

**COMPREHENSIVE FLOW MONITORING PROGRAM  
THE BALTIMORE CITY APPROACH**

Author: Carlos A. Espinosa, P.E.  
KCI Technologies, Inc.  
10 North Park Drive - Suite 200  
Hunt Valley, MD 21032

Co-author: Gary Wyatt, P.E.  
Baltimore City DPW  
200 N. Holiday Street - Room 305  
Baltimore, MD 21202

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**ABSTRACT**

Historically, sewershed rehabilitation projects have yielded mixed results in cities, towns, and counties throughout the United States, including the City of Baltimore, MD. Accurate rainfall and flow data play a key role in the effectiveness of these projects for two reasons. First, and perhaps most important, the hydraulic models used to identify deficiencies in the collection system must be calibrated using current rainfall and flow data. Secondly, the effective identification and elimination of inflow sources - the main cause of wet-weather SSOs – depends greatly on the accurate measurement and characterization of wet-weather flows. In spite of numerous sewershed studies and rehabilitation projects, Baltimore continued to experience wet-weather SSOs. In past projects, rainfall and flow monitoring efforts were under-funded and/or performed by contractors that lack the technology and expertise to execute the work.

Recognizing the importance of accurate data, the City of Baltimore decided to take a different approach this time. The City awarded three contracts (totaling \$18.5 Million) with national firms experienced in large-scale flow monitoring project. Each contract consisted of between 100 and 130 metering sites. By contracting directly with the service providers, the City was able to place higher priority to the flow-metering technology and to the expertise of the service providers. Prior to contracting the service providers, a Flow Monitoring Plan was developed for each of eight sewersheds utilizing the City's Geographical Information System (GIS). Flow monitoring sites were selected and boundaries were drawn for approximately 270 mini-basins. The average mini-basin contained about 25,000 linear feet of pipe.

For the first time, national firms joined forces and develop alliances for the benefit of the City. For the first time the City executed a flow monitoring project of this magnitude, using wireless communication, with multiple service providers and one common database. The flow data generated by the project would be used by Consultants to guide the \$1-Billion Comprehensive Sewer Rehabilitation Program, and the data would be shared with local, State, and Federal organizations that may have use for the data.

## KEYWORDS

Flow monitoring, flow meter, flow data, rainfall, rain gauge, infiltration and inflow, I&I, I&I evaluation

## INTRODUCTION - CONSENT DECREE REQUIREMENTS

In 2002 the City of Baltimore (the City) embarked on a \$1-Billion Comprehensive Sewer System Rehabilitation Program under a Consent Decree issued by the Department of Justice (DOJ) and the Maryland Department of the Environment (MDE). The Consent Decree required the City to study its eight major sewersheds and to develop and submit a Rehabilitation Plan for each sewershed, which resulted in the City hiring eight Sewershed Consultant Teams (Sewershed Consultants) to perform the studies. The City realized that the \$1-Billion Program hinged on the accuracy of the data generated by the \$18.5-million (2%) Flow Monitoring Program. The challenge for the City was to implement an effective rainfall and Flow Monitoring Program to generate accurate data, and a standard process to evaluate inflow and infiltration (I&I). To meet this challenge the City contracted directly the service of national firms experienced in large flow monitoring programs.

## PROGRAM OBJECTIVES

The City established two main objectives for the Comprehensive Flow Monitoring Program:

- 1. Collect accurate rainfall and flow data** – The program accomplished this goal by requiring:
  - The use of the latest metering technology and Doppler radar rainfall measurement.
  - Daily data collection using wireless communication, which identifies equipment malfunctions sooner and, therefore, maximizes rainfall and flow data availability.
  - A multiple-tier data processing and data quality assurance by the service providers and the City.
- 2. Standardize I&I evaluation** – This goal was accomplished by:
  - Establishing standard I&I evaluation parameters and definitions for the use of all Sewershed Contractors.
  - Requiring all Sewershed Contractors to use a standard I&I evaluation software (*Slicer.com*<sup>®</sup>, a registered mark of ADS Corporation).

## EARLY CHALLENGES

Early in the program the City decided to engage three flow monitoring firms for the project. Each firm would select the flow metering equipment best suited for each metering location, which could open the door to substandard equipment. In order to avoid the use of second-rate equipment, the City developed strict equipment specifications that had to be met by any meter used in the project. The specifications require the meters to be area-velocity type, to use primarily ultrasonic level and Doppler velocity sensors, and to incorporate a redundant level sensor such as a pressure sensor.



material, etc.) of the sewer pipe in which the sensors are installed, manhole depth, and other comments deemed pertinent by the Contractor. In addition, survey-grade GPS (Maryland State Plane - +/- 0.5 inch) coordinates, pipe inverts and rim elevations; and three digital images of the site were required, including one showing the sensor installation.

## **EQUIPMENT INSTALLATION**

The Contractor was required to evaluate the level of silt and debris at each monitoring location, and to provide sewer cleaning to ensure accuracy and reliability at each metering site. In case of odd-shape pipes, or in sites where debris or sediment was present, the Contractor developed a profile and accurately determine the cross sectional area of the pipe at the depth-measuring point. A typical flow monitor installation included the primary ultrasonic depth sensor mounted at the crown of the pipe, a redundant depth sensor mounted in the invert, and a Doppler primary velocity sensor also mounted in or near the invert. All flow meters and rain gauges were synchronized in time to the same clock, and programmed to collect depth and velocity data at five (5) minute intervals.

Upon installation and activation of each flow meter, the Contractor took manual depth and velocity readings using an independent instrumentation to confirm that the in-situ monitor yielded data representative of actual field conditions. The field crews were required to take manual velocity readings of the cross-section (velocity profile) of the flow in order to determine the pipe hydraulic profile. Before finalizing and accepting, the Contractor submitted the first two weeks of data and depth-velocity scattergraphs of each installation to assess meter performance. This two-week period was used to confirm that every site was working properly and producing accurate and reliable data.

## **DATA COLLECTION**

The Contractor was required to use a host software support application program for remote wireless data collection. The host software maintained clock synchronization with the host system's clock for all field RTUs, thus insuring time interval integrity for all collected data. The project required the Contractor to use a system employing client/server architecture, capable of storing all project deliverables including flow and rainfall data; equipment configurations; event logs; and site parameters into a SQL database. The software allowed any networked computer (with the appropriate access rights) access to the data stored in the SQL database using a common web browser (e.g. Microsoft Internet Explorer). The web module was read only in order to protect data integrity, and had the ability to present near-real time data. Flow meter measurements could be forwarded to the server immediately following collection by the field RTUs, and the server could immediately post the data to the web site for viewing by authorized parties.

The Contractor was required to employ trained data analysts experienced in processing and analyzing flow and rainfall data from sanitary sewer systems. Various analytical tools, such as hydrographs, scattergraphs, and flow balancing methods were used to verify the accuracy and precision of the flow data. Data collection was performed remotely at least twice a week and was scheduled in a manner to allow data review by a trained data analyst within 24-hours of the

data collection. The analyst assessed any maintenance or monitor performance issues, and a crew was dispatched within 48 hours, and the issue resolved within 72 hours from the time the issue was identified. All measurements, adjustments, and efforts undertaken during site visits were logged in an installation/maintenance log specific to that installation.

## **EQUIPMENT O&M**

The Contractor's qualified field crews visited each monitor installation as appropriate to perform any necessary maintenance to the equipment. As stated above, field crews were dispatched within 48 hours and any O&M issue was resolved within 72 hours from the time the issue was identified. The Contractor was required to collect useable flow data a minimum of 90% of the time throughout the monitoring period, and to submit to the City an "Uptime" table each month demonstrating compliance with the uptime requirement. Monitor uptime was defined as the number of five minute measurement intervals where a flow value can be calculated from a measured depth and a measured or inferred velocity for a common time interval divided by the total number of measurement intervals in the reporting period.

It was agreed between the Contractor and the City that the uptime requirement would be generally satisfied with actual measured data. However, in instances where a velocity measurement was not available, inferred velocity from a reliable depth measurement would not be considered downtime if the Contractor demonstrated that accurate data could be obtained without the velocity measurement, and that the loss of velocity data was not caused by maintenance neglect. In any case, however, no velocity could be inferred for any measurement interval where (1) a corresponding depth measurement has not been obtained for that measurement interval or (2) independent calibration measurements have not been acquired for the site. The Contractor was required to identify all inferred velocity data or other data derived from inferred data in all reports and deliverables.

The Contractor incurred a penalty for every 24 hours (or proportionate amount) of unjustified downtime below the 90% uptime requirement for each monitoring location. The penalty was equal to the sum of the Monthly Equipment O&M plus the Monthly Data Reporting Unit Prices multiplied by the percentage points below 90%. For example, if a site achieves a 70% uptime in any given calendar month and the monthly unit prices for Equipment O&M and Data Reporting add up to \$2,500, the downtime penalty would be calculated as follows:

$$\text{Penalty} = (90\% - 70\%) \times \$2,500 = \$500.00$$

The penalty was incurred as a credit on the Contractor's invoice each month, and was not refunded to the Contractor regardless of the overall or up-to-date uptime achieved.

The Contractor performed dry-weather, independent depth and velocity measurements across the full range of depths during dry weather conditions throughout the project duration, and assessed monitor performance relative to these measurements and make any adjustments to the monitor as necessary to maximize the accuracy of the data with respect to actual conditions. The confirmations were evenly scheduled and performed a minimum of three times during the 18-

month flow monitoring period. Where flow conditions allow it, one of the three required calibrations included the use of a weir to confirm the velocity measured by the meter. The City and the Contractor mutually recognized the difficulties and potential hazards associated with obtaining wet weather calibration measurements. However, the Contractor had to demonstrate a good-faith attempt at acquiring at least two wet weather independent measurements by shifting the emphasis of all field crew activities towards obtaining these measurements during wet weather. It was agreed that a wet-weather confirmation was acceptable at any time the flows are higher than normal during or following a rain event.

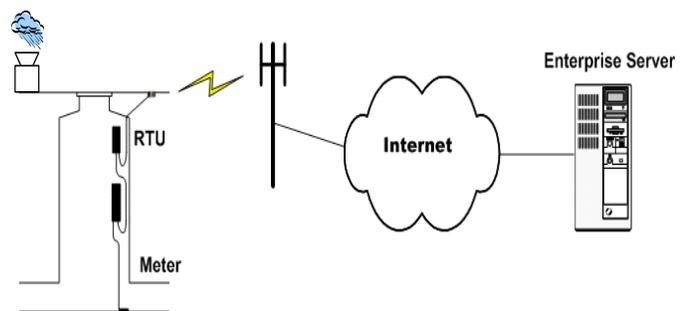
## **DATA ANALYSIS AND REPORTING**

The Contractor provided data analysis services for each flow-monitoring site for the entire duration of the flow-monitoring period. Data analysis included a comprehensive review of collected data upon receipt, to identify data gaps, equipment service needs; as well as the conversion of raw flow data into processes data. Experienced Data Analyst reviewed the flow data in order to verify diurnal patterns and reasonable depths and velocities using data diagnostic tools such as hydrographs and scattergraphs. In addition, the Analyst checked for data anomalies or unusual trends that are recognizable.

The Contractor reported electronic flow and rainfall data monthly by the last day of the month for the previous month. Each submission included time-stamped depth, velocity, and flow data, and scattergraphs of processed depth-velocity readings with discernable calibration measurements overlain. In addition, an Uptime and Data Quality Rating Report of all sites was delivered, including the basis for failure in meeting uptime requirements and any data quality issues. Finally, a Meter Calibration Status Report was submitted indicating by site the number of wet and dry weather calibrations to date.

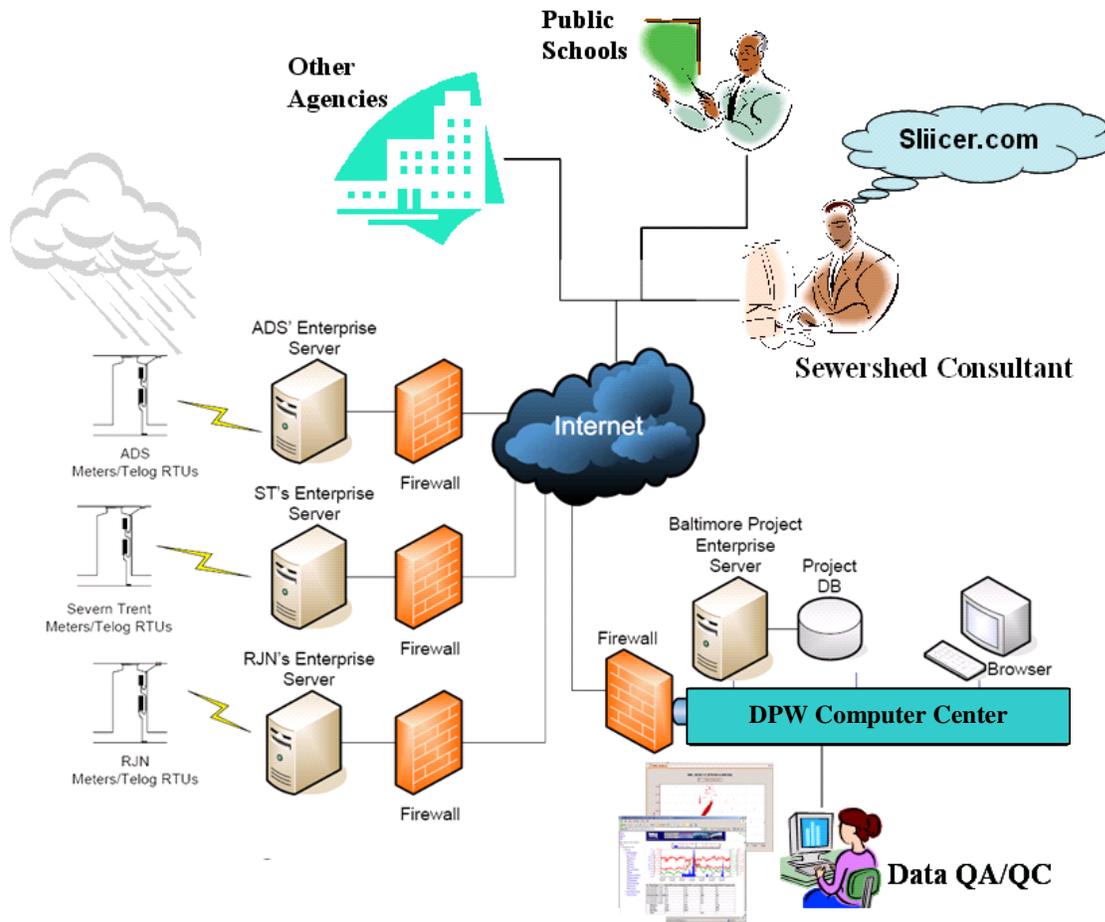
## **WIRELESS COMMUNICATION**

Telog Instruments Inc. was proposed by the Contractors to provide the field RTUs, wireless communications and host application software system for this project. The Telog wireless monitoring system provided the automated means of collecting, archiving, presenting and sharing data from the flow meters and rain gauges. Supported communication options included telephone, cellular, radio, satellite, and Ethernet. The Telog RTUs directly interface with all flow meters and rain and gauges. Referring to the figure above, the RTUs collected and stored the data from the meters and then transmitted the data to the Contractor's Enterprise server.



At least once a day the raw data was remotely collected from the metering equipment. 1XRTT wireless cellular was the primary means for transmission of data across the Internet to the

designated host Enterprise server. The raw data then resided in the Contractor’s Enterprise server awaiting first-tier QC/QA. The figure below depicts how the program collected, processed, finalized, and shared the rainfall and flow data.



## MULTI-TIER QC/QA PROCESS

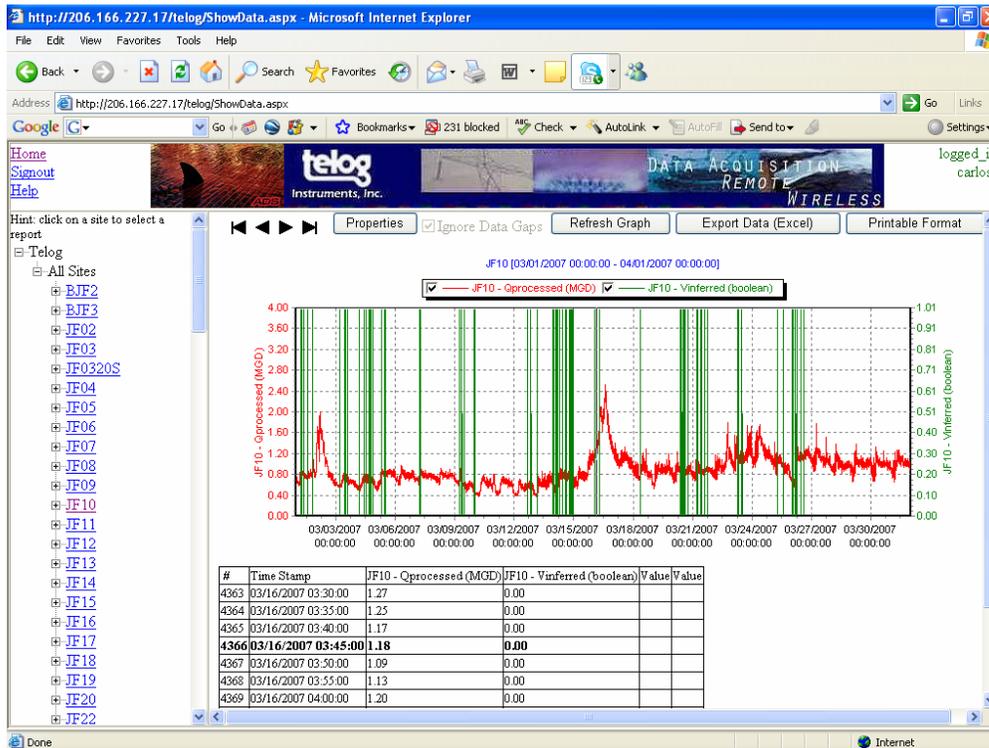
The First –Tier QC/QA was performed by the Contractors using Telog Enterprise tools or other 3rd party software such as ADS’s Profile software. The process consisted at a minimum of Dry Day Balance and Hydraulic Review. At the completion of the First-Tier QC/QA process the data was deemed “Processed Data”.

**Dry Weather Balance** – Dry-weather flows were normalized by basin acres or linear footage of pipe in the basin. The result of this analysis was a calculated “wastewater production rate” for each basin. Each land use had a characteristic wastewater production rate, and unusually high or low rates may identify errors in metering, pipe sizes, connectivity, or basin sizes. This was one of the most effective QC tasks as it could spot errors that are invisible to other QC methods.

**Hydraulic Review** - Flows from all sites were reviewed through hydrographs and scattergraphs to spot irregular and unexplained diurnal patterns, and depth or velocity out of reasonable ranges during minimum and maximum flows. Scattergraphs with iso-Froude lines were used to reveal

the presence of hydraulic jumps that could contribute to meter error or imbalances. With the Manning pipe curve displayed on the scattergraph, backwater, surcharge and sensor failures were easy to spot.

**Uptime Analysis** – As stated above, the project required a 90% uptime. Graphing the uptime gave immediate indication of trouble periods that required further review and explanation.



By the last day of each month, each Contractor posted the processed data for the previous month via FTP for Second-Tier QC/QA processing by the City using Telog Tools. Once validated, the data was deemed “Final Data” at the completion of this check. The Second-Tier QC/QA process consisted of the following steps:

**1. Verify the completeness of the data submittal**

- a) Run scripts on SQL Server to quantify  $D_p$ ,  $V_p$ ,  $Q_p$ , and  $V_i$ .
- b) Generate Missing Data Report, log all missing data in the Review/Tracking Access Database, and e-mail Missing Data Report to the Contractor.

**2. Perform Balance Check**

- a) Run  $Q_{net}$  scripts on SQL Server
- b) Generate  $Q_{net}$  Report
- c) Any negative monthly  $Q_{net}$  average will be reviewed, including hydrograph/scattergraph analysis. Any unexplained negative  $Q_{net}$  will be logged in the Review/Tracking Database for further resolution by the Contractor.

### 3. Validate Uptime

- a) Compare the Monthly Uptime Report from the Contractor against the percent of  $Q_p$  reported in the Missing Data Report.
- b) Reconcile any discrepancies by checking the Monthly Progress Reports from the Contractor (i.e. meters out of service due to P-8 Construction Projects).

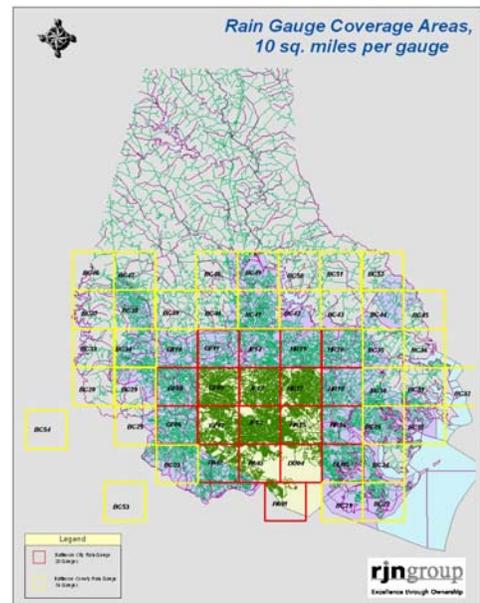
### 4. Confirm and Validate Inferred Velocity ( $V_i$ )

- a) From the Missing Data Report, check the  $V_i$  average and  $V_i$  percent reported.
- b) Any  $V_i$  average above 15% is submitted to the respective Contractor for resolution within 5 days.
- c) Any  $V_i$  average between 5% and 15% will be reviewed including hydrograph/scattergraph analysis. Any site where the  $V_i$  is not justified is submitted to the respective Contractor for resolution within 5 days.

5. **Random Check of Remaining Sites** - Select at least 25% of the remaining sites randomly and perform Hydrograph/Scattergraph Analysis. Any site that presents unexplained variations, low repeatability, unusual hydraulic signature, no response to rain, etc. will be reviewed with the Contractor. Any data that is not reasonably justified by the Contractor will not be accepted.

## RAINFALL AND GROUNDWATER MEASUREMENT

**Rainfall Measurement** – The Contractor was required to measure the contribution from rainfall to all sewersheds within the City’s jurisdictional boundary using a network of rain gauge stations with a minimum coverage of one rain gauge station per ten square miles, as well as data compiled by Doppler radar utilizing a minimum resolution of one pixel per four square kilometers. To measure the contribution from rainfall occurring in portions of the Collection System outside Baltimore City limits, the Contractor installed 32 additional rain gauges outside City limits. The rain gauge equipment was calibrated prior to installation, and consisted of a data logger able to accept data from an industry standard rain tipping bucket. The equipment was able to measure 0.1 inches (1mm) per tip of the bucket. The tipping bucket consisted of a corrosion resistant funnel collector with tipping bucket assembly.

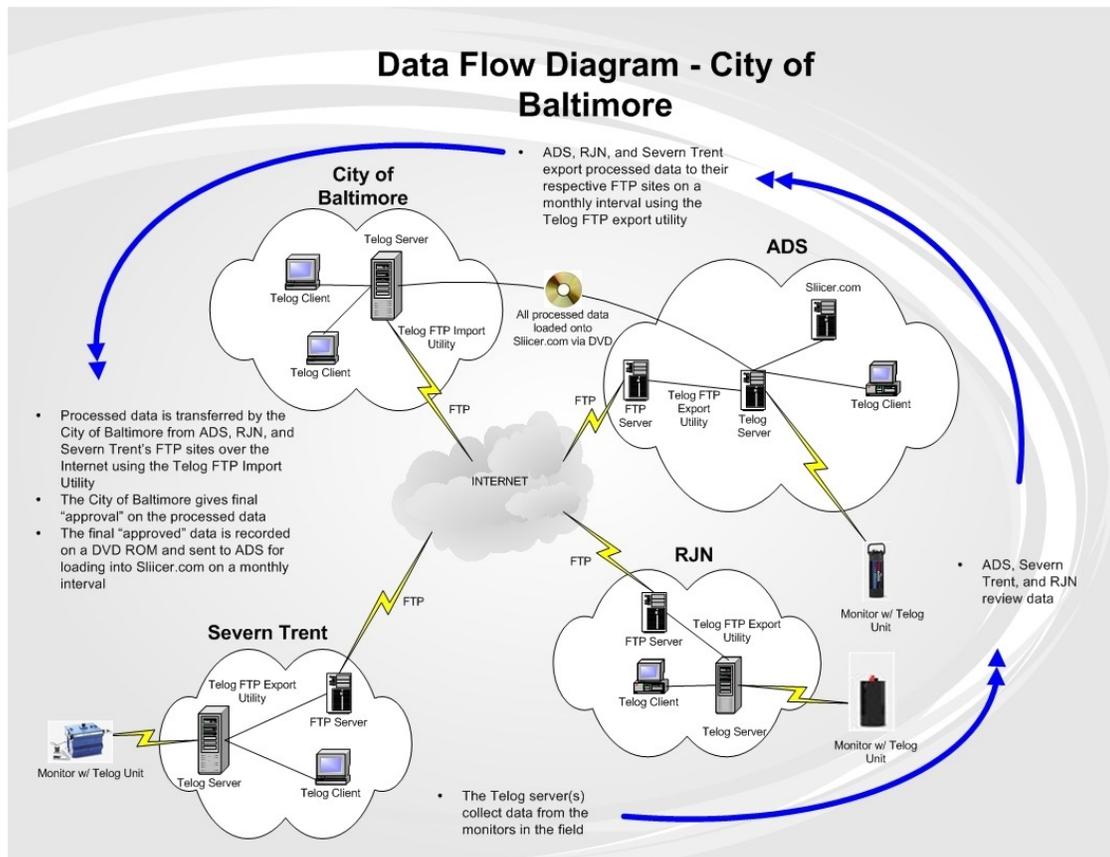


**Groundwater Gauges** - The Contractors installed groundwater gauges at 33 flow monitoring sites designated by the City. Each groundwater gauge consisted of a conduit (preferably a clear flexible tube) of sufficient diameter to accommodate a pressure sensor. The pressure sensor was calibrated prior to installation. The groundwater gauge was connected through the manhole wall to the ground around the manhole near the bench. The conduit was secured to the manhole wall or steps and extended vertically to a point 6 inches below the manhole lid. The connection

through the manhole wall consisted of a drilled hole no larger than 1.25 inches in diameter, through which a PVC or metal pipe extended to approximately 6.0 inches outside the manhole and into the ground. At the end of this PVC or metal pipe a fine mesh covered the pipe to let groundwater through but keep dirt and debris from clogging the pipe.

## I&I EVALUATION TOOL - SLICER.COM

In order to standardize the I&I evaluation process, the City chose Slicer.com, which is a web accessed software product by ADS Environmental Services. The Slicer.com software brought uniformity to the methods used by the Sewershed Consultants and achieved consistent results. Once the data had gone through the Second-Tier QC/QA Process it was deemed “Final Data”. The Final Data was transferred to ADS Environmental Services once a month, and subsequently imported into a Profile® (a registered mark of ADS Corporation) database, which allowed the Sewershed Consultants to perform the I/I evaluation using Slicer.com®. Each Sewershed Consultant operated on its own, password protected database of rain and flow information. The following figure depicts the data flow from Contractor to the City and finally to Slicer.com.



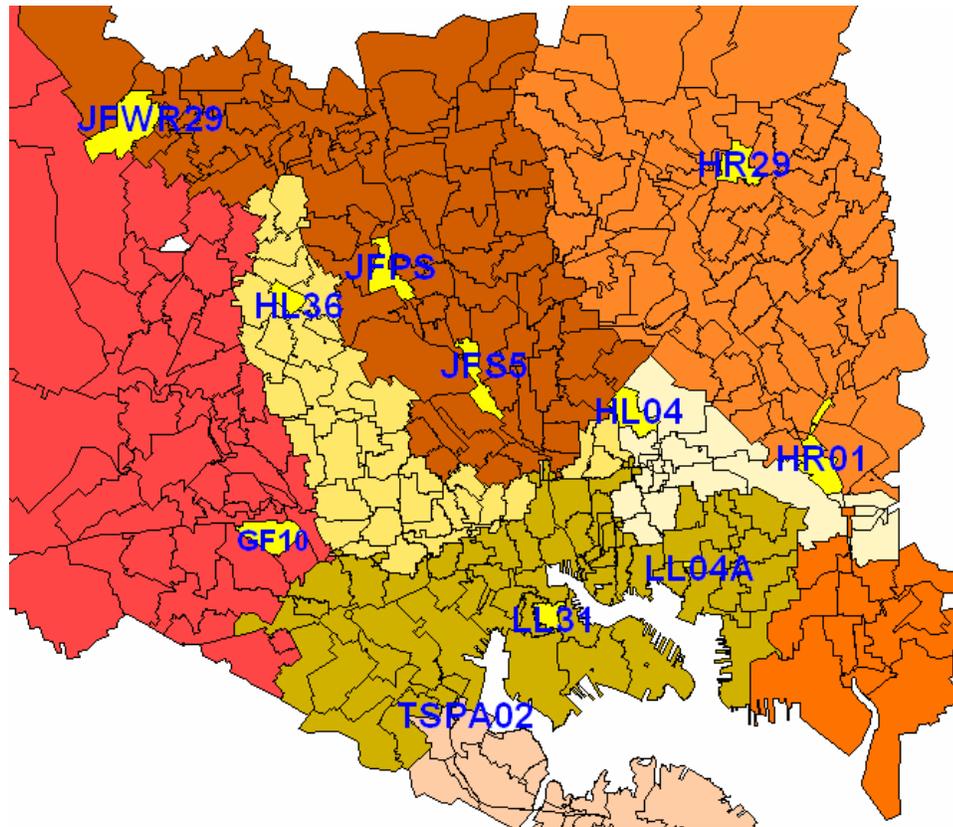
## RAINFALL AND STORM ANALYSIS

The City analyzed and selected Global storms which were used by all Sewershed Consultants. There were 35 storms in 2006 that met the Slicer's default criteria of at least 0.5 inches of rain measured in at least one RG. These storms were evaluated by the use of “Barometer” meters or

basins, which are a collection of 11 meters that were used to judge the overall flow response to the rains. The Barometer Meters/Basins were selected because they:

1. Were distributed geographically throughout the project,
2. Included both upper and lower basins in the sewer shed,
3. Exhibited clear responses to the rains,
4. Exhibited a decent scattergraph and
5. Produced data for most of 2006.

The following figure shows the Barometer basins in yellow.

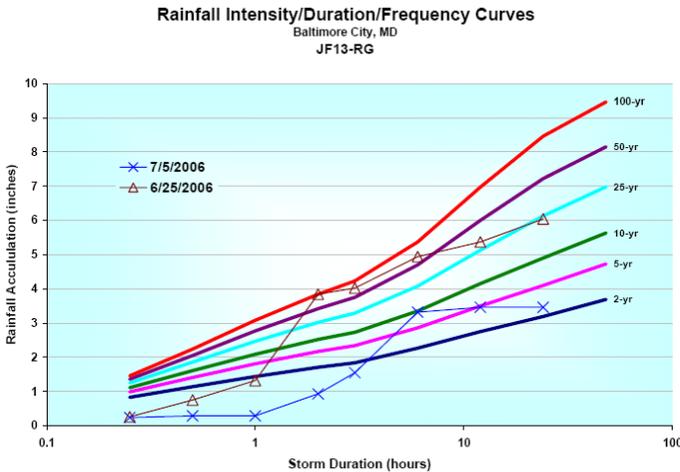


Each of the basins and storms were evaluated according to the following criteria:

1. A significant response to rain of at least 50% of the average dry day flow.
2. A uniform and significant response in at least half of the barometer basins.
3. Un-recovered storms that resulted in flow that did not recover to normal flow prior to the start of a following storm(s). The second or subsequent storm is difficult to analyze because of the Rain Derived I&I (RDII) from prior storms.

Storms that were neither significant nor uniform were deemed “wimpy” storms and removed from further consideration. The RDII calculation from such small storms has very low precision because of both the uncertainty in the subtraction of flow and the uncertainty in the small amount of rainfall. The approach for storms that were close together without time for flow recovery was to extend the Storm Calculation Length of the first storm to include the series of storms and

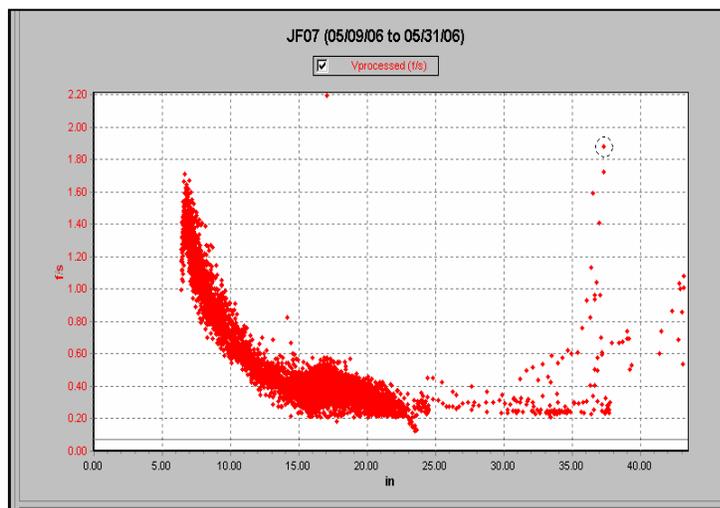
storm recovery. This approach measured the total rainfall for the series of storms as well as the total RDII for the series of storms. In cases where the recovery was over 24 hours after the storm start time, the Storm Calculation Length was lengthened to capture all the RDII.



The most significant storm happened on June 25<sup>th</sup> when almost 6 inches of rain fell over a 24 hour period. Although the storm turned out to be a 25 year storm, at one point it had the intensity of a 100-year storm.

## CHALLENGING METERING SITES

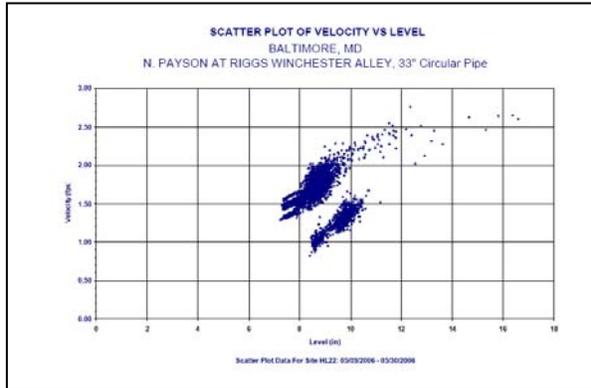
During the site investigation, installation, and the flow monitoring periods, the Contractors dealt with a number of challenging metering sites. The challenges included heavy debris, shifting debris, constant backwater conditions, excessive grease accumulation, shallow flows, and high velocities. Once these conditions were identified, the Contractor adjusted its operation and spent extra time checking debris levels and performing additional field confirmations.



One section of the collection system that presented constant backwater conditions was along the interceptors leading into the Eastern Avenue Pump Station, the largest pump station in the system. Under normal operation the wet well level was maintained high, which created constant backwater conditions in the interceptor. Close coordination with the station operators was necessary every time the equipment require maintenance. Similar backwater conditions existed in a number of sites upstream of siphons and in secondary interceptors

upstream of the connection to a main interceptor. The figure above shows constant backwater at a site in the Maryland Avenue Interceptor (secondary), a few line segments upstream of the Jones Falls Main Interceptor.

Shifting debris created challenging hydraulic conditions at a number of sites as illustrated in the figure on the right. Debris accumulated in the pipe at or downstream of the metering location over time, creating deeper and slower flow conditions. Once the debris was washed down during rain events, a different hydraulic regime develops and is revealed in the scattergraph. The new regime is at lower depths and higher velocities.



The upper sections of the collection system presented a different challenge. Shallow flows were such that the velocity and pressure sensors remain out of the flow during periods of low flows as illustrated in the picture to the left.

## ISSUES WITH EQUIPMENT CLOCK SYNCHRONIZATION

Before the start of the 18-month flow monitoring period, the decision was made to keep the equipment clocks in Eastern Standard Time (EST) and not to observe Daylight Savings Time (DST). This decision was based mainly on the fact that switching to DST introduces unnecessary logistical issues for the Contractors. In order to stay in EST, the DST option had to be disabled in several software locations and in all hardware associated with the project. Inadvertently, the DST option was not disabled everywhere and an unwanted “time shift” was introduced in a considerable number of meters. The shift did not affect the flow calculations, only the time stamp associated with each measurement. This became a significant issue as it affected the generation of the average dry-day curve and consequently the RDII calculation. As soon as this error was detected, all parties involved in the project committed the necessary resources and, although it took some time to figure out the solution, the issue was resolved satisfactorily.

The lessons learned in this unforeseen incident include how important clock synchronization is for projects that bridge across time settings (EST vs. DST). It is also apparent that more efficient communication within the Contractor’s project teams could have prevented this incident. Furthermore, and regardless of time setting, a foolproof procedure should have been in place to check clock synchronization of all hardware involved in the data collection process.

## **CONCLUSIONS**

In conclusion, the City of Baltimore's approach to a comprehensive, citywide flow monitoring program proved very beneficial. The decision to hire flow monitoring firms directly, instead of through Sewershed Consultants as was done in the past, yielded numerous benefits, including:

1. An early start of the flow monitoring program, and the ability to monitor the entire collection system under the same conditions and rain events.
2. The selection of national, more experienced firms to perform the flow monitoring work.
3. Better control of the flow-monitoring equipment used in the field, which kept second-rated equipment from being used in the project.
4. More control over field issues that affect data quality.
5. As a direct result of items 2, 3, and 4 above the flow data generated by the program is superior to any project in the past in terms of data availability and data quality. A more robust and accurate data set is available to the Sewershed Consultants for the evaluation of the collection system.

## **ACKNOWLEDGEMENTS**

The authors wish to acknowledge the valuable contributions provided by the following individuals in the execution of the project and the development of this manuscript:

- Mr. Wazir Qadri, Chief of Wastewater Engineering, Baltimore City DPW
- Mr. Scott Harris, Manager GIS Center, Baltimore City DPW
- Mr. John Huang, Project Manager, Transviron, Inc.
- Mr. Patrick Stevens, P.E., Vice-President of Engineering, ADS Environmental Services
- Mr. Joseph Scarcia, Senior Project Manager, ADS Environmental Services
- Mr. Ted Nadobny, Project Manager, ADS Environmental Services
- Mr. Keith Waites, Project Engineer, ADS Environmental Services
- Mr. Jeff Plymale, Senior Project Manager, RJN Group
- Ms. Laurie Terry, P.E., Senior Project Manager, RJN Group
- Mr. Kevin Chumbley, Project Engineer, RJN Group
- Mr. Barry Ceci, President, Telog Instruments, Inc.
- Mr. Carlton Quallo, General Manager, Telog Instruments, Inc.