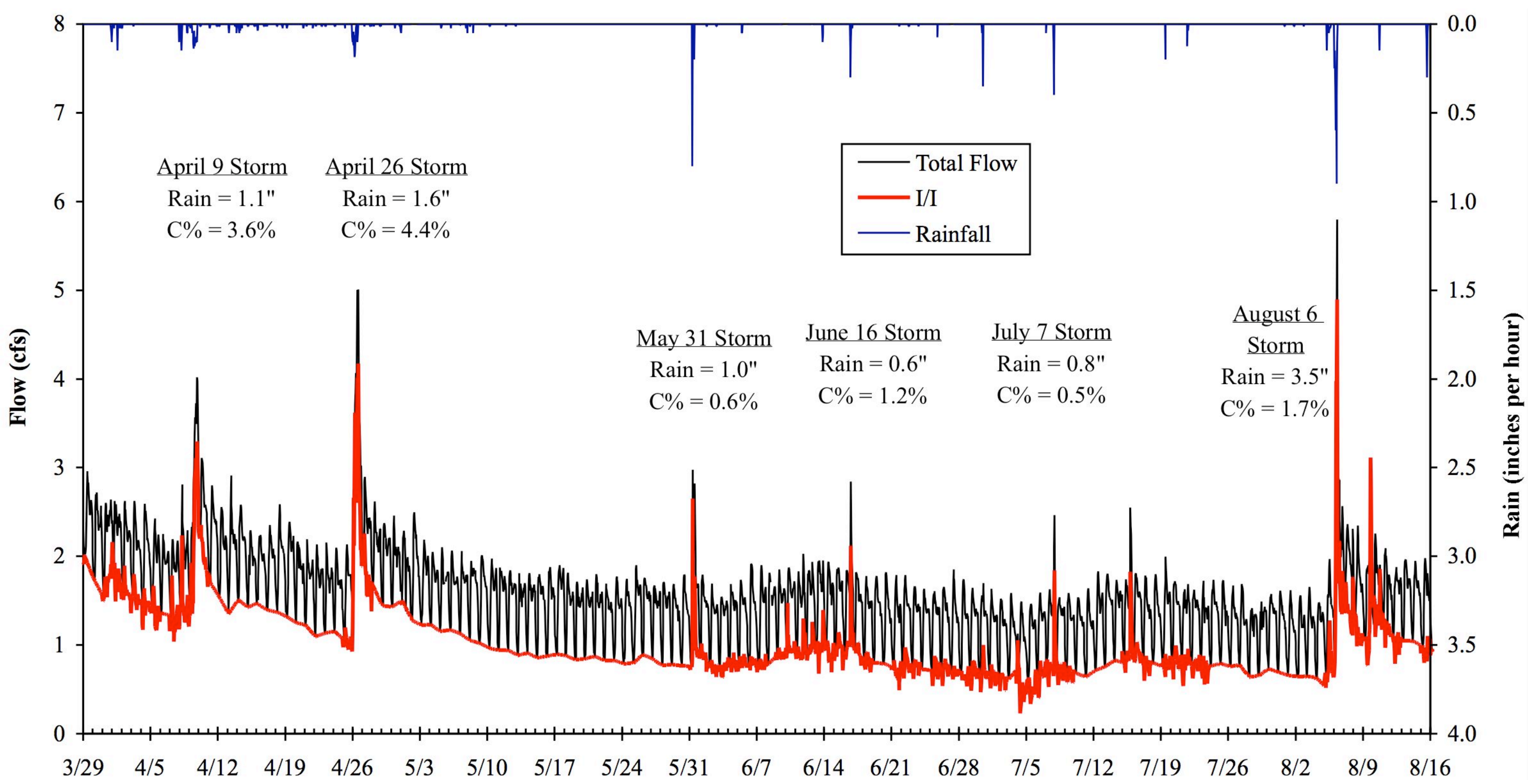

Figure 1 – Antecedent Moisture Effects on I/I
The effects of antecedent moisture can clearly be seen in the I/I flow data. Note the high capture coefficients in the spring and the low values in the summer. The capture coefficients are also affected by the amount of recent rainfall.

The state-of-the-art in modeling I/I has been dependent on physically based modeling derived from stormwater runoff simulations. Historically, collection system models were limited in their ability to account for antecedent moisture conditions. The antecedent moisture conditions that occurred during the period of the flow monitoring or for the "design event" were implicitly incorporated into the collection system model, essentially as a constant condition.

An alternative to purely physical modeling is the use of a modeling procedure known as system identification. The basis of this approach is to allow measured data (in this case flow, rainfall and temperature) to guide the modeling process. It does not assume that the model must adhere to a specific preconceived notion of the physical system, but rather arrives at a statistically relevant description based on the data alone. Accordingly, this procedure differs from purely black-box modeling since it provides a model that offers insight into the underlying mechanics of the system. This is contrary to existing methods, which unduly enforce a predetermined set of physical principles on the data that may or may not be present in the actual system.

A new modeling technique called inflow and infiltration identification (i3D) based on system identification theory was developed specifically to simulate the impacts of antecedent moisture on I/I [Czachorski, 2001]. The i3D model incorporates nonlinear dynamics to account for short-term antecedent rainfall conditions and long-term seasonal variation in the wet weather response. Unlike regression techniques or complex physically based models, the resulting system identification model for antecedent moisture is uniquely identified for each sewershed, is parsimonious in nature (containing relatively few modeling parameters) and predicts the amount of antecedent moisture within the sewershed as a continuous variation in the capture coefficient. A block diagram of the i3D model structure is depicted in Figure 2.

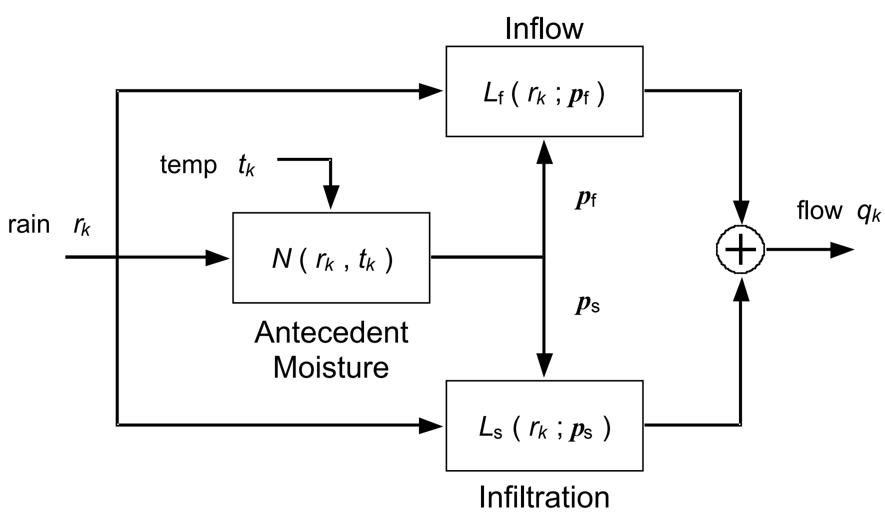

Figure 2 – i3D Model Structure
This figure shows a block diagram of the i3D model. Note that the antecedent moisture block alters the parameters within the separate inflow and infiltration blocks.

In order to gain confidence in the model flow projections and account for antecedent moisture effects, a continuous modeling simulation was performed for the NHVRV system using the i3D model. The model was developed using data from the County's extensive permanent metering system, which contains a period of record of up to 11 years. This metering system provided an excellent long-term flow record that was used to calibrate and validate the model, and evaluate the accuracy of the statistical predictions of the model. For the Wayne County NHVRV project, the i3D model was successfully calibrated and validated using the flow metering data available.

Frequency Analysis

Rather than using an event based modeling approach to size system improvements, a frequency analysis was performed for the NHVRV system. The frequency analysis used the i3D model in a continuous simulation for 18 years of available rainfall records to determine the statistical probability of peak flows. Because the i3D model incorporates the variations in antecedent moisture and predicts the variations in capture coefficient, the resulting frequency analysis incorporated those effects and provided confidence in the results. This eliminates the need to establish a design event and to estimate "average conditions" for use in the event model.

The use of a frequency analysis to design wet weather improvements for sanitary systems is a new and innovative approach. Frequency analyses are very commonly used for river peak flows and flood stage analysis. For those systems, a Log-Pearson Type III analysis is commonly used to represent the statistics of peak flows, including analysis for FEMA Flood Insurance Studies [FEMA, 2002]. To our knowledge, the use of a Log-Pearson Type III analysis is the most applicable technique for performing a statistical frequency analysis on sanitary sewers flows.

The continuous prediction of I/I from the i3D model was used to analyze the statistics of exceeding certain peak flows to assess system performance. This results in a design recurrence interval flow event being used to analyze collection systems, as opposed to a design rain event as is typically used. This design flow event implicitly incorporates many hydrologic variables including rainfall frequency, antecedent moisture and seasonal effects [Van Pelt, 2002]. It is interesting to note that the Michigan Department of Environmental Quality (MDEQ), in establishing a Sanitary Sewer Overflow Policy in December, 2002, allowed for consideration of a design rain event (25-year, 24-hour storm) and also a design recurrence interval event [MDEQ, 2002] by specifying an SSO frequency of less than once every 10 years.

For the NHVRV system, a frequency analysis was performed by utilizing the i3D continuous model output from 18 years of rainfall and temperature data. A Log Pearson Type III statistical analysis was then be used to determine the 10-year recurrence interval peak flow for this system.

Hydraulic Null Modeling

Comparison of the continuous modeling results to observed flow and depth data revealed that there may be a hydraulic restriction affecting system performance in the NHVRV system. A methodology that we call "null modeling" was used to isolate the system model to only the hydraulics in order to evaluate this potential system bottleneck. The null modeling procedure is shown schematically in Figure 3.

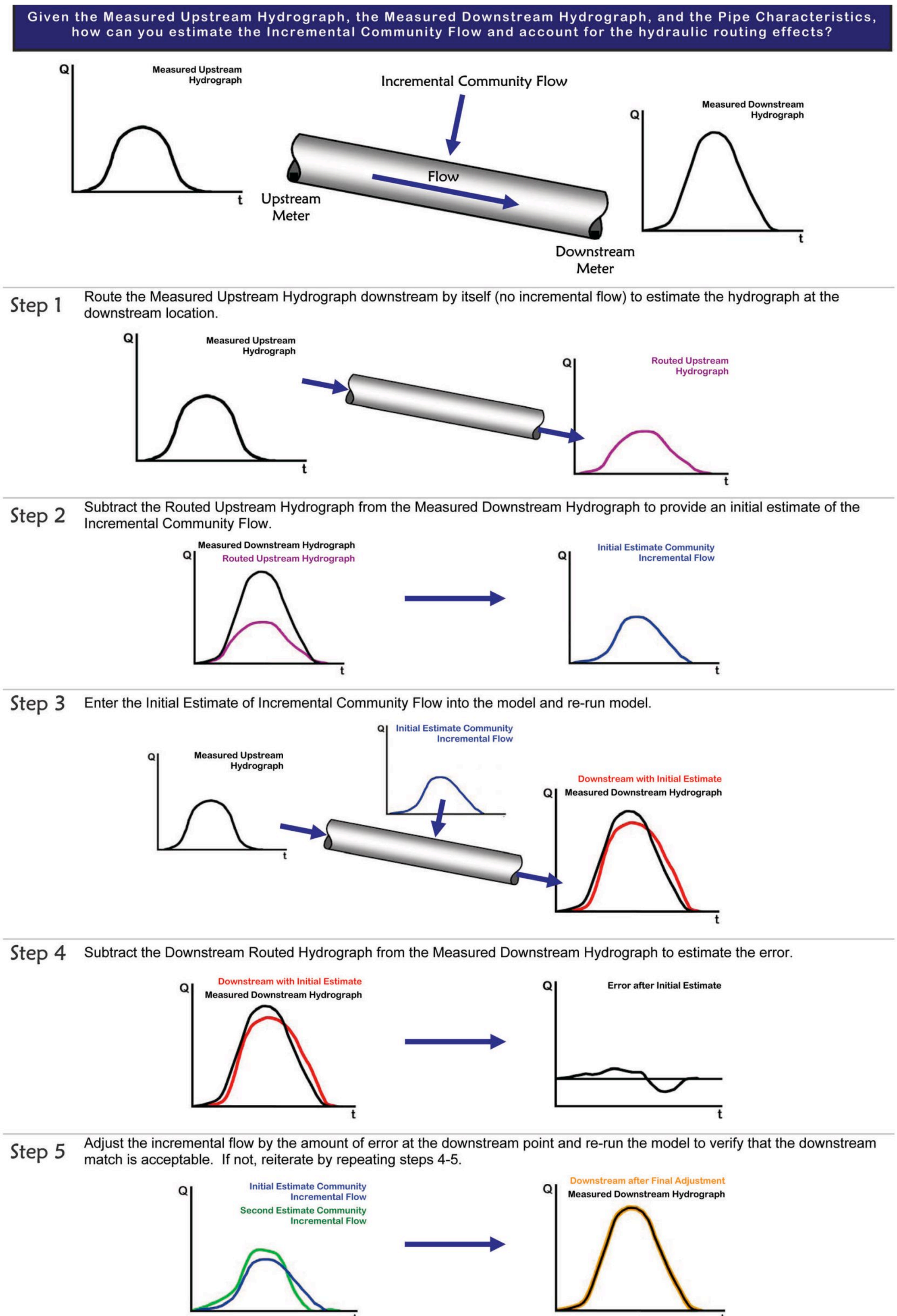

Figure 3 – Hydraulic Null Modeling

This figure shows a schematic of the null modeling procedure used to isolate the model with respect to hydraulics and evaluate potential system hydraulic restrictions.

In mathematics the null set is a set or matrix having no elements. Similarly, in collection system modeling, null modeling is the process of identifying an incremental flow hydrograph without the use of a hydrologic model. When attempting to isolate the hydraulics, a hydrologic model is not needed because the incremental hydrographs (input between flow meters) can be determined from the downstream hydrograph, upstream hydrograph and piping characteristics. The process requires iterations to solve because of the routing effects of the piping system. However, this process can be automated using a hydraulic model such as the EXTRAN block of EPA SWMM.

The process is simple in that it relies on observed metering data and known characteristics of the piping system to estimate the incremental flow. An initial estimate of the incremental hydrograph is determined by first routing the observed upstream hydrograph through the piping system by itself, and then subtracting the routed hydrograph from the observed downstream hydrograph. However, the key to the null modeling process is that this initial estimate of the incremental hydrograph is corrected and rerouted in the model to improve the incremental hydrograph until an acceptable match is achieved at the downstream end. This iterative correction implicitly incorporates the hydraulic routing effects of both the upstream hydrograph and the incremental hydrograph into the estimate of the incremental hydrograph, which results in improved accuracy.

The null modeling has the added benefit of producing an accurate flow estimate of the system for use in hydraulic model calibration. Because the system flows very accurately match observed flows, and are not assumed based on a hydrologic model, the resulting model performance is isolated to the hydraulics. This means that any discrepancy between the model depths and observed depths is the result of hydraulic effects and not caused by the inaccuracies of hydrologic models. This isolation of the hydraulic effects allows for a detailed hydraulic model calibration to be performed and for an evaluation of any potential system hydraulic restrictions.

RESULTS

Several innovative analysis techniques were used to evaluate the required recommendations for the NHVRV SSO control project. These included the antecedent moisture model, a statistical frequency analysis and null modeling. This section describes how each of these techniques were applied to the NHVRV modeling project and discusses the results achieved.

i3D Model Calibration and Validation

A system schematic was developed to simplify the system and provide a visual explanation of the hydrologic models that were developed. This schematic can be seen in Figure 4. On this figure, as well as throughout the paper, a "+" is used with meter names to denote when the addition of meter data was used. Numbers, such as 1P, 26P, etc. are used to denote meters. The system was divided into 12 sub-areas, two of which are combined systems. i3D models were developed for 11 of these 12 sub-areas and the existing SWMM RUNOFF model was used for the remaining combined area (Sub-area 4). Initially it was planned that i3D models would only be developed for separated areas. However, since the Redford combined area is metered, and the

SWMM runoff model was not matching accurately under some conditions, an i3D model was developed for this area as well.

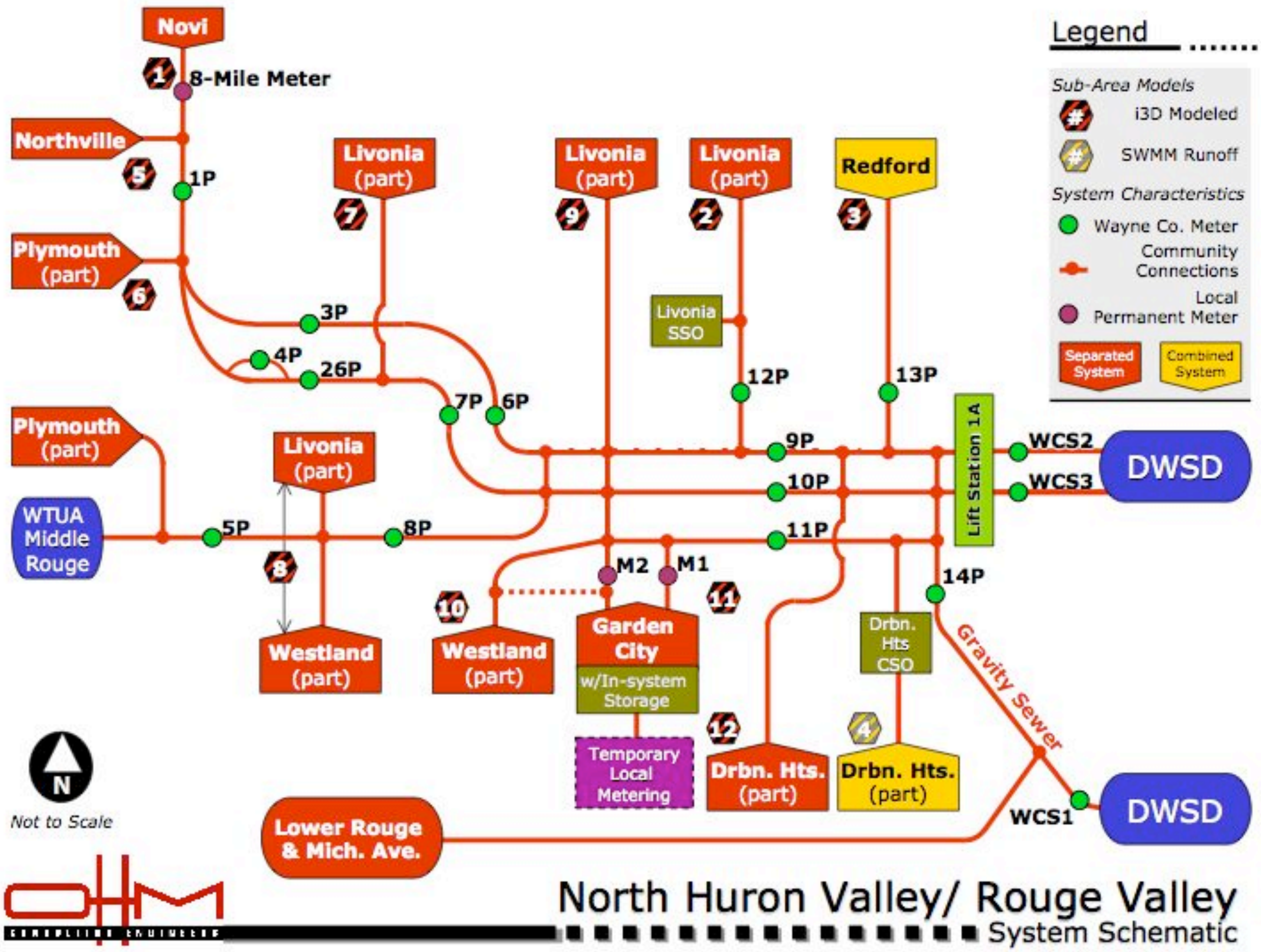

Figure 4 – System Schematic
The NHVRV system is shown schematically in red. There are parallel interceptors for much of the system. i3D models were created for each of the separated areas shown in red using the historic meter data from the meters denoted with green circles.

Sub-areas were chosen primarily based upon available metering data, but community boundaries and previous work were also taken into account. In general, far less sub-areas were included in this modeling effort when compared to previous event model efforts. Existing flow metering data was used to develop hydrologic i3D models. Missing data and meter subtraction were initially concerns. However, use of the continuous model allowed for a large number of comparisons between metered and modeled data, and provided confidence in the model.

Once the observed data for each sub-area were obtained, the daily diurnal flow pattern was filtered so that the resulting observed flow signal only contained inflow and infiltration. The diurnal flow pattern was filtered by determining the daily nighttime minimum flows. This was assumed to be the base infiltration. It is acknowledged that there may be some nighttime users or minimal nighttime sewage usage; however, this is accounted for in the hydraulic model through the average base sewage flow. The base infiltration was then subtracted from dry weather flow data to estimate a dry diurnal pattern. For wet days, this dry diurnal pattern is replicated from dry days based on the day of the week. The inflow and infiltration flow signal is then estimated by subtracting the continuous estimate of the diurnal flow from the total metered flow. All of the flow graphs shown in this paper are the I/I flow signal after the diurnal flows have been subtracted using this methodology.

Two years (2000 and 2001) of meter data were used initially to build the i3D models. The models for these years were input into the hydraulic model for routing and then compared to actual meter data. A sample from the two-year calibration fit is shown in Figure 5. This figure shows the model prediction and the observed I/I flow for a two-month period in the fall of 2001. The figure shows the resulting model fits at three meter locations along the interceptor system:

1. Meters 6P+7P+8P measure the upstream areas of the system, which contains drier, separate areas.
2. Meters 9P+10P+11P includes the central area of the system, which is a wetter, separate area.
3. The outlet includes the combined areas near the downstream portion of the system.

The time period in Figure 5 contains an excellent variation in antecedent moisture for calibration, as nearly 8-inches of rain fell in a 15 day period. This is over 5 times the normal precipitation for this time of year. This series of back-to-back rain events produced a very large variation in capture coefficient as the system became wetter. The i3D model was calibrated to replicate this relationship between the system wetness and the resulting capture coefficients. As shown in the figure, the i3D model does an excellent job of accurately simulating these dynamics.

Once calibrated, the models were then validated. Validation tests the model performance for years not included in the calibration. Validation is necessary because it is possible for an incorrect model to be calibrated such that it fits specific observed data to a reasonable degree of accuracy, yet in general is an inaccurate model of the system. Consequently, the ability to calibrate a model to a given data set does not solely validate the model. A more confident evaluation lies in the ability of a model to fit a set of data that was not used for calibration. Two years of additional data not used in calibration (2002 and 2003) were used to validate the models. A sample from the two-year validation is shown in Figure 6. This validation was successful and was critical to providing confidence in the model for both Wayne County and the MDEQ.

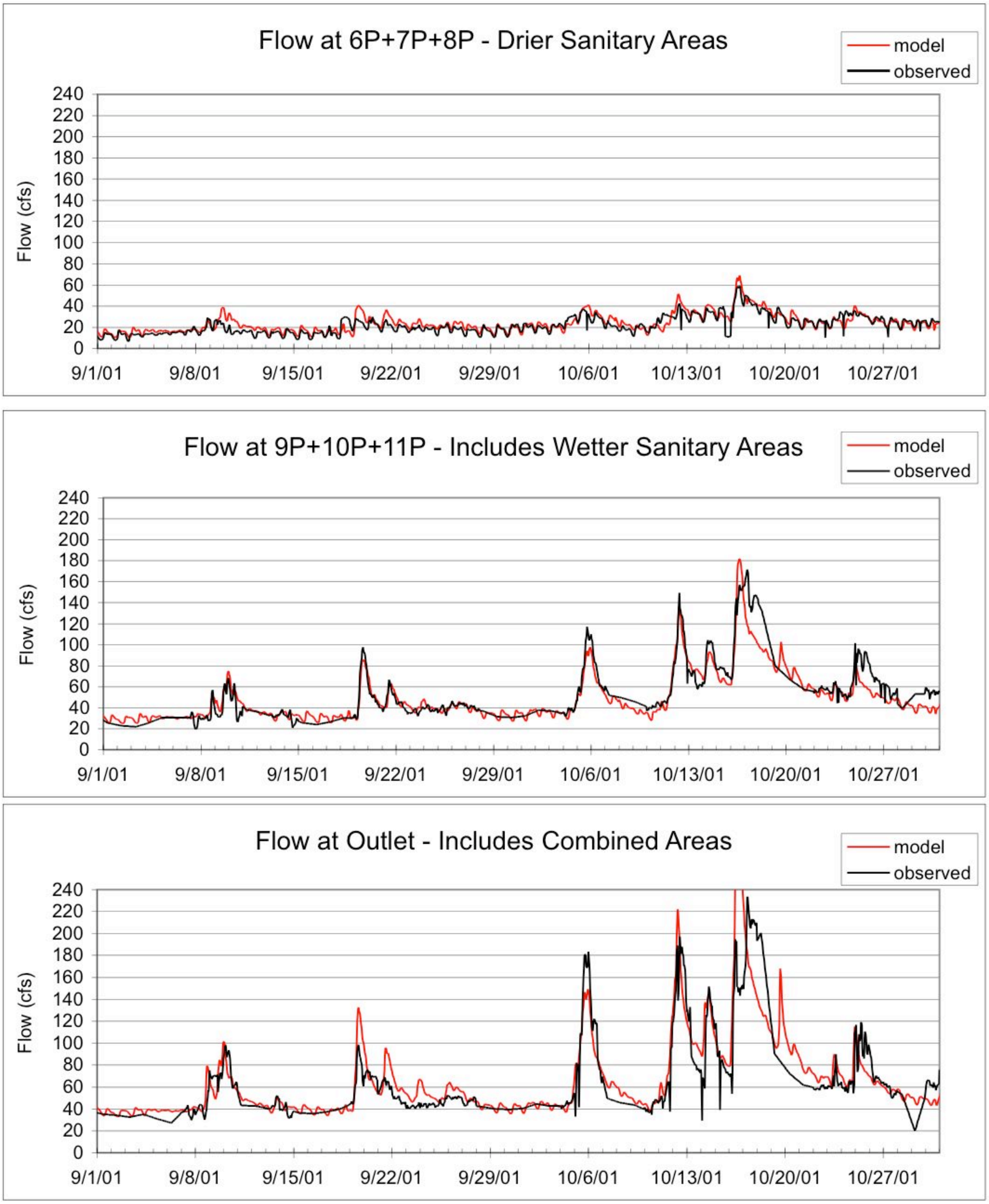

Figure 5 – Model Calibration Example

The model was calibrated to the years 2000-2001. This figure shows a portion of the calibration with a 15-day period with nearly 8-inches of rain, which produced highly varied AM conditions. The model accurately predicted these variations.

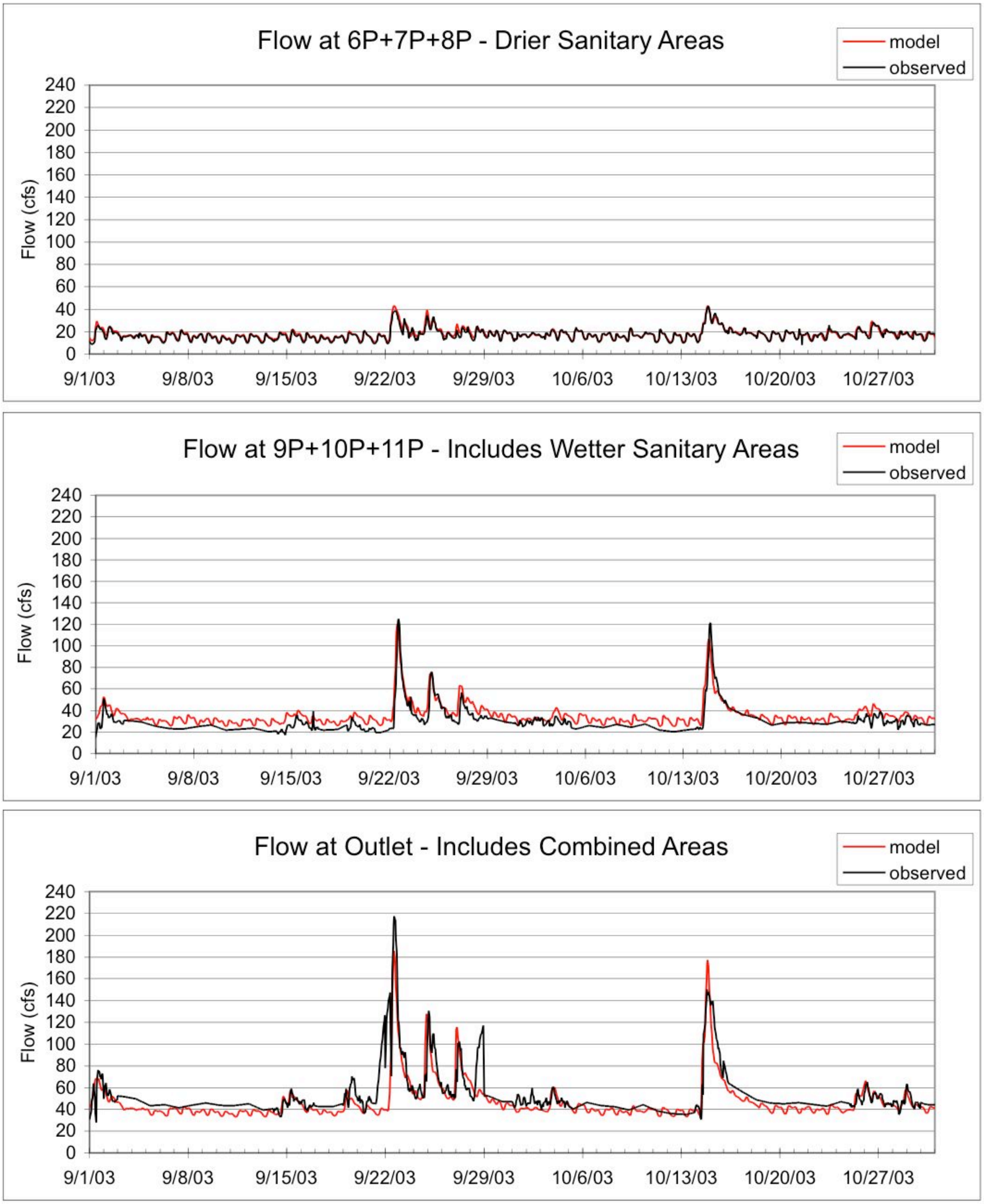

Figure 6 – Model Validation Example
The model was validated to the years 2002-2003. Validation was performed to test the model with no further manipulation of the model by the user. Rainfall and temperature were entered into the model and the output was compared against observations.

An accuracy of fit analysis was performed to quantify the performance of the model. The accuracy of fit analysis evaluated the ability of the model to predict peak flows and volumes for the four largest storms in each of the four years from the calibration/validation period. Figure 7 depicts a sample of the accuracy of fit results for the flow meter in Novi. Note that the i3D model accurately predicts the volumes, even for significant variations in capture coefficient. This is evident by examining the fit for the April 20 and July 30 storms, which have similar rainfalls, but different capture volumes. The overall model performance for the entire system resulted in less than 1% error in net peak flows and less than 5% error in net volumes for the four year period. Individual years had a greater variation in the accuracy than those for the entire four year period. For example, figure 7 shows that for the single year shown for Novi, the net error in peak flow and volume was 0.3% and 9.6%, respectively. This is viewed as excellent model performance, especially considering that, once calibrated, the model is predicting the variations in capture coefficient with no additional input from the modeler.

Comparing these accuracies to those from other studies should be done very carefully. Other studies that we examined used calibration data rather than validation data, used observed capture coefficients for simulations, selectively included or excluded events for analysis, or included base flows in the volume, all of which tend to artificially minimize error percentage.

System Hydraulic Restriction Findings

The EPA Storm Water Management Model (SWMM) was used to perform the hydraulic simulations for this study. Previous event-based modeling was done by another consultant and was performed in SWMM Version 4. For this project, the existing model was converted to SWMM 5.0 for use in the continuous simulation. The EXTRAN block of SWMM 5.0 was run using Dynamic Wave routing, which takes into account both the continuity and momentum equations for conduits, and a volume continuity equation at nodes. Data produced by the hydrologic models were used as input hydrographs in the hydraulic model.

The hydraulic model was first used in conjunction with the hydrologic model for calibration. This was mainly done to get a good match between modeled and observed flows. Because of the reported SSOs that have occurred, depths were also checked against observed data for storms that had known surcharging from 2000-2003. These comparisons were made at meters 9P, 10P, and 11P, which are located nearest to the locations of reported overflows. These comparisons revealed that the depths at 9P, 10P, and 11P were much less in the model than recorded in the observed data. The model showed that if the piping system functioned as modeled, no SSOs would have occurred from 2000-2003.

To validate these findings and ensure that the model accurately reflected the system, several steps were taken. First, the model was checked with the previous design event EXTRAN model (from SWMM Version 4) to ensure that translation of the hydraulic model was not causing the discrepancy. This work was performed by the same consultant that originally developed the SWMM 4 hydraulic model. The verification was done successfully and the resulting depths matched, indicating that hydraulic model translation was not the cause for the discrepancy.

Storm	Rain (in)	Observed Peak (cfs)	Model Peak (cfs)	Peak Flow Error (%)	Observed RDII Vol (1000's cf)	Model RDII Vol (1000's cf)	Volume Error (%)	Notes
04/20/00	2.26	15.1	13.6	-10.0%	1,477	1,454	-1.5%	
06/25/00	3.82	24.2	22.1	-8.4%	1,733	1,426	-17.7%	
07/30/00	1.82	17.5	17.8	1.3%	421	429	1.9%	
09/10/00	5.59	20.8	24.1	15.7%	3,324	2,621	-21.2%	River inflow event

	Peak Flow Error (%)	Volume Error (%)
Net Average Error	-0.3%	-9.6%
Total Average Error	8.9%	10.6%

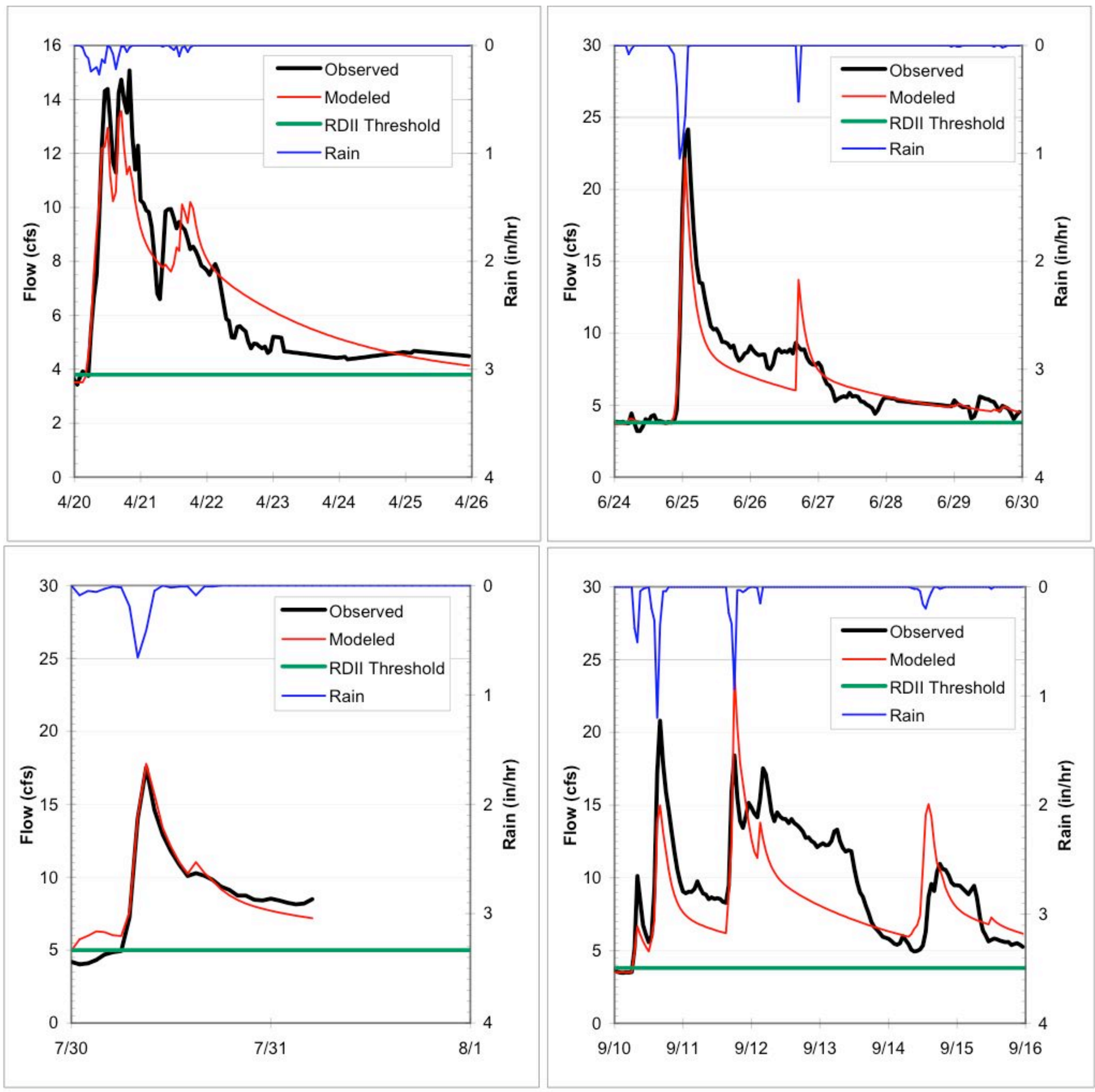

Figure 7 – Sample of Accuracy of Fit Analysis
An accuracy of fit analysis was performed for the four largest storms in each year. The overall net accuracy of fit was < 1% for peaks and < 5% for volumes. This is an excellent fit considering that the model predicts the variations in capture coefficients.

The next step taken was to input the actual observed flows and boundary conditions into the hydraulic model to eliminate the possibility of the discrepancy being caused by AM model hydrologic errors. This was done by following the null modeling procedures described earlier. This isolated the model to just the hydraulic simulation, because actual observed flows were used, and not the AM models. These models also showed that the system did not surcharge at 9P, 10P, and 11P, as the observed data indicated. Figure 8 depicts the results of this model simulation. Note that the depths match well during low flows, but during high flows there is a significant discrepancy between the modeled and observed depths.

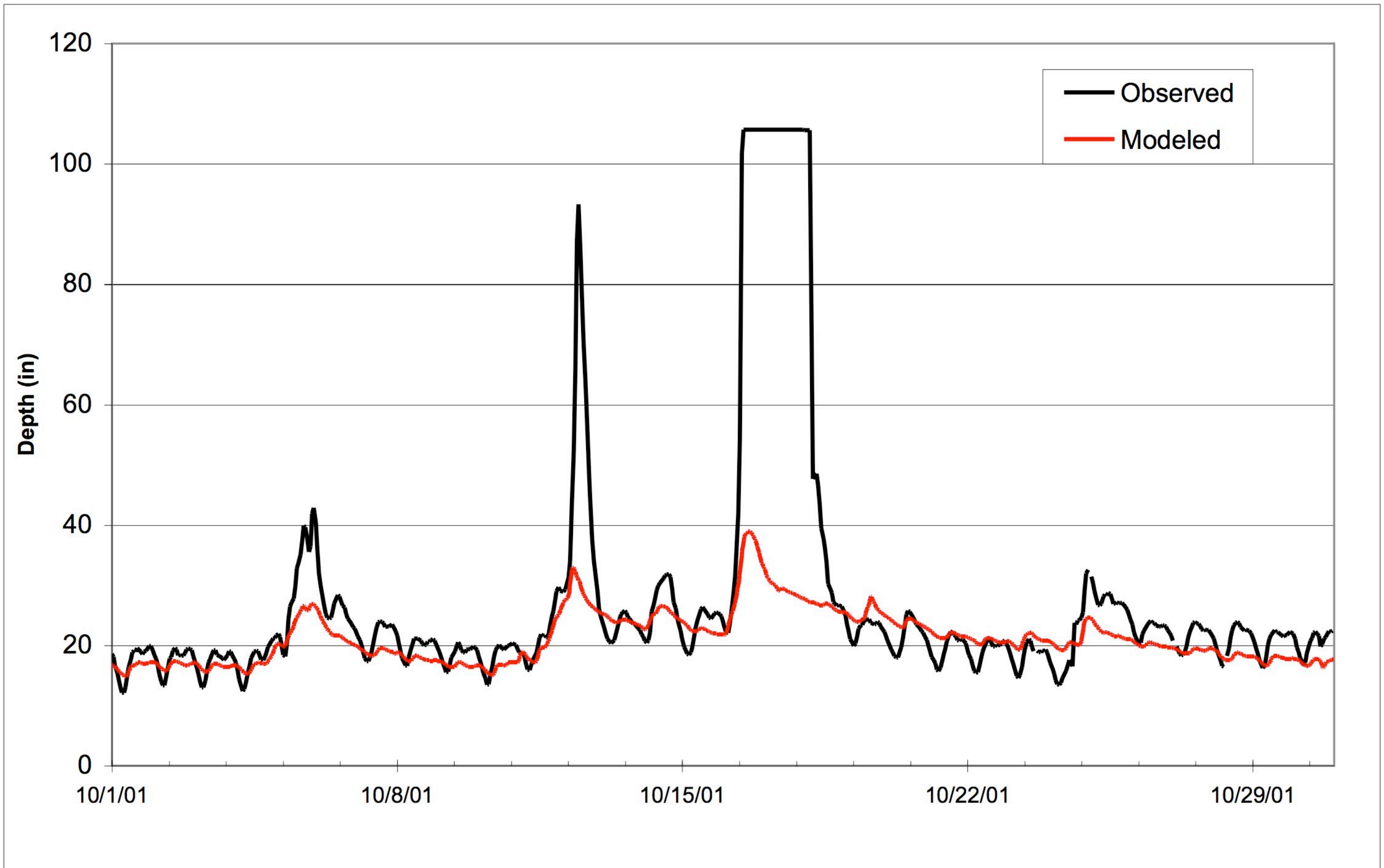

Figure 8 – Modeled Versus Observed Depths
Observed depths show significant back-ups for the largest storms, whereas the model predicted only moderate increases. From the information available at this time, the hydraulic discrepancy is thought to be the result of river inflow, a hydraulic restriction, or downstream hydraulic gradients. (Observed depth above 105-inches are not recorded due to meter limitation. Actual depth may have been higher.)

These results lead to the belief that there is possibly an influence on the system from the adjacent Rouge River, a blockage somewhere in the system, or influence from downstream flow levels. Since it is difficult to determine from existing data whether a system blockage or downstream levels may be the source of the discrepancy, further investigation is required. There may be open river flap gates in the system that may be the sources of river inflow. Yearly peak flow data for the nearest known USGS stream gauge (Middle Rouge River at Dearborn Heights) was gathered. The dates of reported SSOs all were determined to be peak yearly flows for the stream gauge, supporting the idea that river influence may explain or partly explain the elevated levels in the system. For the remainder of the study, the conditions causing the hydraulic discrepancy were assumed to be correctable and therefore were not integrated in further modeling. This assumption was also made for the null modeling described above, which may have slightly biased the estimation of the incremental flow hydrographs by lumping the hydraulic restriction effects into the null model.

This finding resulted in a recommendation to perform a physical investigation of the interceptor to locate and remove the source of the hydraulic discrepancy. The model results suggest that if the hydraulic discrepancy is located and removed, no SSOs would have occurred during the 2000-2003 period. This is a significant finding, as observations from the system suggest that several SSOs occurred during this period.

Continuous 18-Year Simulation

The calibrated and validated model was used to perform an 18-year continuous simulation for use in the frequency analysis. The existing EXTRAN model was used for all simulations, which assumes that the source or sources of hydraulic restriction are identified and corrected. Rainfall data was used from a series of seven (7) gauges located throughout the system to approximate the spatial variation in rainfall. Spatial variation of rainfall is a critical input to this type of analysis, and results are enhanced the more accurately it is represented in model runs. The 18-year period was used for the continuous simulation because that represented the period of record for which the spatially varied rainfall was available (1988-2005). The 18-year continuous simulation was used to represent how the current system would respond to a variety of rainfall events, providing data for use in the frequency analysis.

Frequency Analysis for Peak Flows

Based upon prior modeling work, frequency analyses were performed in order to determine the 10-year peak flow in the NHVRV system. The frequency analysis focused on meters 9P+10P+11P since this is near where SSOs have occurred. April 1 – October 31 was defined as the period of concern by MDEQ, so the analysis was limited to this period. A Log Pearson Type III probability function was used to describe the peak flow data. In addition to predicting the peak flow with a frequency of once every ten years, the probability distribution was used to estimate the frequency of exceeding the existing system's design capacity, which was determined to be approximately 200 cfs at meters 9P+10P+11P, based on the threshold that produced surcharging in the model.

Figure 9 shows the frequency analysis that was performed for existing conditions. This figure shows the peak flow versus the annual exceedance probability of that flow. As shown on this figure, the Log-Pearson Type III distribution can be used to determine the 10-year frequency peak flow (indicated by the dashed black line) and can also be used to determine the probability of exceeding the 200 cfs capacity of the system at meters 9P+10P+11P (indicated by the dashed blue line).

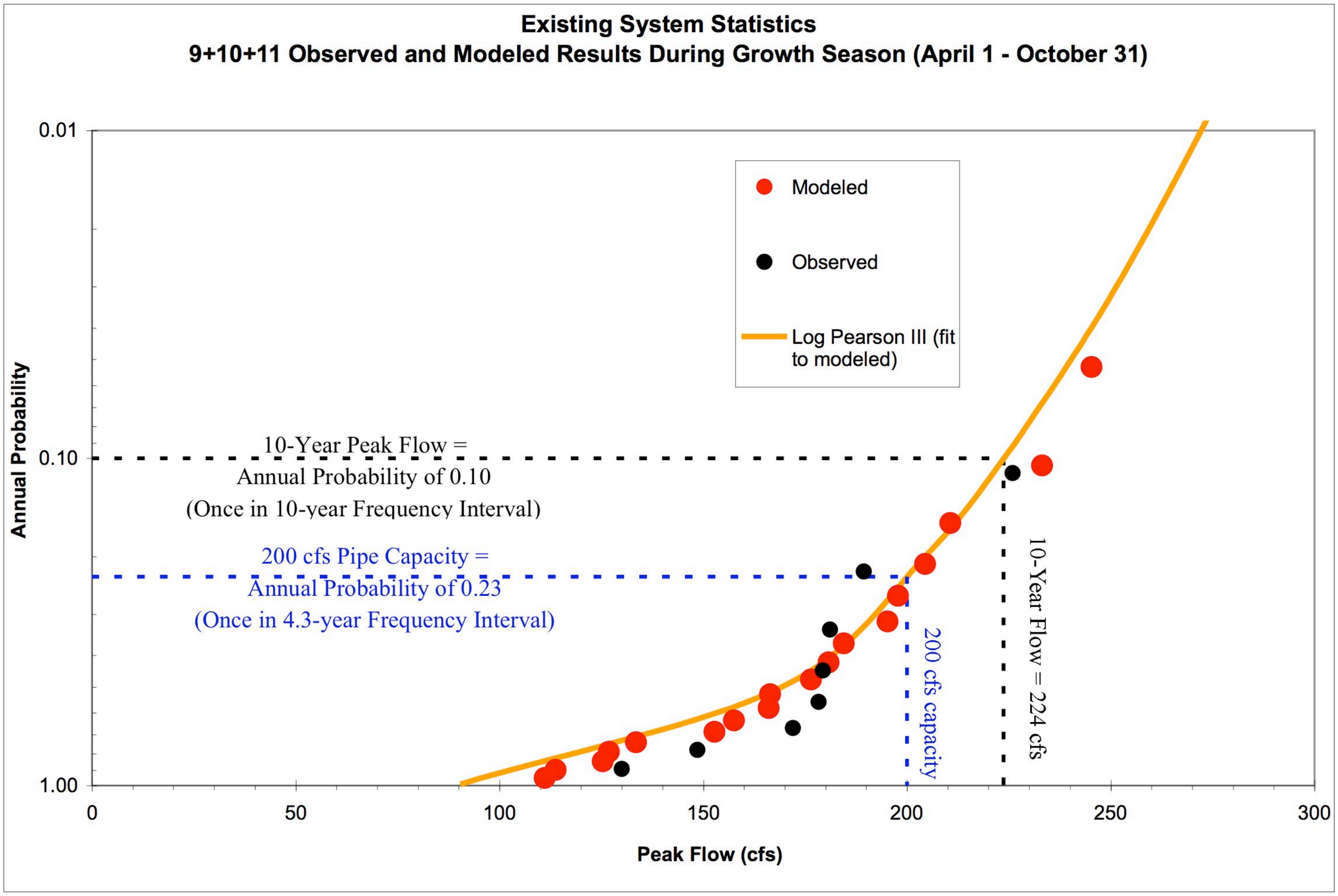

Figure 9 – Existing Peak Flow Statistics
This plot shows the results of the Log-Pearson Type III analysis for existing peak flows. Note that the observed points match very well with the modeled points. The plot was used to determine the 10-year flow and the frequency of exceeding the system capacity.

Each red point in Figure 9 represents the highest peak flow modeled for each of the 18-years. The black points show the results from observations for each of the 8-years available. The good match between the model points and observed points is evidence of the accuracy of the model. This provided confidence in the modeling results and statistical analysis of peak flows.

The frequency analysis demonstrated that the capacity of the existing system will be exceeded approximately once every 4.3 years (23% annual exceedance) and that the 10-year peak flow rate is 224 cfs (10% annual exceedance). The 4.3 year frequency for exceeding system capacity seems reasonable considering the observed frequency of SSOs. These results also produced confidence in the modeling and statistical analysis for peak flows.

Tunnel Volume Sizing

The final step in the process assumed that construction of a transport / storage tunnel would be required to augment system capacity to minimize SSOs. To account for future conditions adjustments for growth, future flows were entered into the model and the frequency analysis was revised. Additionally, the future conditions continuous model was modified to include a transport/storage tunnel to handle flows that exceed the system capacity. Figure 10 shows the results of the Log-Pearson Type III analysis for future conditions. The plot also contains the volume that entered the tunnel in the model for each of the events that exceeded existing system capacity.

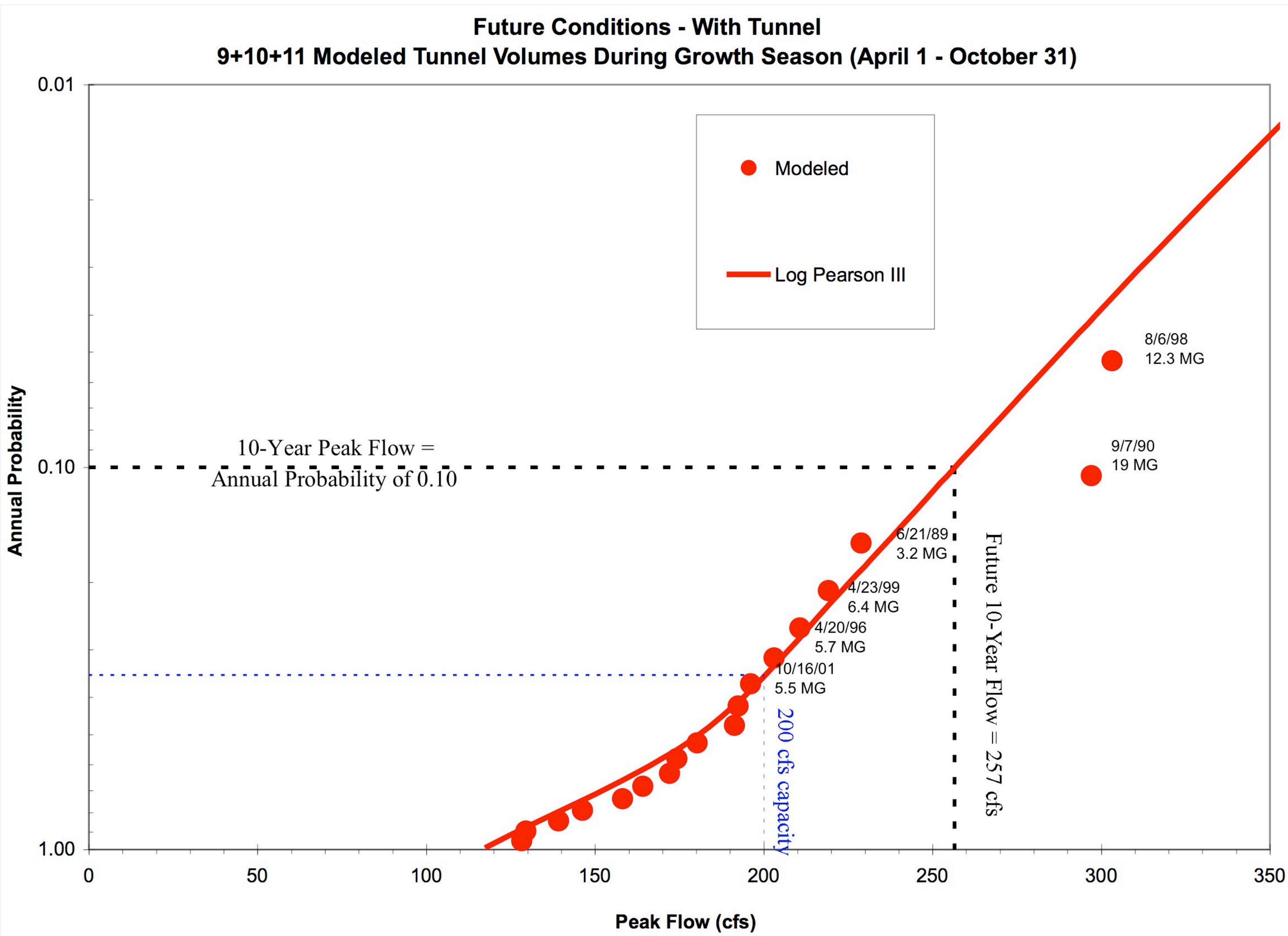

Figure 10 – Tunnel Volume Sizing
This plot shows the results of the Log-Pearson Type III analysis for future peak flows. Events that exceeded system capacity are labeled with the volume discharged to the tunnel. A 6.4 MG tunnel is required to capture all historic storms up to a 10-year flow.

There were six (6) events in the 18-year simulation that exceeded the existing system capacity of 200 cfs. Four (4) of these events had peak flows that were less than the 10-year peak flow rate estimate from the Log Pearson Type III analysis, and two (2) events had peak flows that were greater than the 10-year peak flows. The tunnel volume was selected to completely capture the volume generated from storms in the model that produced up to the 10-year peak flow. This resulted in a recommended 7.5-foot diameter, approximately 20,000 feet in length tunnel with an effective volume of 6.4 MG. It should be noted that the MDEQ appears comfortable with the modeling and peak flow statistics, but has not concurred with the volume recommendation at this time. For peak flows above a 10-year frequency, opportunities may exist to route tunnel overflow through a nearby CSO basin for treatment.

DISCUSSION

Previous event modeling had led to the conclusion that a relief/storage tunnel with an outlet to a CSO retention treatment basin would likely be the required SSO control project. Previous analysis also estimated that the largest constructable tunnel was 9.5-feet in diameter, which would result in a total volume of approximately 10 MG. Frequency of SSO events was explored with this tunnel size by trying to use an event model, but the confidence in the results was not as high as desired for the anticipated magnitude of the capital investment involved.

The use of the i3D AM model resulted in a continuous model prediction that closely matched system observations. This match was achieved for both continuous flow predictions and for the system peak flow statistics. This provided confidence in the model, the predicted frequency analysis, and resulting tunnel sizing for the historic peak flow events.

The results from the antecedent moisture modeling revealed a potential system hydraulic restriction. Additional sewer system physical evaluation is required to determine the cause of the restriction, but the EXTRAN model was felt to accurately represent the hydraulic characteristics of the system with the bottleneck removed. Though the cause of the hydraulic restriction is unknown, the current model was used to size the tunnel improvements by assuming that the source or sources of the restriction can be located and corrected.

Using this methodology, an effective tunnel size of 6.4 MG was recommended to capture the flow for up to a 10-year frequency event. The tunnel size will be revisited once the source or sources of the hydraulic restriction is located and removed, and it can be verified that the hydraulic model accurately represents the system after rehabilitation. The following recommendations have been made as a result of the study:

- A Sewer System Evaluation Survey (SSES) was recommended to determine the cause and solution for the hydraulic restriction identified as a result of modeling work.

- Several of the existing system meters are not as effective as desired in obtaining good system data during critical conditions (especially at the outlet). It was recommended that the metering system be modified to better capture this data. This can be accomplished by moving meters 4P and 8P (shown on figure 4) to downstream locations near the outlet to better record downstream hydraulic gradients.

- A relief tunnel was recommended with a diameter of approximately 7.5 feet with one intermediate control point to provide an effective storage volume of approximately 6.4 million gallons.

- The relief tunnel would ideally be connected to a local CSO basin to accept flows beyond the 10-year frequency event to provide some degree of treatment and protect water quality in the river to the maximum degree practical.

- An option that was suggested by MDEQ was to consider adjusting the regulators for the combined sewer areas to a minimal setting to allow for additional flow from separate sewer areas. The model is planned for expansion to the Lower Branch of the system, which will provide better information to adequately examine this alternative.

CONCLUSIONS

The frequency analysis for the NHVRV system was performed using a new and innovative hydrologic modeling approach that incorporates antecedent moisture effects. We offer the following conclusions regarding the use of this approach:

- The use of the antecedent moisture model produced output that accurately matches system flow observations, even for highly varied rainfall and system capture coefficients, providing confidence in the resulting analysis, design simulations and recommendations for improvements.
- Spatially varied rainfall had a significant impact on the observed flow in the system. It is critical to account for spatially varied rainfall to perform an accurate frequency analysis.
- A hydraulic restriction in the system was uncovered through a process called null modeling that isolated the model performance to the hydraulics. This restriction was not found during the event modeling because hydrologic model imprecision masked the hydraulic effects of the restriction. It is important to isolate the hydraulic model to accurately assess the system hydraulic performance.
- A frequency basis may be preferable to a design storm event for regulatory agencies. The use of a frequency analysis eliminates the need to develop "average conditions" or to assume a capture coefficient for design event simulations.
- Use of the antecedent moisture model as opposed to a design storm event eliminated many of the conservatisms that are frequently included in design event models, can result in the identification of cost effective projects to address capacity deficiencies, and provide a greater degree of confidence that the system will perform as predicted.

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