Impacts of Rainfall Data on Model Refinement in Greater Pittsburgh

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The Allegheny County Sanitary Authority (ALCOSAN) and its 83 member municipalities in the greater Pittsburgh, Pennsylvania region are in the process of implementing a comprehensive wet weather sewer overflow management program to improve and preserve the water environment in the service area. Simulation models are required to develop, evaluate and select technically viable, cost-effective regional facilities and operational changes needed to control wastewater flow. High resolution spatially- and temporally-varied precipitation data is needed for the region so that models can accurately quantify and characterize complex interrelationships between rainfall, runoff, wastewater flow, and overflow volumes. The costs to develop and implement control facilities can be high and ALCOSAN aggressively is pursuing all opportunities to significantly reduce this cost for its customers. Therefore, the investment was made to implement a regional radar-rainfall system with the belief that improved precipitation estimates would significantly reduce the ultimate cost for wastewater management and regulatory compliance.

It has been demonstrated and documented in cities throughout the United States and around the world that calibrated radar-rainfall systems significantly can improve the accuracy and precision of rainfall measurement for large geographic areas. However, quantitative evaluations are relatively sparse documenting whether enhanced rainfall measurement actually translates to improved wastewater flow prediction performance from hydraulic/hydrologic models. The ALCOSAN Lower Ohio River basin project provided a unique

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opportunity to characterize and quantify the impacts of improved precipitation estimates on the accuracy and reliability of model-predicted wastewater flow and CSO/SSO frequencies and volumes. Analyses were conducted for 46 monitored storm events to determine if simulated/monitored storm peak and volume relationships improved significantly as a result of improved rainfall measurement.

The Lower Ohio basin study was successful in quantifying and characterizing the levels of improvement to modeling accuracy, resulting from improvements to the accuracy and resolution of precipitation data. In general, significant improvements consistently were observed between simulated and observed storm peaks as refinements to model input precipitation data were made. In contrast, within many of the analyzed sewersheds relatively little improvement was observed between simulated and observed total storm volumes as refinements were made to the precipitation data. Results were highly mixed within the analyzed sewersheds regarding the continued level of improvement to simulation model results when the source of precipitation data was upgraded from the gauge network to the radar rainfall system. The study demonstrated that the geographic distribution of storm depths, intensities and durations is significant in the greater Pittsburgh region. If a traditional gauge network were to be employed, many gauge sites would be needed to monitor the orographic distribution of rainfall, and the level of effort and cost to maintain the gauge network would be high. It was concluded that developing and implementing a regional gauge adjusted radar-rainfall system was a worthwhile investment that will result in multiple benefits to the region and reduce the ultimate cost for wastewater management and regulatory compliance.

18.1 Background Information

The ALCOSAN Authority:

ALCOSAN serves the City of Pittsburgh and all or part of 82 other municipalities in the region. The Authority provides wastewater conveyance and treatment to a service area of approximately 310 square miles (800 sq-km) and a service population of approximately 823,000 people. ALCOSAN maintains 90 miles (144 km) of interceptor sewers, which includes both deep tunnel and shallow-cut interceptors, and a 225 million gallon per day (mgd) secondary wastewater treatment plant (850 million liters/day). The regional wet weather control plan includes expansion of the

wet weather capacity of the plant to 875 mgd (3,300 million l/d). Along the interceptor system are over 300 regulator structures that intercept dry weather flow and control wet weather flow into the ALCOSAN system. ALCOSAN does not have jurisdiction over the collection systems, which are owned and operated by the individual municipalities. The ALCOSAN authority is in the process of refining and implementing a Regional Long Term Wet Weather Control Plan to control CSO and SSO discharges into area water bodies. It has been estimated that the cost for ALCOSAN and its satellite service communities to implement this plan may be as high as \$3 billion (US\$). Approximately \$1 billion would be invested during the first 10 to 15 years of plan implementation and the remainder spread over a 50 y period. Opportunities to reduce this cost largely depend on the refinement of the hydrologic and hydraulic characterization of combined and separate sewer systems within the region, the refinement of the control facilities design process, and municipalities working together. A system-wide hydrologic/hydraulic model has been developed and is being refined as a tool to develop, evaluate and guide the selection of alternative control facilities.

Precipitation Measurement in Allegheny County:

A gauge adjusted radar-rainfall system was implemented in April 2000, to monitor precipitation within the greater Pittsburgh region. The system is owned and operated by the 3 Rivers Wet Weather Demonstration Program (3RWWD), a regional non-profit organization who made the investment to implement the system with the belief that improved precipitation estimates could significantly reduce the ultimate cost for regulatory compliance. The radar-rainfall system utilizes a geo-referenced 1 sq-km pixel grid, and 872 pixel squares were required to cover the entire ALCOSAN service area. The original system was supported by a network of 21 heated precipitation gauges installed at an average density of one gauge per 15 square miles (40 sq km). The radar-rainfall system provides continuous coverage in 15 min time steps for medium- and larger-magnitude storms meeting specified minimum criteria for intensity and total storm depth. For smaller storms not meeting the defined criteria and occurring between defined storm events, the gauge adjusted radar-rainfall data was “filled” with gauge data, distributed over the pixels via the inverse-distance method, to provide a continuous precipitation record that was input into the hydrologic/ hydraulic model.

The precipitation data is provided to engineers, municipalities, and other interested individuals via an Internet site maintained by 3RWWD. The initial start-up cost to implement the system was approximately \$175,000 (US),

which included the gauge equipment, electrical and telephone service connections, installation labor, geo-referencing, and radar customization. The monthly maintenance cost was approximately \$5,500 (US), which includes phone lines, system maintenance, radar image and gauge analyses, data quality reviews, monthly reporting, and web-site maintenance. In the spring of 2003, the radar-rainfall system was expanded to provide county-wide coverage and the web site was upgraded to provide real-time precipitation data. The current system is supported by 32 heated gauges, and over 2300 pixels are required to cover the entire county.

Wastewater Flow Measurement:

The ability to assess the accuracy of a hydrological/hydraulic model and potential benefits from improved rainfall data depends on the availability of accurate and reliable monitored wastewater flow data. A network of monitors was therefore established and maintained throughout the Lower Ohio basin to provide the required depth and flow data. Monitoring equipment was maintained continuously at 14 sites over 12 consecutive months. During the monitoring period, data from 46 significant storm events were collected and reviewed. The 12-month monitoring duration and the large quantity of monitored storms allowed the quantification and characterization of seasonal variations in the sewer system responses to wet weather.

Flow measurement devices are susceptible to malfunctions and/or hydraulic conditions which may result in errant and/or missing data. Because simulation model accuracy is determined relative to observed depth and flow data, any uncertainty or bias in the observed data is transferred to the model during the calibration/verification process. Therefore, an effective quality assurance and quality control (QA/QC) program, both in the field and in the post-collection data review, is implemented to ensure that the data collected and used to support the model is accurate and reliable.

Description of the Study Area:

The Lower Ohio Basin study area is located in the northwestern corner of the ALCOSAN service area. The basin has an area of approximately 16.5 square miles (42.7 km²) and contains a service population of approximately 48,180 people who reside in 15 municipalities. Approximately 9% of the basin area and 15% of the service population are served by combined sewer systems. The remaining service population is served by separate sanitary sewers. The lower Ohio Interceptor system is comprised of 3.3 miles (5.3 km) of deep tunnel interceptor along the northern bank of the Ohio River and 1.3 miles

(2.1 km) of shallow-cut interceptor along the southern bank. A network of 21 regulator structures controls the wet weather flow contributed by the service communities to the ALCOSAN interceptor system.

18.2 Analysis Methodology

To analyze and assess whether enhanced rainfall measurement actually translates to improved wastewater flow prediction performance from hydraulic and hydrologic simulation models, four alternative sources of precipitation data commonly used for model application projects were used. A SWMM model of the Lower Ohio Basin was prepared. Most of the study area sewersheds are served by separate sanitary sewer systems, so rainfall dependent infiltration and inflow (RDII) that is present in these sewer systems during and after storms would be the primary force driving the values of storm peaks and total storm hydrograph volumes. Model input parameters used to simulate RDII responses to storms were calibrated using the high-resolution radar-rainfall and monitored wastewater flow data. A one year continuous simulation model run was conducted and each of the simulated storm peaks and volumes for each monitored sewershed for each of the 46 monitored events was compared with the corresponding observed data values.

The calibrated model was modified by sequentially replacing the precipitation input data derived from the radar-rainfall system with input data derived from each of the other three precipitation data sources listed above. Since only the precipitation input was changed, and all other model parameters remained the same, any differences in the degree of correlation between simulated and monitored storm peaks and simulated and monitored storm volumes would be directly attributable to the differences in the rainfall data. Admittedly, a superior approach would have been to re-calibrate the model using each of the alternative precipitation data sources, but the corresponding level of effort and cost were well beyond the limits approved for the conference paper upon which this chapter was based. To determine if improved precipitation measurement actually improved model simulations, a series of linear regression analyses were performed on the model output resulting from each of the four alternative precipitation input sources. The varying levels of correlation between simulated and observed values for each of the 46 monitored events were quantified for each precipitation data source.

18.2.1 Alternative Precipitation Data Sources

Four alternative sources of precipitation data were analyzed and assessed for the Lower Ohio Basin project in order to quantify and characterize the benefits of enhanced rainfall measurement. The alternatives were selected to represent the “typical” range of precipitation sources used for sewershed modeling and analyses.

Long-Term Regional Gauge:

The long-term regional gauge for the Pittsburgh region is located at the Pittsburgh International Airport, approximately 10.4 miles (16.6 km) away from the Lower Ohio Basin study area. Hourly digital data is readily available from this gauge for a monitoring duration spanning from 1948 to the present. Several sewershed studies have been performed using this data, when no other precipitation data sources were available. Using a single regional gauge necessitates the assumption of a uniform precipitation distribution over the sewershed area being studied. The relative locations of the regional gauge and the study sewersheds are provided in Figure 18.1

Nearest Gauge:

Three gauging stations were established and maintained in the vicinity of the Lower Ohio Basin study area. The heated gauge sites provide continuous precipitation data in 15 min increments. For the analysis, the gauge located closest to the sewershed area being analyzed was utilized – again assuming uniform rainfall over each of the sewersheds being analyzed. Many sewershed analyses in the Pittsburgh region have been performed with this approach of installing and maintaining a single gauge within or adjacent to the study area to provide needed precipitation data. The relative locations of the three gauge sites and their proximity to the sewersheds being analyzed are also shown in Figure 18.1.

Network of Gauges:

A medium-density network of three continuous recording gauges was installed within and around the Lower Ohio Basin study area. These gauges are a part of the regional network of 32 gauges that are used to support the regional radar-rainfall system. The heated gauge sites are synchronized on a weekly basis and provide continuous data in 15 min increments.

Figure 18.1 Alternative rainfall data sources – regional gauge and nearest gauge.

The gauge network allows the analyst to use the inverse distance method to approximate the spatial distribution of rainfall over the study area. Some sewershed analyses in the Pittsburgh region have been performed with this approach of installing several gauges in and around the area of study to provide additional insights into the spatial distribution of precipitation. Figure 18.2 shows the location of each of the gauges in the network and illustrates how the inverse distance method was applied to obtain spatially-varied precipitation patterns within the study basin.

Calibrated Radar-Rainfall System:

For mid-sized and larger storms that meet specific criteria, radar reflectivity data are related to precipitation intensity at a high degree of spatial and temporal detail. Weather radar imagery is calibrated to a network of 32 geo-referenced and synchronized gauges to provide a more precise representation of rainfall through space and time. The pixel grid values are later area-weighted to provide continuous rainfall data for individual sewersheds and sub-sewersheds. Precipitation data from the calibrated radar-rainfall system is used by ALCOSAN and the 3RWWD in support of demonstration projects and the regional Long Term Control Plan. Figure 18.2 shows the geo-referenced pixel grid over the study area sewersheds and the gauge sites used to adjust the radar data.

Figure 18.2 Alternative rainfall data sources – Inverse distance and radar-rainfall.

18.2.2 Quantification and Characterization of RDII

Rainfall dependent infiltration and inflow (RDII) is extraneous surface runoff and groundwater flow that is present in sewer systems during and after storms. RDII quantities tend to increase rapidly during a storm, and then dissipate gradually to seasonal base flow levels over the next few days. A series of RDII analyses were conducted, external to the SWMM model, to quantify and characterize RDII in the monitored portions of the Lower Ohio Basin study area. The high resolution radar-rainfall precipitation data and monitored wastewater flow data were utilized for the RDII analyses. To quantify RDII for each of the monitored sewersheds, a five-step process was used to perform dry-weather and wet-weather flow analyses for the monitored sewersheds in the study area. The analysis procedure and corresponding continuous simulation modeling approach, summarized briefly below, is

described in greater detail in chapter 21 of this Monograph (Loehlein et. al., 2005).

Flow Data Preparation: The monitored flow data was entered into the RDII Utilities Program and reviewed to confirm that it was complete, properly formatted, and compatible with the requirements of the subsequent RDII analysis processes. The review also included error checking, identifying data gaps, and filling in periods of missing data.

Precipitation Data Preparation: Gauged precipitation data were entered and reviewed to confirm that they were complete and met the requirements of the RDII analysis process. To quantify RDII, there must be a corresponding rainfall data point for each wastewater flow data point.

Dry-Weather Flow Evaluations: Days that were not affected by a rainfall event were identified within the monitoring period of record. Mean maximum, minimum, and average daily flows for the selected dry-weather days were computed and used to identify base flow ground water infiltration (GWI) rates. Average weekday and weekend dry-weather flow hydrographs were computed and used in subsequent analysis processes to determine the RDII flows during rainfall events.

Hydrograph Decomposition: To quantify RDII for each of the monitored storms, the monitored wastewater hydrographs (total storm flow) were broken down into three components: base wastewater flow (BWVF), ground water infiltration (GWI), and RDII. GWI rates were manually adjusted to account for seasonal variations. The seasonal adjustments were based on the assumption that the difference between monitored flows and the computed average daily dry weather flow (ADDWF) hydrograph should be approximately zero before and after a storm. RDII volumes and peak flows for individual storm events were calculated by subtracting the seasonally adjusted dry-weather flow hydrograph (BWVF plus GWI) from the total monitored flow (BWVF plus GWI plus RDII). An illustrative example of hydrograph decomposition can be seen on Figure 18.3.

Once the hydrograph decomposition process was completed for each monitored storm and sewershed, the total rainfall volume over the monitored sewershed area, the storm-induced RDII volume, and the total R-value were computed. The total R-value is defined as the ratio of the calculated RDII volume to the rainfall volume over the sewershed area, expressed as a %. An R-value of 0.07 would indicate that 7% of the monitored rainfall volume that fell over the sewershed area made its way into the sewer system as monitored RDII.

Figure 18.3 Example of hydrograph decomposition.

Triangular Unit Hydrograph Curve Fitting: The final step in the analysis process, external to the SWMM model, was to optimize a set of three triangular unit hydrographs for each monitored storm event to match simulated RDII responses with monitored RDII responses. The three unit hydrographs simulate the fast, moderate and slow sewer system response flows. An illustrative example of triangular unit hydrograph curve fitting can be seen on Figure 18.4. Each unit hydrograph in the figure was described by the following parameters:

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

Using the 5 step process, R-T-K values were calculated for each storm for each sewershed area. To account for seasonal variations in sewer system RDII responses, R-T-K results for individual storms were averaged together on a monthly basis, and the monthly-varied series of 36 composite R-T-K values (3 unit hydrographs for each of 12 months) were input into the SWMM model for each sewershed area. The SWMM program applied the unit hydrographs to the precipitation input to simulate the RDII flow for each time increment of

rainfall. The total simulated storm response equaled the sum of the flows generated from the three unit hydrographs (RDII component), and the inputted BWWF and GWI time series (dry weather flow components).

Figure 18.4 Characterization of RDII using 3 triangular unit hydrographs.

18.2.3 Continuous Simulation Modeling

The regional gauge data (alternative precipitation source #1) was input into the calibrated and verified SWMM model for the Lower Ohio Basin study area. A one year continuous simulation model run was conducted and the data output was subsequently analyzed. For each of the 46 monitored events, the simulated storm peaks and volumes for each monitored sewershed were compared with the corresponding monitored wastewater peak and volume values. Linear regression analyses were conducted to make the comparisons and evaluate the success of the model simulations.

The model subsequently was modified by replacing the precipitation input data derived from the regional gauge with precipitation data derived from the nearest gauge (alternative precipitation source #2). A continuous simulation model run was conducted and the resulting output data for each of the monitored storms were assessed in the same way utilizing the linear regression analyses. The process was repeated, replacing the precipitation input data with the corresponding data derived from the network of gauges (alternative precipitation source #3) and the continuous precipitation data from the radar-rainfall system (alternative precipitation source #4). Since only the precipitation input was changed, and all other model parameters remained the same, any differences in the simulated storm peaks and volumes would be directly attributable to the differences in the rainfall data. Similarly, any differences in the degree of correlation between simulated and monitored storm peaks and simulated and monitored storm volumes (as quantified from the regression analyses) would be directly attributable to the differences in the rainfall data. It was the results from the series of linear regression analyses that were the basis of comparison for the four alternative precipitation data sources and the basis for quantifying the benefits of improved rainfall measurement. The large number of monitored storm events, occurring in all seasons of the year, provides additional confidence to the validity of the analysis results and that the simulation models accurately reflect seasonal variations in the ways separate sanitary sewer systems respond to rainfall.

18.3 Summary of Analysis Results

In general, significant improvements were consistently observed between simulated and observed storm peaks as refinements to model input precipitation data were made. In contrast, within many of the analyzed sewersheds relatively little improvement was observed between simulated and observed total storm volumes as refinements were made to the precipitation data. For all of the analyzed sewershed areas, monitored precipitation from the regional gauge was found not to be representative of actual rainfall over the monitored sewershed. When the source of rainfall data input to the model was improved from the single nearest gauge to a network of adjacent gauges, utilizing the inverse distance method to determine the relative weight given to adjacent gauges, continued improvement to model simulation results were observed in most of the sewershed areas. However, results were highly mixed within the analyzed sewersheds regarding the continued level of improvement

to simulation model results when the source of precipitation data was upgraded from the gauge network to the radar rainfall system. The analysis results from the Spruce Run sewershed were selected to illustrate the trends typically observed for the majority of the monitored sewershed areas for which analyses were conducted, and are provided and described below.

18.3.1 Comparison of Analysis Results for Simulated and Monitored Storm Peaks

It clearly can be seen from the regression analysis results that the monitored precipitation from the regional gauge at the Pittsburgh International Airport was not representative of actual rainfall over the Spruce Run sewershed. Figure 18.5 shows the graphical results of the linear regression analyses conducted to compare simulated versus monitored storm peaks when regional gauge data were utilized as model input for the 46 monitored events within the sewershed. Corresponding comparisons between regression slopes, intercepts, R-square, and root mean square error (RMSE) are presented in Table 18.1. The regression line slope of 0.1800 is significantly different from an ideal fit of 1.000 and the intercept value of 2.045 million gallons per day (mgd) is significantly different from an ideal fit 0.000 mgd. This would be expected since the regional gauge is over 10 miles (16 km) away from the monitored sewershed and orographic influences on rainfall are significant in the Pittsburgh region. The terrain within the Pittsburgh area is very hilly and storm fronts tend to be strongly influenced as they pass over the Allegheny Mountain range. These results are consistent with the results observed in all the analyzed sewersheds.

The analysis results show that when precipitation data from the nearest gauge, located approximately 1.6 miles (1.0 km) away from the sewershed, are substituted for regional gauge data, a significant improvement is observed in the correlation between simulated versus monitored values for the 46 monitored events. The results of the linear regression analyses are depicted in Figure 18.6 and in Table 18.1. The regression line slope of 0.895 is reasonably close to an ideal fit of 1.000 and significantly improved over the regression slope value of 0.1800 produced by the regional gauge data. Similarly the y-intercept value of 0.576 mgd is a significant improvement over the comparable intercept value produced from the regional gauge data. The significant increase in the R-square value and the significant decrease in the RMSE show that the level of uncertainty in the model simulation, as represented in the degree of scatter in the data points around the regression

slope, improved significantly as a result of improved rainfall measurement. These results are consistent with the results observed in all the analyzed sewersheds within the Lower Ohio basin.

Figure 18.5 Regression analysis results for regional gauge.

Table 18.1 Regression analysis results for regional gauge and nearest gauge

Regression Analysis Parameter	Regional Gauge	Nearest Adjacent Gauge
Slope	0.1800	0.8950
Intercept	2.0450	0.5760
R-Square	0.1848	0.7184
RMSE	1.2210	0.7106

Figure 18.7 shows the linear regression analysis graph for the comparison between simulated versus monitored storm peaks when the more refined precipitation data from the gauge network were utilized as model input. Corresponding comparisons between regression slopes, intercepts, R-square, and root mean square error (RMSE) are presented in Table 18.2.

Figure 18.6 Regression analysis results for nearest gauge.

The regression analysis results show that there is little difference between the degree of correlation between simulated and observed storm peaks when comparing the nearest gauge and gauge network rainfall data sources. The regression line slope of 0.857 is reasonably close to an ideal fit of 1.000 and comparable to the regression slope resulting from the nearest gauge data. The intercept value of 0.597 million gallons per day (mgd) is reasonably close to an ideal fit of 0.000 mgd and comparable to the intercept value resulting from the nearest gauge data. This would mean that both precipitation data sources are equally representative of actual rainfall over the Spruce Run sewershed. One would have expected a better representation of rainfall distribution from a network of gauges, rather than a single gauge. The reason this was not the case for the Spruce Run sewershed probably is explained because of the close proximity to the nearest gauge. The analyses of the 46 monitored storms produced mixed results in the other analyzed sewersheds within the Lower Ohio basin. For many of the sewersheds, substituting precipitation data from a single nearest gauge to data from the gauge network yielded noticeable improvements to simulation model results. For others, the results were similar to those observed at Spruce Run and little if any improvement was observed.

Figure 18.8 shows the linear regression analysis graph for the comparison between simulated versus monitored storm peaks when the high resolution gauge-adjusted radar data were utilized as model input. Corresponding

comparisons between regression slopes, intercepts, R-square, and root mean square error (RMSE) are presented in Table 18.2.

Figure 18.7 Regression analysis results for network of gauges.

Table 18.2 Regression analysis results for gauge network and radar-rainfall system.

Regression Analysis Parameter	Gauge Network	Radar-Rainfall System
Slope	0.8570	0.9990
Intercept	0.5970	- 0.0580
R-Square	0.7103	0.9061
RMSE	1.7656	1.037

The regression analysis results show that there was a significant improvement to the degree of correlation between simulated and observed storm peaks when comparing the gauge network and radar-rainfall rainfall data sources. The regression line slope of 0.999 is almost identical to an ideal fit of 1.000 and is a significant improvement over the comparable regression slope of 0.8575 resulting from the gauge network data. The intercept value of -0.0580 million gallons per day (mgd) is nearly identical to an ideal fit of 0.000 mgd

and is a significant improvement over the intercept value resulting from the data from the gauge network.

Figure 18.8 Regression analysis results for radar-rainfall system.

The relatively high level of observed improvement is enlightening since both the gauge network and radar-rainfall data provide spatially-varied precipitation over the Spruce Run sewershed, which was not provided from the other two alternative precipitation data sources. The significant improvement for all four regression analysis indicator parameters would indicate that the radar-rainfall data was more representative of actual rainfall over the Spruce Run sewershed. For this to occur, one must reason that several of the 46 monitored storms must have had relatively small storm cells that passed between the gauges in the network. Hence, some the more intense portions of the storms were undetected by the gauge network but were detected by the radar images and accounted for with the radar-rainfall system. The significant increase in the R-square value indicates that the level of uncertainty in the model simulation, as represented in the degree of scatter in the data points around the 1.000 regression line slope, improved significantly as a result of improved rainfall measurement.

The regression analyses of the 46 monitored storms produced mixed results in the other analyzed sewersheds within the Lower Ohio basin. For some of the monitored sewersheds, substituting radar-rainfall data for gauge

network precipitation data yielded noticeable improvements to simulation model results and the levels of correlation between simulated and observed storm peaks, similar to those observed for Spruce Run. For other sewersheds, the regression results indicated that the radar-rainfall data produced little if any improvement in model simulations.

18.3.2 Comparison of Analysis Results for Simulated and Monitored Storm Volumes

In contrast to the analysis results from the comparison between simulated and observed storm peaks, within many of the analyzed sewersheds relatively little improvement was observed between simulated and observed total storm volumes as refinements were made to the precipitation data.

Figure 18.9 Regression analysis results for regional gauge, storm volume.

Table 18.3 Regression analysis results for regional gauge and radar-rainfall system, total storm volume

Regression Analysis Parameter	Regional Gauge	Radar-Rainfall System
Slope	0.9220	0.9220
Intercept	0.0760	-0.2080
R-Square	0.9228	0.9491
RMSE	0.2964	0.2372

Figure 18.9 and Table 18.3 show the results of the linear regression analysis conducted to compare simulated to monitored storm volumes when regional gauge data were utilized as model input for the 46 monitored events within the sewershed. The regression line slope of 0.922 is reasonably close to an ideal fit of 1.000 and the intercept value of 0.076 mgd is nearly identical to an ideal fit of 0.000 mgd. This result would not be expected given the distance between the airport gauge and the Spruce Run sewershed. This would indicate that while monitored rainfall intensity at the regional gauge are not representative of actual rainfall over the sewershed, hence the poor correlation between simulated and monitored storm peaks, the total storm volume monitored by the regional gauge was reasonably close to the total storm depth over the sewershed. This analysis result also would indicate that the total storm volume over the sewershed was independent of the orographic distribution of rainfall over the basin. The analysis produced mixed results in the other analyzed sewersheds within the Lower Ohio basin. For some of the sewersheds, the correlation between simulated and monitored storm volumes was reasonably good. For other sewersheds, the correlation was poor.

Figure 18.10 shows the linear regression analysis graph for the comparison between simulated and observed storm volumes when the high resolution, spatially distributed radar-rainfall data were used as model input. Corresponding comparisons between regression slopes, intercepts, R-square and RMSE are presented in Table 18.3. The regression analysis shows that there is little difference between the degree of correlation between the simulated and observed storm volumes when comparing the least refined and most refined precipitation data sources. For this reason, regression analysis results are not shown for the nearest gauge and gauge network alternative data sources. The regression line slope of 0.922 is identical to that from the regional gauge data and is reasonably close to an ideal fit. The regression line slope from the radar-rainfall data actually got worse and increased to 0.2080, indicating a stronger bias toward over-simulating the smaller storms and under-simulating the larger events. The r-square and RMSE values improved slightly, showing that the degree of data scatter and level of uncertainty in the model simulation decreased slightly with the refinement in precipitation data. The analysis produced mixed results in the other analyzed sewersheds within the basin. For some of the sewersheds, the correlation between simulated and monitored storm volumes improved as more refined precipitation data was input into the model. For other sewersheds, the correlation did not improve.

Figure 18.10 Regression analysis results for radar-rainfall data, storm volume.

18.4 Conclusions

In the greater Pittsburgh region, the ALCOSAN authority has made a significant investment to develop and refine the comprehensive wet weather management program that is intended to control CSO and SSO discharges into area water bodies and improve the water environment within the service area. Significant investments were and are still being made to better inventory and characterize ALCOSAN's regional wastewater conveyance and treatment systems and the tributary municipal collection systems. Complex hydrologic and hydraulic models have been prepared and are in the process of being refined to better quantify and characterize extraneous groundwater and storm water flow in sewer systems and the corresponding frequency and duration of CSO/SSO discharges. These models are used to develop, evaluate, and select optimal regional facilities needed to control wastewater flow. An investment also was made to significantly improve the precision and accuracy of precipitation measurement. It was concluded that the expenditure in developing and implementing a regional gauge adjusted radar-rainfall system was a worthwhile investment that will result in multiple benefits to the region

and reduce the ultimate cost for wastewater management and regulatory compliance. This conclusion is supported below.

Orographic influences in the Pittsburgh area were found to be significant. If the ALCOSAN service area was flat and rainfall tended to be relatively uniform over the Pittsburgh region, then refinements to precipitation monitoring may not have been needed. However, the terrain within the Pittsburgh area is highly variable and storm fronts tend to be strongly influenced as they pass over the Allegheny Mountain range. The improved resolution of precipitation data and the corresponding improvement to model simulations provided by the high-resolution radar-rainfall system demonstrated that the geographic distribution of storm depths, intensities and durations is significant in the greater Pittsburgh region. A relatively dense network of rain gauges would be needed to provide adequate resolution over the ALCOSAN service area. If a traditional gauge network were to be employed, many gauge sites would be needed to monitor the orographic distribution of rainfall, and the level of effort and cost to maintain the gauge network would be high. With a traditional gauge network system, malfunctioning gauges and missing data can significantly compromise the quality of precipitation data for the model. The radar-rainfall system provided the high resolution needed to support the modeling efforts and because the entire gauge network is used to adjust the radar data, less gauging stations are needed and there is a reduced dependency on an individual gauge site. The analyses demonstrated that a more simplified approach to rainfall measurement would have reduced the quality of model simulations which would have been detrimental to the development of the regional wet weather control plan.

The level of uncertainty in the analysis results decreased as a result of improved rainfall measurement. Improvements in rainfall measurement reduced the level of uncertainty associated with simulation model results, as was demonstrated by the significant improvements to the R-square and RMSE regression analysis values. Without improvement to precipitation measurement, the uncertainty associated with rainfall would have been significantly larger than the uncertainty associated with modeling, facility sizing, or cost estimation. That is to say that imprecise or non-representative precipitation measurement would have been the “weakest link” in the analysis and design process for the greater Pittsburgh region. Precipitation is the driving force that determines the quantity of extraneous flow that enters the sewer system and the frequency and duration of wastewater discharges to receiving water bodies. The analyses showed that the investment made to

improve the precision and accuracy of regional precipitation measurement resulted in better simulation model results which significantly reduced the level of uncertainty. Reduced uncertainty in the simulation model results translates to reduced facility sizes and capacity requirements and reduces the ultimate cost of regulatory compliance.

Imprecise or non-representative rainfall could lead to incorrect or misdirected remedial action. It has been estimated that over 1 billion dollars may need to be invested in the rehabilitation and reconstruction of municipal collection systems and private service lateral connections to control CSO and SSO discharges and meet the requirements of regulatory agencies. The completed and ongoing physical investigations and modeling analyses are used to estimate the level of effort needed to reduce extraneous flows into the sewer system. The investigations and analyses were also used to prioritize the individual sewersheds in terms of which ones would need higher or lower levels of corrective effort and to determine which sewersheds would be given higher priority to receive corrective action. The Lower Ohio Basin study showed that improvements to the accuracy and precision of rainfall measurement produced improved model results and more precise and accurate characterizations of the extraneous flow entering individual sewershed areas. The analyses demonstrated that less precise and accurate rainfall data would have compromised the accuracy and reliability of the model simulation results which could have resulted in misdirected rehabilitation effort, unnecessary remediation expenditures and increased cost.

Study results were inconclusive regarding the relative value added from a high-density gauge network versus a gauge-adjusted radar-rainfall system. The Lower Ohio basin study was successful in quantifying and characterizing the levels of improvement to modeling accuracy resulting from improvements to the accuracy and resolution of precipitation data. The regression analyses demonstrated that using data from a nearby gauge located within reasonable proximity to the sewershed provided reasonable model simulation results with a reasonably good correlation between simulated and monitored storm peaks in most sewersheds that were studied. When the precipitation data source was upgraded to a network of gauges, and precipitation distributions were taken into account, study results were mixed regarding the corresponding improvement to the quality of simulation model results. For roughly half of the sewersheds that were studied, especially the largest sewersheds, there was a significant improvement in the correlation between simulated and monitored storm peaks. However for other sewersheds, especially the smaller sewershed areas where the special distribution of the rainfall was less significant, there was no discernable improvement to model simulation results. Study results

also were mixed when model runs were compared using input precipitation data from the high-density gauge network and data from the calibrated radar-rainfall system. This observation was unexpected since the pixel grid resolution associated with the radar-rainfall systems is much higher than the corresponding density of the gauge network. Significant improvement in the modeled peak wet weather flow was observed in half of the sewershed areas that were analyzed. No differences were observed in the other half of the sewersheds. In roughly half of the analyzed sewershed areas, radar-rainfall data significantly increased the R-square regression value and decreased the RMSE, demonstrating an improved level of uncertainty in the model simulation, as represented in the reduced degree of scatter in the data points. However, no significant improvement in the level of uncertainty was observed in the other half of the analyzed sewersheds. Additional analyses in other study areas within the ALCOSAN system will show whether or not this trend will continue.

The estimated cost for the ALCOSAN service area to implement the Regional Long Term Wet Weather Control Plan has been estimated to be as high as \$3 billion (US\$), spread over a duration of 50 years. In support of this plan, significant regional investments are being made for data collection, field investigations, GIS mapping and facilities design. A regional investment is also being made for precipitation monitoring. By comparison, the initial start-up cost to implement the radar-rainfall system and the total cost to keep the system running over a period of 10 years has been estimated to be approximately \$660 thousand. It would appear that the cost associated with accurate and precise rainfall measurement is relatively low when compared with the other costs associated with developing and implementing the regional control plan. If the overall cost of implementing the regional LTCP were reduced by even 5 % as a result of improved precipitation measurement, there would be a 200 fold return on the investment. It is therefore concluded that improving the accuracy and resolution of precipitation measurement in the greater Pittsburgh region was a wise investment.

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