Watershed-Scale Evaluation of a System of Storm Water Detention Basins

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Abstract: The effectiveness of an existing system of storm water detention basins operating at the watershed scale is evaluated. Data utilized in the study were collected from Valley Creek watershed in Chester County, Pa., which has undergone rapid development from the westward spread of suburban Philadelphia. Since the late 1970s, more than 100 storm water detention basins have been constructed in this 62 km^2 (24 mi^2) watershed, each designed on a site-by-site basis. The design objective of these detention basins is to limit a site's postconstruction peak flow rate to or below its predevelopment level for 2- through 100-year storms. To evaluate the watershed-wide effectiveness of the network of detention basins, all basins were surveyed and included in a hydrologic model of the watershed. The U.S. Army Corps of Engineers Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) model was calibrated by using measured rainfall and observed streamflow from a U.S. Geological Survey (USGS) stream gauge. Results from modeling six measured storm events show that the detention basins reduce watershed-wide peak storm flows by an average of only 0.3%, and can potentially increase peak flow rates. The model was also used to investigate the effects of alternate on-site stormwater management strategies, including outlet structure modification and runoff volume-based management. Results indicate that a runoff volume-based plan is the most effective means of attenuating watershed-wide peak flow rates.

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Introduction

Valley Creek watershed is located in suburban Philadelphia, 35 km (22 mi) northwest of the city. The watershed has been heavily developed for the past 50 years, which has resulted in 17% impervious surface coverage, as of March 2000. Despite this development, Valley Creek continues to have significant historical and ecological value, since it flows through Valley Forge National Historical Park and is currently listed as an Exceptional Value stream in the Commonwealth of Pennsylvania (25 Pa. Code § 93.9f 2002). The watershed supports a reproducing population of brown trout and is one of only two Class A (>40 kg/ha) trout fisheries, as designated by the Pennsylvania Fish and Boat Commission in the five-county region of Southeastern Pennsylvania (Alan Everett, Pennsylvania Department of Environmental Protection, personal communication, July 2003). The creek may have recently supported a reproducing population of native brook trout (Kemp 1994). However, as development has continued, the creek has experienced more frequent and severe flooding, as noted by residents of the area. Accompanying this flooding is increased channel erosion and its consequent sediment loads. The channel erosion is so severe in Valley Forge National Historical Park that the creek is fenced off from the public with signage reading "Danger—Area closed due to eroding stream banks."

More than 100 storm water detention basins have been constructed in the watershed to control runoff from new development. The purpose of these detention basins is to attenuate on-site peak flow rates so that they are no greater than predevelopment levels for large storms of 2- to 100-year return periods. The detention basins have been designed to limit the peak flow rate at the site's downstream property line. The rationale behind the design of the detention basins presents three major shortcomings. First, the detention basins are not designed to attenuate runoff volume. Although the peak flow rate may be reduced, the extended runoff rates and increased volume are known to increase stream bank erosion (USEPA 2002; McCuen and Moglen 1988; Malcom 1980). Second, the detention basins are designed for 2- to 100-year storms, which constitute only a small fraction of the yearly precipitation. Third, because the detention basins are designed on a site-by-site basis, their watershed-wide performance can not be assured (McCuen 1979).

It is the authors' opinion that although storm water management appropriately begins at the site scale, its effectiveness should be evaluated at the watershed scale. Storm water flows released from multiple sites eventually accumulate and affect flow and erosive potential in the main watershed channels. We hypothesize that onsite detention basins do not significantly affect storm

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hydrographs resulting from frequent watershed-wide storm events. This paper uses hydrologic modeling to quantify the impact of a network of existing detention basins, each designed to control an individual site for 2- to 100-year storms, on watershed-wide storm flows, using Valley Creek watershed as a case study.

Methods

The U.S. Army Corps of Engineers Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) (Scharffenberg 2001) was used to model stream flow under storm conditions, including the effects of the detention basins within the watershed. The model was subsequently used to predict the performance of outlet structure modifications to the basins and a runoff-volume-based stormwater management plan, both at the watershed scale.

A reconnaissance mission that was based on a preliminary survey (Cahill Associates 2001) and aerial photographs revealed a large network of detention basins in Valley Creek watershed. Because copies of many of the engineering drawings and specifications for the basins either had not been saved or had been archived by the municipalities in such a manner such that they were not retrievable, the information required to quantify the storage and routing characteristics of the basins was obtained by manual survey (Emerson 2003). The survey included detailed measurements of each outlet structure and a rough topographic survey of the basin. The topographic survey included pacing off the dimensions by foot and measuring the side and bottom slopes with a lock level and surveyor's tape. A comprehensive photographic record of each detention basin was created, along with a GPS record marking the coordinates of the outlet structure. The survey data were used to create scaled contoured drawings of each basin. A stage-versus-storage relationship for each basin was developed on the basis of digital planimetering of the basin contours. These data were then combined with a stage-versus-outflow curve, computed using basic hydraulic equations for weir and orifice flow, to create a storage-versus-outflow curve for each detention basin. This paired data set was used to route flows through reservoirs using the Modified Puls (level pool) routing subroutine in HEC-HMS (Feldman 2000). This process was performed for a total of 82 detention basins ultimately included in the model.

The remainder of the information required as model input was derived from geographic information system (GIS) data. The Army Corps of Engineers Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) (Doan 2000) was used as a preprocessor to HEC-HMS, creating required input data that were based on relatively standard GIS data. HEC-GeoHMS is an extension that runs in the ArcView GIS software. The extension develops watershed boundaries and drainage networks on the basis of topographic data contained in a digital elevation model (DEM). The DEM was a combination of two standard 30-m resolution USGS DEMs (Valley Forge and Malvern, Pa.), joined by Cahill Associates. However, the 30-m resolution of the DEM did not contain enough detail to enable HEC-GeoHMS to delineate each smaller subwatershed that drains to a detention basin, and these boundaries are not always dictated by topography alone. Therefore, it was necessary to resample and manually edit the DEM to create the desired drainage areas for each of the 82 detention basins included in the model. The original HEC-GeoHMS delineation produced nine subwatersheds, averaging 6.0 km^2 (2.3 mi^2) each. The manual drainage delineations produced an additional 82 subbasins, for a total of 91 (Fig. 1). The area of the subbasins draining to detention basins ranged from $2.6 \cdot 10^{-3}$ km^2 (0.64 acres) to

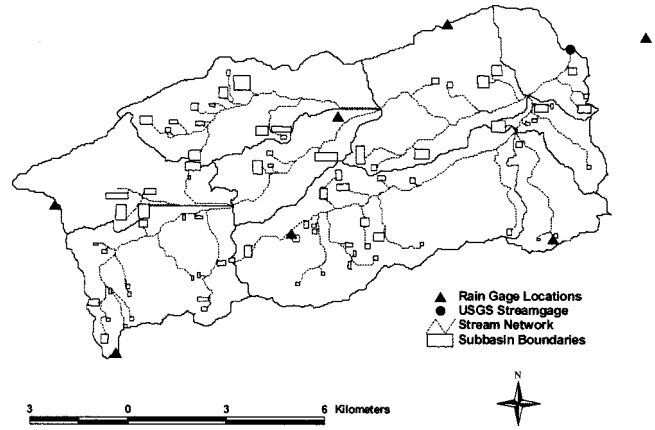

Fig. 1. Valley Creek watershed with complete subbasin delineation, showing streams and both rain gauge and U.S. Geological Survey stream gauge locations

0.11 km^2 (26 acres), with an average of 0.03 km^2 (6.3 acres). The total area draining to detention basins in the model constituted only 4% of the total modeled watershed area. However, contained in this 4% was 39% of the entire watershed's directly connected impervious area.

The Green and Ampt method was chosen to model the precipitation losses to infiltration. The soil-type data were taken from the Chester County, Pennsylvania, soil survey (USDA 1963). A GIS was used to reclassify and assign Green and Ampt parameters to these soil types based on the general soil-texture class, as described by Rawls et al. (1982). The GIS was then used to calculate average values for each of the 91 subwatersheds. Channel routing was accomplished by using standard Muskingum routing. There were 165 reaches in the final model. The Muskingum "*K*" was estimated by using travel time estimates that were based on channel slope and length values, as calculated by the GIS. A distributed runoff transformation was employed to route precipitation excess to the outlet of each subbasin. The only distributed runoff transformation currently available in HEC-HMS is the modified Clark unit hydrograph, or "ModClark" (Kull and Feldman 1998). This distributed method requires grid-based precipitation. The precipitation data for the study were gathered by a network of between five and seven recording rain gauges (Spectrum Technologies, Inc., Datalogging Digital Rain Gauge, Model 120) deployed to the watershed. The rain gauges were set to record at 5-min intervals. The point gauge data were interpolated by using the inverse-distance-squared method to create unique precipitation grids for each 5-min time step within each storm-event period. The Army Corps of Engineers' GageInterp software was used to create the precipitation grids in the required Hydrologic Engineering Center Data Storage System (HEC-DSS) file format (Evans 2002). The ModClark transformation requires that the subbasins be divided into a grid (created in HEC-GeoHMS). Each grid cell received unique precipitation data, the excess of which were routed to the outlet of the subbasin based on the basis of its distance to the outlet and the subbasin's assigned time of concentration and Clark storage coefficient (Scharffenberg 2001).

A stream gauge and a network of recording rain gauges were used to calibrate the watershed model. Locations of the gauges are shown in Fig. 1. The U.S. Geological Survey (USGS) maintains a stream gauge (Station Number 01473169) 3.4 km (2.1 mi) upstream of the mouth of the watershed. Only the uppermost

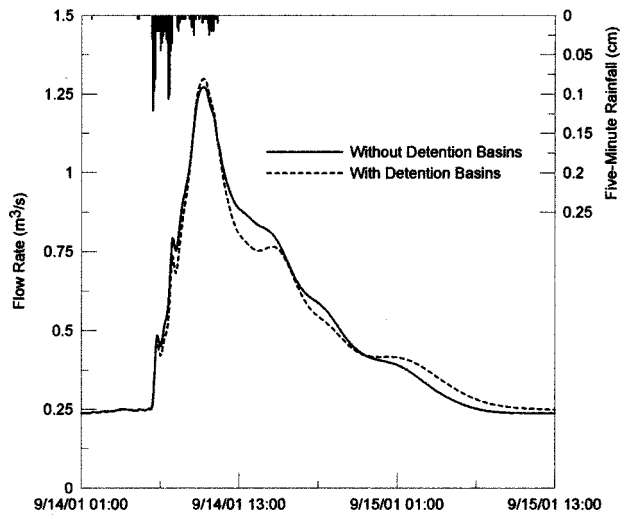

Fig. 2. Simulation results for September 14, 2001, storm, showing hydrographs both with and without detention basins

54 km^2 (21 mi^2) of the watershed, upstream of the gauge, were included in the model. The precipitation data and the observed USGS flow data were used to calibrate the Green and Ampt and ModClark parameters of the model. In total, six storm events were measured between September 2001 and August 2002 with the network of recording rain gauges. The six events ranged from 1.2 to 5.0 cm (0.47 to 1.97 in.) of rainfall. The rainfall data demonstrated significant spatial variability. The average maximum difference among the gauges for the six storms was 1.5 cm (0.61 in.), with a maximum of 3.1 cm (1.2 in.) for the September 20, 2001, storm. In the southeast region of Pennsylvania, the 2-year 24-h storm is defined by a depth of 8.6 cm (3.4 in.); therefore, none of the six measured storms approached the magnitude of a typical design storm.

Since the total area attenuated by detention basins had a much higher percentage of impervious cover, relatively dry initial moisture conditions were used throughout the model in an effort to better show any potential effect of the detention basins. In other words, simulating events without significant antecedent precipitation will minimize runoff from pervious areas; this runoff may otherwise overshadow the attenuating effect that the detention basins may be having on their predominantly impervious drainage areas. The model was first run with all the detention basins in place as per the field survey. To determine the influence of the detention basins, the model was run a second time with all detention basin elements removed.

Results

A comparison of the model output hydrographs at the furthest downstream point on the main stem of the creek indicated that the existing system of detention basins in Valley Creek watershed provided essentially no attenuation to the watershed's storm water flow regime (Fig. 2). Table 1 summarizes the computed peak flow rates at the outlet of the watershed for the six input storms. Computed peak flow rates were nearly identical between the two runs (detention basins versus no detention basins) for all input storm events, with the largest peak flow rate reduction of 4% (0.08 m^3/s or 3 cu ft/s) and an average peak flow rate reduction for all six events of 0.3%. In two of the six measured storms, the peak flow rate of the run with the detention basins actually produced a higher peak flow rate than without the detention basins, with the largest increase being 3.5%, (0.05 m^3/s or 2 cu ft/s) as computed for the August 24, 2002, storm. Fig. 2 shows the computed results from the September 14, 2001, event. In both this storm and the August 24, 2002, storm, the computed peak outflow was slightly increased by the presence of detention basins. This phenomenon occurred because the peak flow rate of the unattenuated original nine subbasins (those not connected with detention basins) occurred during a receding limb (produced by a bimodal runoff distribution) of the flow from the areas that are attenuated by detention basins. During this receding limb, the flow with detention was 0.05 m^3/s (2 cu ft/s) higher than the flow without detention. Although the observed increases are relatively insignificant, this outcome illustrates that the flows from the attenuated areas and the unattenuated areas can merge to produce a higher peak flow rate, as shown in Fig. 2.

Outlet Structure Modifications

The theory behind outlet structure modifications, or retrofits, is to increase a basin's detention capabilities by further restricting the lowest orifice, or low-flow orifice. To test the concept of watershed-wide detention retrofits, the HEC-HMS model was changed to reflect two possible retrofit detention scenarios. The first condition was a watershed-wide, low-flow orifice modification, and the second was the same modification of only the upstream basins. The smallest-diameter low-flow orifice found dur-

Table 1. Summary of Simulation Results for Six Measured Storms

	Average rain gauge totals		Peak flow rate without detention		Percent peak flow rate reduction				
					With detention basins	With modified detention basins	With prescribed capture depths		
Storm date	(cm)	(in.)	(m^3/s)	(cu ft/s)			1.3 cm (0.5 in.)	2.5 cm (1.0 in.)	5.1 cm (2.0 in.)
09/14/01	1.2	0.47	1.3	45	−2.1	0.56	6.7	6.7	6.7
09/20/01	5.0	2.00	3.3	120	2.3	7.2	9.5	14	15
05/12/02	3.4	1.40	1.7	61	0.62	0.62	8.2	11	11
06/06/02	4.2	1.70	3.9	140	0.39	7.4	5.9	11	13
08/24/02	1.5	0.59	1.4	50.	−3.5	0.67	12	12	12
08/28/02	3.0	1.20	2.2	78	4.0	9.3	13	18	18

ing the study survey was 10 cm (4 in.). Of the basins in the survey, 16% had 10-cm low-flow orifices. Other detention basins, generally with larger contributing areas, had larger low-flow orifices, some larger than 30 cm (1 ft). The remaining detention basins had alternative outlet structure designs, with the lowest outlet being a weir or perforated standpipe; generally, these outlets were not as restrictive as a 10-cm orifice. Therefore, the model was modified such that the low-flow orifices of all the detention basins were restricted to this minimum diameter. The storage-versus-outflow curves for all 82 detention basins were recalculated to reflect the modified outlet structures. The six measured storm events were all analyzed with the model containing the modified outlet structures. The peak flow results from these simulations are summarized in Table 1. In all but one storm, the results with the modified outlet structures show improved peak flow reductions compared with the previous simulations with the unmodified outlet structures. The largest peak flow reduction of 9% was found for the August 28, 2002, storm. No peak flow increases were observed, and the average percent peak flow reduction for the six measured storms was 4%.

Stratified Detention

The second modification scenario incorporated a heuristic optimization of the detention basins, with the objective of limiting the stream flow rate at the outlet of the study area. For this scenario, the upstream detention basins were simulated as being retrofitted with the 10-cm-diameter outlet, whereas the remaining downstream basins were relinquished of all detention capabilities. A GIS was used to determine which basins would be retrofitted and which would be removed. HEC-GeoHMS enables the user to trace the flow paths, in this case from each detention basin to the outlet of the study area, by clicking on the point of interest in the DEM, and provides some basic statistics on flow paths, including their distance to the outlet of the watershed. The distances from all 82 basins to the watershed outlet were calculated by using this feature. The detention basins were then divided in half on the basis of their travel distances downstream to the outlet. The results for this scenario were not nearly as effective at limiting peak flows as the previous scenario, with only three events showing any peak flow reduction. The attenuation observed in these three events was minor, with a 2% maximum reduction. The average peak flow reduction among the six storms was 0.8%.

Runoff Source Control Management Plan

The final adaptation of the HEC-HMS model was to evaluate the impact of a network of source control, or volume-based storm water management practices on the watershed-wide storm water flow regime. This analysis was of key interest to the study because runoff volume attenuation is envisioned to replace the standard release-rate method of storm water management (PADEP 2002).

Three different scenarios were analyzed: capture of the first 1.3 cm (0.5 in.), 2.5 cm (1.0 in.), and 5.1 cm (2.0 in.) of runoff. Only runoff from within the attenuated areas (draining to detention basins) was captured for volume management. The runoff represents the portion of precipitation landing on directly connected impervious surfaces and the precipitation that is in excess of the Green and Ampt losses. A specific capture volume of runoff was calculated for each of the 82 areas by multiplying the area of that subbasin by the desired capture depth. The model then removed the specified volume of runoff as it was routed to the outlet of the subbasin. All runoff in excess of the captured volume was unaffected by the process. The same six measured storm events were used in these simulations. As indicated in Table 1, the results show significant peak flow reductions across all six storms, with a maximum peak flow reduction of 18% found for the August 28, 2002, storm. The average peak flow reductions achieved with the 1.3, 2.5, and 5.1 cm hypothetical volume-based management strategies were 9.2, 12, and 13%, respectively. In the measured storms in which the total precipitation does not exceed the capture depth, the results for that capture depth are identical to the simulations from the previous capture depth. In these situations, there is no runoff from the attenuated areas, and the surrounding areas (those not attenuated by detention basins) are responsible for the entire watershed's hydrograph. For that reason, the 1.2 cm (0.5 in.) increase in capture depth from the 1.3 cm to the 2.5 cm scenario produced a 2.8% improvement, whereas the larger 2.5 cm (1.0 in.) increase from the 2.5 cm to the 5.1 cm capture-depth scenario only produced a 1% improvement. Therefore, the total storm depths must be taken into consideration when comparing the peak flow reductions for the three capture depths.

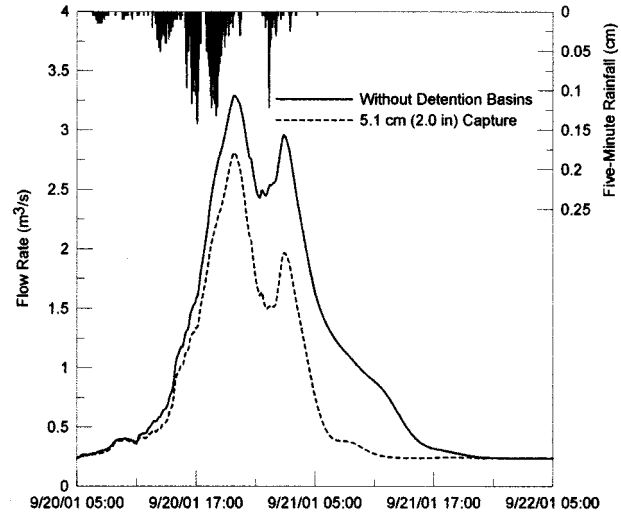

Fig. 3. Simulation results for September 20, 2001, storm, showing hydrographs both with detention and with 5.1 cm (2.0 in.) capture depth

Fig. 3 shows the computed hydrographs for the September 20, 2001, event. Since the average total rainfall for this storm was approximately the same as the 5.1-cm capture depth, the attenuated subbasins produced no runoff. Therefore, the area between the two hydrographs in Fig. 3 represents the volume of runoff that was captured for this storm.

Discussion

Simulation results for the six measured storm events indicate that the existing network of detention basins has little attenuation on watershed-wide peak flow rates, with an average peak flow reduction of only 0.3%. The hypothesis that on-site detention basins do not affect storm hydrographs resulting from frequent watershed-wide storm events is supported by this analysis. Widespread low-flow orifice modifications enhanced the performance of the detention basins for the six measured storms to an average peak flow

reduction of 4%. A second modification, runoff volume attenuation, was shown to significantly improve the watershed-wide performance. With a capture volume of 1.3 cm, the watershed experienced an average peak flow reduction of 9% for the six storms that were modeled.

The design basis for the detention basins has been to limit the peak flow rate at the downstream property line to predevelopment levels for 2- to 100-year storms. These requirements present three main shortcomings. First, the detention concept is solely focused on peak flow attenuation; therefore, detention-based designs do not include any runoff volume attenuation. Although the postdevelopment peak flow rate is often significantly increased, the total runoff volume can also be drastically increased compared with predevelopment conditions. In smaller storms, such as the six measured in this study, pervious areas produce very little runoff, and the storm hydrographs are dominated by runoff from impervious areas. Generally, detaining this excess runoff will only be an effective means of limiting watershed-wide peak flow rates if the runoff is released after the watershed's peak flow has occurred. However, this would require large storage volumes and long retention times and would still prolong higher flows and still contribute to in-stream erosion and sedimentation. In a volume-based scenario, the excess runoff created from impervious surfaces would be completely removed from the storm hydrograph and it therefore would not contribute to the watershed's peak flow rate nor would it help sustain elevated flow rates during the hydrograph's receding limb.

A second problem with detention-based design methods is that the basins are designed for large storm events. Generally the detention basins are designed for the 2- to 100-year storms. In the southeast region of Pennsylvania, a 2-year storm of a 24-h duration is one in which there is approximately 8.6 cm (3.4 in.) of rainfall, and a 100-year storm is one with approximately 21 cm (8.2 in.) of rainfall in a 24-h period (Aron et al. 1986). However, these larger events only constitute a small fraction of the yearly precipitation. Southeastern Pennsylvania receives 114 cm (45 in.) of precipitation in an average year. An analysis of a 50-year record of local historical daily rainfall data shows that on average storms of the 2-year return period and greater constitute only 3.1 cm (1.2 in.), or 3%, of the yearly precipitation (Emerson 2003). Therefore, there are no requirements on managing the remaining 97% of the annual precipitation.

A third design problem is that because the detention basins are designed on a site-by-site basis, they are not operating in a coordinated fashion. The hydrologic model of Valley Creek watershed has shown mathematically that the detention basins are actually capable of increasing watershed-wide peak flow rates. The upstream low-flow orifice modification results showed that a simple upstream/downstream approach is not sufficient because of the spatial and temporal variability of natural rainfall patterns.

Conclusion

The results support the hypothesis that on-site detention basins do not affect watershed-wide storm hydrographs resulting from frequent storm events. An existing system of detention basins was manually surveyed and incorporated into a watershed-wide hydrologic model of Valley Creek watershed. The HEC-HMS model was calibrated by using measured rainfall from a network of recording rain gauges and observed flow data from a USGS streamflow gauge. The calibrated model was used to compare the watershed's response with six measured storms, both with and without detention basins. Results indicated that the existing network of detention basins has little impact on the watershed-wide storm water flow regime. The detention basins provided an average of a 0.3% peak flow rate reduction for the six measured storms. The simulations also showed that the detention basins are capable of actually increasing watershed-wide peak flow rates. The model was then modified to reflect several alternative management plans. Two different low-flow orifice modification scenarios were simulated. The watershed-wide modification of implementing a 10-cm low-flow orifice in all basins improved the performance of the detention and produced an average peak flow reduction of 4%. Orifice modification of the upstream basins was not nearly as effective, with an average peak-flow reduction of 0.8%. The final modification to the model was runoff source control, where a prescribed runoff depth was removed from storm flow. This modification proved to be the most effective means of attenuating watershed-wide peak flow rates. With only a 1.3 cm (0.5 in.) capture volume, the volume-based control method produced an average peak flow reduction of 9%.

This paper has quantitatively demonstrated that the stormwater management method of peak flow rate control now widely implemented is flawed when viewed in terms of the impacts on the main receiving water body of a watershed. This result points to a need for fundamental reevaluation of the basis for stormwater management if the goal is protecting natural resources at the watershed scale. Modeling results indicated that the volume-control approach shows promise for attaining this goal and should be considered by water resource managers in evaluating their stormwater management plans.

Future work could include spatially refined measurement of rainfall and modeling of more storm events. The use of NEXRAD radar reflectivity data calibrated to ground-deployed rain gauges would provide a more detailed coverage of the rainfall distribution within the watershed and help resolve potential rain gauge interpolation errors. Equipping some of the detention basins with monitoring equipment to verify their predicted performance would also be a beneficial addition to the study.

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