Sewer Assessment, I/I Assessment and Recalibration Saves Millions

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The Metropolitan Sewer District of Greater Cincinnati (MSDGC, the District) is committed to the elimination of sanitary sewer overflows (SSO) and basement flooding events in their combined and sanitary sewer networks. In meeting this commitment in the Richmond/Orchard study area, the District has completed a Storm Water Removal Program, conducted flow monitoring and hydraulic modeling, and prepared a remedial measures plan to reduce SSO activity and basement flooding complaints. The recommended remedial plan was considered costly. As a result the District undertook to further evaluate area hydraulic and flooding problems with a focus to improve upon the previous studies when it was determined they did not have the benefit of complete and accurate calibration and system geometry data. A hydraulic model, MIKE SWMM, was developed and calibrated using flow monitoring data collected during the study period and verified using historical monitoring data. Model verification included a more complete consideration of flow, volume, stage, and hydraulic conveyance properties throughout the collection system. The study resulted in a combination of system improvements at an estimated cost of approximately one third of the original estimates to reduce SSO and basement flooding occurrences.

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34.1 Introduction

Richmond/Orchard and Blue Ash/Clifford are two adjacent sanitary drainage areas located in Hamilton County in the southwest corner of Ohio that have a history of basement flooding complaints and SSOs. A previous District Storm Removal Program identified and corrected sources of rainfall derived inflow/infiltration (RDI/I), much of the corrective work focused on the removal of direct inflow connections from sources such as driveway drains, roof leaders, and catchbasin cross-connections. The program, although successful in reducing a portion of RDI/I observed in the sanitary system was not sufficient to control SSO or eliminate basement flooding events. In response to the continued SSO and basement flooding events, the District had undertaken two previous investigations:

- Special Investigation Richmond/Orchard and Blue Ash/Clifford, March 1998.
- Special Project Richmond/Orchard and Blue Ash/Clifford Detention Basin Evaluation, May 1998.

These studies involved flow monitoring, sewer inspection programs, and hydraulic modeling.

Completed in 1998, the initial study identified a combination of pipe upgrades, storage, and system rehabilitation that was estimated to cost approximately US\$21.0 million to implement. The costs were considered prohibitive for the area, and questions were raised regarding the information used in the development and evaluation of alternatives. A second opinion was sought regarding the sizing of a proposed detention basin. The supplemental work did not result in any significant reduction in costs. However, several shortcomings were identified in the first study that could affect the proposed corrective measures. The following shortcomings were identified:

- Limited flow monitoring data for wet weather events. Flow data were collected at select locations between 1996 and 1998 with limited wet weather events except for one significant event April 15-16, 1998, that caused basement flooding and the SSO to activate.
- Influence of the storm system on the sanitary system associated with the SSO. The SSO has a backwater flap gate that may be closed if the downstream storm sewer surcharges. According to the previous study, the storm system was not adequately sized for the service area, creating the potential for the storm sewer system to surcharge closing off the flap gate. Potential impacts

of the storm system on the sanitary system were suspected but unknown and required investigation.

- The MSDGC rain gauge used for previous assessments was suspected of producing poor quality data and required verification.
- System outlet restrictions were identified in previous studies in the study area; further investigation on the extent of these restrictions outside of the study area was identified as a factor that may change control alternatives.

Given the previous studies' proposed remediation cost of US\$21 million, these shortcomings warranted another area assessment. This project goal was to eliminate SSO and basement flooding events, by building on existing information while addressing the previous studies shortcomings. This study was also premised on managing wet weather flows in the sanitary system rather than focusing on the elimination of extraneous flows.

34.2 Methodology

Given the identified shortcomings in the previous study and the significant investment the District had made in the Richmond/Orchard area, the project approach focused on establishing a defensible data set and hydraulic model for use in developing and evaluating control alternatives.

Figure 34.1 Study area.

The Richmond/Orchard study area is approximately 89 hectares (220 acres) of predominately medium density residential development with commercial strips along main roads located in Hamilton County, Ohio, Figure 34.1. The Richmond/Orchard and Blue Ash/Clifford monitoring locations are shown in Figure 34.2. This study area is highlighted by two main sanitary drainage systems in the area that ultimately discharge into a downstream combined sewer system. The study area is serviced by four separate storm sewers systems that also discharge into combined sewer systems outside of the immediate study area.

Figure 34.2 Flow monitoring locations.

34.3 Field Programs and Inspections

The study involved a field program which included a flow monitoring program that began April 7, 2000 and was completed by August 8, 2000 for a total of four months. The monitoring program included the installation of a combination of Sigma 910 and Sigma 920 data-logging area-velocity flow meters, along with the installation of one tipping bucket rain gauge and three groundwater monitors.

The selection of flow monitoring sites was founded on:

- the review of previous monitoring locations;
- the need to define the performance of the local storm system and possible interaction with the sanitary system;
- the need to define downstream boundary conditions for the sanitary, combined, and storm outlet conditions; and
- to characterize RDI/I at the local level.

A total of 10 flow monitoring locations were selected to meet the monitoring objectives of the project including a combination of sanitary, combined, and storm sewer installations. The flow monitoring installations were inspected, cleaned, and field verified with portable instruments at least once per month during the program. Data were downloaded and reviewed weekly ensuring meters continued to operate properly and provide reliable data.

To support the flow monitoring program a study tipping bucket rain gauge and standard sight gauge were installed to compare with the MSDGC Deer Park tipping bucket rain gauge located in close proximity to the study area. The Deer Park rain gauge was used as the primary source of rainfall data for the previous studies. The rainfall measurements from the MSDGC Deer Park gauge were found to consistently underestimate the rainfall in the area in comparison to the study gauge and sight gauge. Subsequent to this assessment, MSDGC contracted with Vieux & Associates Inc. to undertake a detailed review of all 25 MSDGC rain gauge locations. Results of the review confirmed the findings of this study and determined the Deer Park gauge was located in a rain shadow of a building, did not perform well and had approximately a -45% error. This finding was significant as all previous modeling was done using the Deer Park rain gauge. As such, for this study the project rain gauge was used for all analysis.

Ground water monitors were also installed at three locations throughout the study area. Simple groundwater monitors were installed by drilling a hole through the manhole wall at the base of the manhole and inserting a piezometric tube into the surrounding media. The piezometric tube is translucent and groundwater can fill the tube and rise to the same hydraulic grade line as the groundwater surrounding the manhole. The groundwater level was manually recorded during visits to the monitoring location and was found not to be a significant factor in this area. This approach is a cost effective method for assessing the potential influence of groundwater in the immediate vicinity of the manhole and whether groundwater should be considered in any further evaluation.

The flow monitoring data collected were assessed over the entire monitoring period for both dry and wet weather conditions. To characterize the dry weather flow, typical diurnal flows were developed for each monitoring station. A dry weather flow period was defined as having no rainfall in the preceding 72 h. The typical 24-h hydrograph is based on at least three representative days of dry weather flow averaged together. In all cases, the three days averaged together were consecutive. From the typical dry weather flow hydrographs the average, peak, and minimum flow values were calculated. The dry weather flow analysis identified the following characteristics:

- the 1998 and the 2000 dry weather monitoring data were consistent for common monitoring stations;
- dry weather flows observed were within typical sanitary sewer design rates of 303 to 380 L/capita/day (80 to 100 gal/capita/day); and
- dry weather flow infiltration was not a significant source of extraneous flow.

Prior to undertaking the wet weather flow analysis the rain gauge data was assessed to identify events that would be suitable for model calibration. Three events were selected from the 2000 monitoring program for their distinct precipitation characteristics:

- May 13 (27 mm/1.07 in.);
- May 27 (32 mm/1.26 in.); and
- June 16-19 (71.3 mm/2.81 in.).

These storms represented the largest events over the monitoring period for surcharge and backwater conditions in the network. In addition, a review of historical flow data collected in 1997 and 1998 was undertaken to identify critical flow events. From this review, the April 15-16, 1998 event stood out. This event caused basement flooding, activated the SSO, and data from eight flow monitoring stations were considered reliable. For this April 1998 event, the Deer Park rain gauge recorded 41.7 mm (1.64 in.). However, radar imagery for the April 15-16, 1998 obtained through Vieux & Associates Inc. determined the actual rainfall to be 84.3 mm (3.32 in.). The rainfall total from the radar imagery is consistent with the -45% error determined and the measurements observed at the study rain gauge. The April 15-16, 1998 event was selected to verify the system hydraulic model.

Figure 34.3 presents the Cincinnati intensity-duration-frequency (IDF) curves in comparison to the three events from the 2000 monitoring program and the April 15-16, 1998 event. In reviewing the IDF curves, the June 17, 2000, event has the most intense 15-min period, close to the 1-y event. The rainfall

Figure 34.3 Cincinnati IDF curve.

characteristics of the April 15-16, 1998, event show that the event was not particularly intense, but persistent, and longer in duration. From discussions with MSDGC staff and review of flow records, the Richmond/Orchard area is more sensitive to long duration, low intensity events, versus short duration, high intensity events. Anecdotal information from MSDGC staff identified that basement flooding in the area was typically associated with saturated ground conditions as a result of longer low intensity rainfall events.

The wet weather analysis assessed the three wet weather events from the 2000 monitoring program and the April 15-16, 1998 event. To characterize RDI/I, the volumetric runoff coefficient (C_v) is calculated. The C_v is the percentage of rainfall volume that shows up as RDI/I flow in the sewer over a given service area. Table 34.1 gives a summary of C_v values for the three events in 2000 and the 1998 event at common monitoring points.

The following observations were made:

- For the May 13 and 27 events, the volumes of wet weather were reasonably consistent for similar size events.
- C_v for the sanitary system range from approximately 5% to 10%, which is considered high for sanitary sewers of this age and material. Typical C_v values for a sanitary sewer system range between 1% to 5%.
- For the storm monitoring sites, the C_v ranges from 12% to 15%, which is considered low for a storm system in an urban area.

Table 34.1 Volumetric runoff coefficients.

Site	Area (ac)	Runoff Volume (ft ³)				Volumetric Runoff Coefficient, Cv			
		May 13, 2000 (1.07")	May 27, 2000 (1.26")	June 16- 19, 2000 (2.81")	April 15, 1998 (3.32")	May 13, 2000	May 27, 2000	June 16- 19, 2000	April 15, 1998
MS2 (sanitary)	45.17	9,800	8,600	32,000	-	5.6%	4.2%	6.9%	-
MS3 (sanitary)	22.47	4,900	5,300	19,000	85,600	5.6%	5.2%	8.3%	31.6%
MS4 (sanitary)	18.1	3,000	3,300	14,000	-	4.3%	4.0%	7.6%	-
MS5 (sanitary)	31.91	6,400	10,000	35,000	88,500	5.2%	6.9%	10.8%	23.0%
MS6(Combined)	127.31	38,000	44,000	140,000	400,000	7.7%	7.6%	10.8%	26.1%
MS7 (storm)	78.9	36,000	50,000	115,000	-	11.8%	13.8%	14.3%	-
MS8 (storm)	33.6	18,000	23,000	51,000	-	13.8%	15.0%	14.9%	-
MS9 (storm)	36.4	17,000	19,000	51,000	-	12.0%	11.4%	13.7%	-
MS10 (sanitary)	87.3	48,000	28,000	77,000	279,000	14.2%	7.0%	8.7%	26.5%

This may indicate that the storm system is underutilized. Typical storm area C_v values are greater than 25% for areas with a runoff coefficient of approximately 50%.

- MS10 C_v decreases in May because of the removal of storm flow from the combined system through local improvements made in the area during the monitoring period.
- The C_v are significantly higher for the April 15-16, 1998 event in comparison to the 2000 monitoring results.

In addition to the monitoring program a system survey and inspection program was undertaken with the objective of verifying collection system physical geometry and connectivity in support of the hydraulic model development. In 1997, an investigation of 37 sanitary manholes was performed by a consultant in the Richmond/Orchard study area. This investigation included evaluating evidence of surcharging, overall structural condition, and evidence of infiltration/inflow. The survey was carried out for the main branches of the sanitary collection system in the study area and included determining manhole and pipe inverts at designated manhole locations. The majority of the survey confirmed the data currently in the Cincinnati Area Geographic Information System (CAGIS). The most significant discrepancies between CAGIS and the field survey were found in pipe diameter. The most evident pipe diameter differences occurred where slip lining was conducted had been updated in CAGIS and when the pipe had a bell section at the manhole that led to a smaller pipe. Supplemental inspections were undertaken at selected points in the system requiring full entry. The inspections were used to further verify dimensions associated with the system such as drops, pipe material (e.g. lined pipes), and to accurately measure relevant elevations. The information collected was represented in the updated system model and played an important role in the model calibration as discussed in section 34.5.

34.4 Hydraulic Model Development

The previous SWMM system models were developed from CAGIS system data and calibrated using flow monitoring data. This data was collected in the study area from August 1996 through the summer of 1998 with rainfall data from the MSDGC Deer Park rain gauge. The previous studies were developed to address basement flooding and SSO elimination and reported the following modeling limitations:

- Outlet (or boundary) conditions at SSO 579 and on Glenellyn Drive (the main sanitary outlet for the area) were not well defined.
- Model calibration was brought into question. This was further complicated given the MSDGC Deer Park rain gauge was used as the primary source of rainfall data and was suspect.
- The wet weather events used for calibration were limited in volume with the exception of the April 15-16, 1998 event. As a result, confidence in the evaluation of alternative controls was limited to the range of events observed.

To address these limitations, the MIKE SWMM program was used as the collection system model so that the Richmond/Orchard model could be incorporated into the District's ongoing System-Wide Model project. The extent of the MIKE SWMM model used for the Richmond/Orchard assessment went beyond the previous modeled network and extended further downstream to include critical sections of the combined and sanitary sewer systems outside of the immediate study area. As well, the storm network was added to the model to evaluate its potential influence on the sanitary system especially back through the SSO. The extension of the network model was supported by the selection of flow monitoring sites used to define outlet conditions. The monitoring program defined the following outlet conditions that were used in model development and calibration:

- The outlet of SSO 579 is not limited by the storm system discharge point. Based upon available monitoring data, the storm system does not cause backwater conditions at the SSO flap gate, which would result in adverse conditions in the sanitary system and increase the potential for basement flooding.
- Outlet conditions for the combined and sanitary sewer pipes on Glenellyn Drive were defined through the flow monitoring. During most wet weather events, the 300 mm (12 in.) sanitary sewer pipe became surcharged, and backwater conditions were evident. The 675 mm (27 in.) combined sewer pipe operated freely during observed wet weather events and additional hydraulic capacity was created with the diversion of stormwater.
- Other storm sewer outlets monitored displayed no adverse capacity problems during the monitoring period.

The collection systems were represented in the model with a high resolution in detail. All pipes and manholes in the study area were included in the hydraulic model in order to capture the changes and variety of pipe diameters and pipe materials. CAGIS data were used to define pipe diameter, pipe length,

manhole invert, pipe inverts, and ground elevations. This information was updated with the field survey data. Catchments were similarly defined at a high level of detail.

Two approaches are available to simulate the hydrologic response. The first is to use a similar approach that is typically used for combined sewer systems. Surface runoff is defined by rainfall excess and overland flow routing, both of which can be modeled using available map based data to define catchment imperviousness, pervious area infiltration characteristics, basin geometry, ground slope, roughness, and other losses using the RUNOFF routine in SWMM. This approach is well suited to modeling combined and storm system hydrology but can be limiting with respect to sanitary sewer RDI/I.

The second approach is to use the unit hydrograph methods. Hydrologic processes in sanitary sewer systems are influenced by numerous variables, both directly and indirectly, in response to wet weather. Empirical methods offer a quick, pragmatic approximation of the hydrologic response in the sanitary sewer, rather than deterministically modeling of highly variable and uncertain physical processes as is done in the first approach.

The SWMM model has an RDI/I routine based on a unit hydrograph approach to characterize the relationship between rainfall and inflow/infiltration in sanitary systems. This routine uses three triangular unit runoff hydrographs. Each runoff hydrograph represents:

- fast response, which can represent direct hydraulic connects potential associated with cross connections, roof leaders, etc.;
- medium response, which can represent more direct infiltration such as weeping tile or lateral drains; and,
- slow response, which can represent infiltration through pipe cracks.

By using the drainage area, defining the shape of the unit hydrographs, and the contribution of each unit hydrograph, the RDI/I response can be defined at each monitoring location.

Once the RDI/I response has been determined, the parameters used to define the unit hydrographs can be applied to sub-catchments upstream of the monitoring point. The parameters used to define the unit hydrographs include:

- R - The fraction of rainfall volume that enters the sanitary sewer system
- T - The time to peak in hours
- K - The ratio of time to recession to the time to peak

The network inflow RDI/I hydrograph considers rainfall depth, service area, antecedent moisture conditions (AMC) and the definition of unit hydrographs. For the Richmond/Orchard study, the RUNOFF and the RDI/I routines were used. The RUNOFF routine was used to define the hydrologic response in the storm and combined sewer systems. The RDI/I routine was used to define the hydrologic response in the sanitary sewer system.

34.5 System Model Calibration and Verification

Calibration of the MIKE SWMM model was achieved by adjusting model parameters until the model produced flow hydrographs at the monitoring locations that matched the collected field data with respect to peak flow, volume, and shape. As mentioned earlier, the RDI/I routine was used to model the sanitary system, while the RUNOFF routine was used to model the storm and combined systems. In addition to the flow hydrograph calibration, plots of flow versus head for selected pipe segments were compared between modeled and field data to confirm that the hydraulic properties of the physical network were properly represented.

For the three 2000 wet weather events (May 13, May 27, and June 16-19) a good calibration was achieved at all flow monitoring stations. Figure 34.4 compares the modeled wet weather flow to the actual flow at one monitoring location illustrating the agreement between modeled and actual flows. Table 34.2 details the percent difference between measured and modeled flow volume and peak stage for each of our calibrated events. Note that dry weather flow was removed from the measured flows (as described in Section 34.3) and was not represented in the model.

It was considered important to undertake a model verification using an independent historical event given the previous questions raised on model calibration. The objective of model verification was to independently test the calibration against another storm event with different characteristics to verify the calibration.

The model calibration was limited to the events recorded in the 2000 monitoring program. None of the three 2000 calibration events were significant enough to cause an SSO, but they did result in system backwater and surcharging in the system. To undertake the model verification, the April 15-16, 1998, event was used. The rainfall volume of 84 mm (3.3 in.) approximates the Cincinnati area 10-y 24-h design event volume that was used for subsequent hydraulic assessment and caused basement flooding.

Table 34.2 Percent difference between measured and modeled peak stage and flow volume.

Site	Runoff Volume (ft ³)								
	13-May-00			27-May-00			16-Jun-00		
	Measured	Modeled	Percent difference	Measured	Modeled	Percent difference	Measured	Modeled	Percent difference
MS2 (sanitary)	9,800	8,800	-10%	8,600	10,900	27%	32,000	33,000	3%
MS3 (sanitary)	6,300	5,000	-21%	5,300	6,200	17%	19,000	20,000	5%
MS4 (sanitary)	3,900	3,900	0%	3,300	4,800	45%	14,000	14,400	3%
MS5 (sanitary)	8,300	8,800	6%	10,000	11,000	10%	35,000	36,000	3%
MS6(Combined)	38,000	36,800	-3%	43,000	44,000	2%	140,000	130,000	-7%
MS7 (storm)	36,000	41,000	14%	50,000	48,000	-4%	115,000	110,000	-4%
MS8 (storm)	18,000	19,000	6%	23,000	22,000	-4%	51,000	49,000	-4%
MS9 (storm)	17,000	18,000	6%	19,000	21,000	11%	51,000	47,000	-8%
MS10 (sanitary)	65,000	46,000	-29%	47,000	58,000	23%	128,000	157,000	23%
Site	Peak Flow (cfs)								
	13-May-00			27-May-00			16-Jun-00		
	Measured	Modeled	Percent difference	Measured	Modeled	Percent difference	Measured	Modeled	Percent difference
MS2 (sanitary)	0.55	0.62	13%	0.85	0.77	-9%	0.84	0.83	-1%
MS3 (sanitary)	0.35	0.41	17%	0.44	0.49	11%	0.44	0.66	50%
MS4 (sanitary)	0.32	0.35	9%	0.43	0.39	-9%	0.49	0.57	16%
MS5 (sanitary)	0.66	0.92	39%	1.03	0.93	-10%	0.86	1.15	34%
MS6(Combined)	2.74	2.46	-10%	3.78	3.06	-19%	2.94	3.18	8%
MS7 (storm)	6.74	12.1	80%	9.69	9.40	-3%	19.5	27.4	41%
MS8 (storm)	5.36	6.35	18%	5.51	4.66	-15%	12.1	14.4	19%
MS9 (storm)	5.58	6.76	21%	5.06	4.93	-3%	18.9	15.4	-19%
MS10 (sanitary)	8.79	7.09	-19%	5.11	5.97	17%	10.5	15.0	43%

Figure 34.4 MS5 - calibration event - June 16-19, 2000.

The calibrated system model was run with the April 15-16, 1998, event and model flow hydrographs were compared to the actual flow hydrographs at each monitoring location used in the 1998 monitoring program. In the comparison, the calibrated system model generated appreciably less wet weather flow than observed in the 1998 flow data, approximately 1/3 the volume observed in the 1998 monitoring data. The calibrated model hydrograph did not adequately represent the flow monitoring data, underestimating the peak flows and total flow volumes.

The flow data, radar information, and physical network were scrutinized to account for the significant difference in peak flow and event volume for the verification event. Furthermore, historical rainfall records for April 1998 showed a significant wet weather event of 72 mm (2.84 in.) five days prior to the April 15th event with scattered rain occurring in between. Based on available data and historical rainfall trends, it was deduced that ground conditions were saturated. As observed in the wet weather data analysis, the volumetric response during the April 15-16, 1998, event was significantly greater than observed for events observed in the 2000 monitoring program. Given the response in the collection system was more severe for the April 15-16, 1998, event and event rainfall volume was closer to the 10-y 24-h design event, the system model was re-calibrated to the April 15-16, 1998 verification event.

The initial step in the re-calibration involved increasing the RDI/I volume to account for saturated ground conditions. This was accomplished by increasing the percentage of rainfall that became I/I. In the re-calibration process it was found that the additional RDI/I volume, although the correct magnitude, could not be conveyed by the system without surcharging in the model to the ground surface. Actual flow data did not support this response. To eliminate surcharge conditions in the model the conveyance capacity would need to increase, thus resulting in a lower flow head. To achieve this pipe roughness, the model was calibrated to better match the measured Q-h rating curve. Reviewing CAGIS database and inspection records, the portions of the collection system that have been lined or replaced with PVC pipe were assigned lower roughness factors. Lowering the roughness factors on PVC and lined pipes in the system model as part of the re-calibration process had a significant affect on the Q-h relationship for the 1998 event. The same pipe roughness changes for the 2000 calibration events does not have a significant affect on head because the system was not under the same surcharged conditions. This refinement in the pipe hydraulic factors increased the conveyance capacity along select sections and brought the modeled flow and flow depth into agreement with actual monitoring data throughout the network. Re-calibration was successfully completed with acceptable agreement for the April 15-16, 1998, event between model and actual flow data for flow and depth hydrographs. Figure 34.5 shows an example of flow data with model results using the re-calibrated model, as well as showing the difference in RDI/I response between 1998 and 2000 model parameters.

The outcome of the model verification identified the limitations of the original calibration highlighting the variability in RDI/I response and the significance of pipe hydraulic characteristics when performing detailed network modeling. The final re-calibrated and verified model used to develop control alternatives was based on the 1998 wet antecedent conditions.

The re-calibrated model was used to reassess previously developed alternatives and evaluate potential new alternatives to reduce SSO activity and basement flooding based on a 10 y-24 h design event criteria. With improved system geometry and physical parameters, as well as better wet weather calibration rainfall data there was a significant saving realized. The original remedial program was estimated to cost approximately US\$21 million and include the replacement of most local sewers, construction of a storage facility and pipe rehabilitation. The recommended program using the re-calibrated model represents a US\$14 million saving at US\$7 million, and includes selective pipe upgrades in the study area.

Figure 34.5 MS5 re-calibration April 15-16, 1998.

34.6 Conclusion

The Richmond/Orchard study area was subject to numerous initiatives designed to address basement flooding complaints and eliminate SSO occurrences. Despite the efforts involving data collection, system modeling, and development of alternatives the outcome was a solution that was considered cost prohibitive for such a small service area. Prior to proceeding with any recommendations the District decided it would be in the best interest of the community and District to undertake a third evaluation of the area to address questions that were raised in the previous reports addressing boundary conditions, the local storm system, and the reliability of rainfall data. This study addressed these concerns and developed a comprehensive work program that built on the past body of work and addressed the shortcomings identified. Specifically the following activities played an important role in understanding the performance of the system and the development of analytical tools suitable for evaluating alternatives:

- Including areas outside the immediate study area to adequately define downstream boundary conditions. By venturing outside the previous study boundaries, downstream capacity was identified in the existing combined system;

- Inclusion of a study rain gauge and radar rainfall data, which clearly indicated the unreliability of the Deer Park rain gauge. This had a significant affect on the hydrologic - flow response relationship, grossly overestimating the wet weather response for a given rainfall;
- Development of a detailed manhole-to-manhole hydraulic model that was based on field-verified measurements of pipe diameter and other relevant physical data provided the level of definition to evaluate all segments of the system;
- The calibration/verification process illustrated the importance of event selection and the limitations of hydraulic models to the events used for calibration. Model verification with an independent historical event proved to change the RDI/I response significantly having a direct influence on the development of alternative controls;
- The calibration/verification also identified that pipe material, diameters, and roughness factors were important elements when calibrating under surcharged conditions requiring flow, volume, and level to be compared to achieve calibration.
- The detailed understanding of current system conditions and the verification of data sources in the study area allowed the development of potential solutions to the basement flooding and SSO problems not previously considered. The preferred solution from the study reduced the estimated mitigation cost from US\$21 million to US\$7 million when compared to the proposed preferred solution from previous studies.

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