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Performance evaluation of a retention pond for stormwater quantity and quality using SWMM

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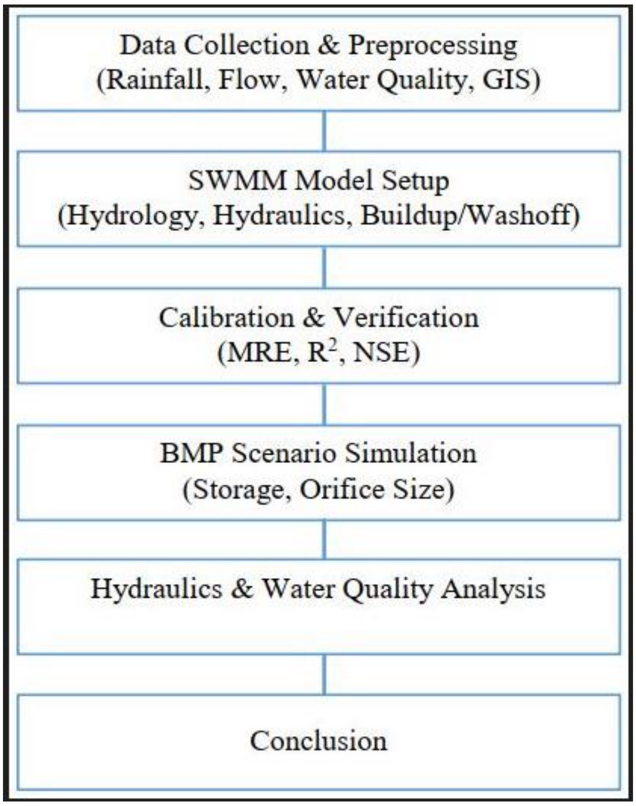
Graphical abstract



Abstract

This study evaluates the hydrologic and water quality performance of a proposed retention pond located downstream of an existing stormwater structural control in the City of San Angelo, Texas. The Storm Water Management Model (SWMM) was calibrated and verified using six monitored storm events, yielding mean relative error (MRE) values of -0.23 to 0.40, correlation coefficient (R^2) values of 0.80 to 0.90, and Nash–Sutcliffe Efficiency (NSE) values of 0.59 to 0.92. The verified model was applied to assess retention pond performance under varying initial storage volumes (0~100%) and three outlet orifice sizes. Results indicate peak flow reductions of 2.6~3.3%, runoff volume reductions of 0.4~40%, and pollutant load reductions of 41.4~64.3% depending on storage availability. Smaller orifices provided slightly greater peak flow attenuation under full storage conditions due to increased hydraulic retention time. Overall, the proposed retention pond can enhance flood mitigation, improve downstream water quality, and increase stormwater availability for supplemental municipal use. These findings demonstrate the value of retention-based Best Management Practices in semi-arid urban watersheds.

Keywords: Hydraulic Retention Time; Pollutant Load Reduction; Semi-arid Watershed; Urban Runoff Control

1. Introduction

The City of San Angelo (COSA), located downstream of the North Concho River, has experienced recurring issues such as water contamination, fish kill events, and aesthetic water quality degradation, primarily driven by stormwater discharges from nonpoint sources. In response, the city adopted multiple non-structural measures, including public education and outreach initiatives, as well as structural controls such as retention and detention ponds implemented under its Best Management Practices (BMPs) program. Nevertheless, rapid population growth and limitations in the existing sewer and drainage systems have resulted in the need for a more comprehensive, citywide stormwater management strategy.

To address these challenges, COSA initiated a coordinated stormwater management program in partnership with the Upper Colorado River Authority (UCRA). As part of this initiative, the watershed was subdivided into several monitored subcatchments equipped with stormwater gauging stations. Structural BMPs were subsequently implemented in selected subcatchments to mitigate urban flooding and improve water quality conditions.

Among the monitored areas, one subcatchment within COSA (**Figure 1**) was selected for the design and evaluation of a conventional stormwater control structure. Owing to its high runoff generation, this subcatchment was identified as having potential to

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contribute supplementary municipal water supplies during dry periods.

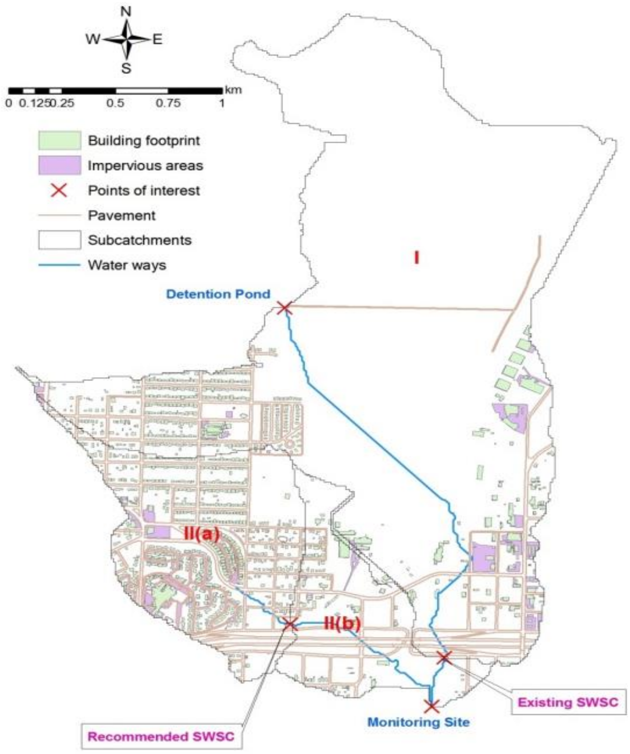


Figure 1. Case Study Area in the City of San Angelo, Texas

Between August 2010 and July 2012, this subcatchment produced peak stormwater flows of up to 11.96 m^3/s, representing approximately 65% of COSA's annual municipal water demand (UCRA, 2013). This substantial runoff generation highlights the potential for stormwater harvesting to supplement municipal water supplies while simultaneously improving downstream water quality. BMPs designed to retain high volume runoff can further reduce pollutant loads during storm events.

The Storm Water Management Model (SWMM) has been widely applied to evaluate the hydrologic and water quality performance of urban BMPs, primarily focusing on peak flow attenuation or pollutant reduction under fixed initial storage assumptions (Sehrawat *et al.*, 2025). Recent studies have further extended SWMM-based analyses by incorporating Low Impact Development (LID) practices and alternative BMP configurations, while machine learning approaches have increasingly been used to enhance prediction accuracy in water quality and environmental systems (Venkatraman *et al.*, 2024; Surendran *et al.*, 2024). However, many of these studies emphasize either predictive performance or individual hydraulic or water quality responses, with limited consideration of operational variability.

Field-based and synthesis studies have demonstrated that retention-based BMPs, including stormwater ponds and bioretention systems, can effectively reduce runoff volumes and pollutant loads (Landon *et al.*, 2025; Sabbagh *et al.*, 2025). Nevertheless, the ability of existing modeling approaches to represent realistic operational conditions—such as varying antecedent storage levels and outlet configurations—remains limited, particularly in semi-arid regions.

Therefore, the aim of this study is to assess the hydraulic attenuation, pollutant reduction, and potential municipal water supply benefits of a proposed stormwater retention pond by integrating water quantity and water quality modeling with scenario-based evaluation of initial storage conditions and outlet orifice configurations.

To provide a clearer quantitative basis for the problem formulation, the watershed characteristics relevant to stormwater response are explicitly described. Subcatchment II(a), which contributes the majority of runoff, contains approximately *40.78% impervious area*, whereas subcatchment II(b) has *18.01% imperviousness*, based on the COSA (2010) GIS dataset. Because imperviousness strongly governs runoff generation, the substantially higher impervious surface coverage in subcatchment II(a) explains its dominant contribution to peak flows and supports its selection for BMP evaluation.

The specific objectives of this study are to:

(1) verify the SWMM model for both water quantity and water quality using observed storm event data;
(2) evaluate the performance of the proposed retention pond under alternative initial storage volumes and outlet orifice configurations; and
(3) quantify the resulting changes in downstream hydraulic response and pollutant loads.

The scope of this study is limited to a representative urban subcatchment within COSA and focuses on scenario-based simulations rather than long-term optimization or real-time operational control. Nevertheless, the proposed framework is transferable to similar semi-arid urban watersheds.

These simulations enable the assessment of existing watershed conditions, BMP performance, and expected changes in stormwater quantity and quality following implementation of the proposed structural control. The simulation results are used to evaluate how the proposed Storm Water Structural Control (SWSC), namely the retention pond configuration, affects the hydraulic response of the urban watershed at the downstream monitoring station, providing an integrated basis for assessing BMP performance and predicting changes in stormwater quantity and quality under the recommended structural controls.

Therefore, to provide a clear visual summary of the methodology, the overall workflow of the study is presented in **Figure 2**, which illustrates the sequence from data collection to SWMM implementation, calibration and verification, BMP scenario evaluation, and the final assessment of hydraulic and water quality outcomes.

This schematic diagram illustrates (1) the collection and preprocessing of rainfall, flow, water quality, land use, and soil type data; (2) the SWMM model setup, including watershed delineation, hydraulic geometry, hydrologic parameterization, and pollutant buildup/washoff configuration; (3) model calibration and verification using six monitored storm events with performance indicators such as mean relative error (MRE), correlation coefficient (R^2), and Nash–Sutcliffe Efficiency (NSE); (4) development of BMP scenarios through alternative initial storage conditions and outlet orifice configurations for the proposed retention pond; and (5) comparative analysis of hydraulic response and water quality outcomes at the downstream monitoring station. The flowchart highlights the key inputs, simulation paths, and performance outputs, making the methodological framework more accessible to readers.

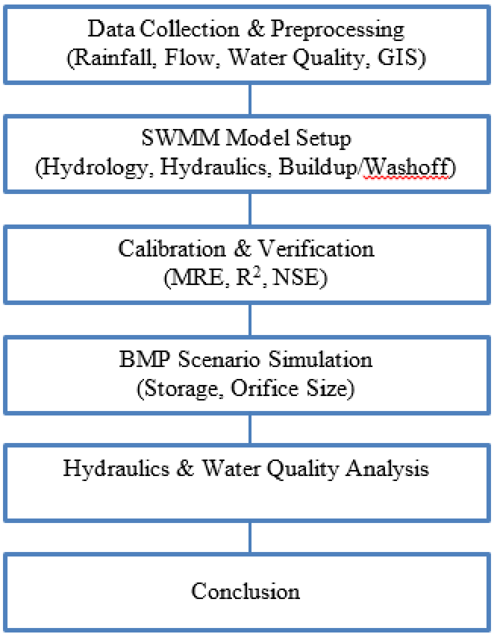


Figure 2. Overall Workflow of the Methodology.

2. Case Study Area

The COSA is located at the confluence of the North and South Concho Rivers, on the southwestern edge of the Edwards Plateau and the northeastern boundary of the Chihuahuan Desert within Tom Green County, Texas. The city relies on three major reservoirs - Twin Buttes Reservoir, O.C. Fisher Reservoir, and Lake Nasworthy - for municipal and recreational water supply. For watershed assessment and stormwater planning, the entire city was delineated into subcatchments using ArcSWAT (Arc Soil Water Assessment Tool) with 30 m resolution Digital Elevation Models (DEMs), resulting in 10 permanent monitoring stations, 12 temporary stations, and 23 additional points of interest (UCRA, 2013).

The site indicated in **Figure 1** was identified as a suitable location for constructing a large dry or wet pond to reduce pollutant loadings, particularly suspended sediments. Numerous studies have demonstrated that wet and dry detention ponds are effective at reducing sediment and nutrient loads by promoting settling and extended hydraulic retention (USEPA, 2002; Wong & Geiger, 1997). In addition, the site offers opportunities for stormwater reuse, water conservation, and potential recreational enhancements.

Specifically, a large wet pond with a controlled release structure can be constructed immediately downstream of the South Chadbourne Bridge. Such a facility would provide temporary storage of excess stormwater that can be released gradually downstream, used on-site, or potentially incorporated into municipal water supply augmentation. The pond would also contribute to sediment, Biochemical Oxygen Demand (BOD_5), and nutrient control within the COSA watershed.

The case study area is divided into two primary subcatchments, I and II, as shown in **Figure 1**. A SWSC facility has already been constructed in subcatchment I, while an additional SWSC is planned for subcatchment II to support potential municipal water supply augmentation. The existing SWSC in subcatchment I primarily regulates runoff originating from the upper watershed. However, monitoring data indicate that subcatchment II contributes a substantial portion of the total flow to the downstream gauging station. Therefore, the construction of a retention pond within subcatchment II is recommended to control runoff volumes and reduce pollutant transport. For analysis purposes, subcatchment II was further divided into subcatchments II(a) and II(b), with the proposed retention pond positioned near the center of subcatchment II.

Accordingly, a large wet retention pond with a controlled release structure and sediment forebay is recommended at the outlet of subcatchment II(a) to provide temporary storage of excess stormwater. The proposed system would support water conservation benefits, attenuate peak flows, and reduce pollutant loadings. The objective of this study is to assess water availability, hydraulic performance, and pollutant reduction potential associated with the proposed structural controls through: (1) verification of the SWMM model for the study watershed, and (2) evaluation and adaptation of BMP scenarios tailored to the case study area.

3. SWMM Model Verification for Water Quantity and Quality

SWMM (Huber and Dickinson, 1988; Rossman, 2009) has been widely applied for the evaluation of rain gardens, rain barrels (Abi Aad *et al.*, 2010), retention and detention basins (Chang, 2010; Park *et al.*, 2010; Rosenzweig *et al.*, 2011; Alahmady *et al.*, 2013; Tillinghast *et al.*, 2012; Wang and Yu, 2012), and underground detention tanks (Todeschini *et al.*, 2012). In this study, SWMM inputs explicitly incorporate the dominant land use characteristics of subcatchment II, including residential (39.01%) and industrial (14.30%) areas with corresponding imperviousness values of 40.78% and 18.01%. Soil classifications obtained from COSA (2010) indicate that KuD, MuB, and AuB account for 35.48%, 23.28%, and 19.89% of the watershed, respectively, and were used to parameterize infiltration and hydrologic properties in SWMM.

The SWMM model configuration incorporated land use (specific imperviousness) and soil type distributions of subcatchment II as defined in the COSA (2010) GIS dataset. Watershed geometries, channel dimensions, slopes, and Manning's roughness coefficients for both pervious and impervious surfaces were parameterized using field observations (UCRA, 2013). Rainfall hyetographs for each event were constructed from monitored precipitation data, establishing the hydrologic and hydraulic framework for simulating runoff generation and conveyance prior to model calibration.

Stormwater samples and flow measurements were collected during storm events from July 2010 to March 2012 using ISCO 6712 automatic samplers (UCRA, 2013). At the primary monitoring station, cumulative rainfall exhibited a mean of 25.65 mm, with maximum, minimum, and median values of 94.74 mm, 0.25 mm, and 21.34 mm, respectively. Runoff volumes were estimated from measured flow depths using channel geometry (width = 6.71 m), Manning's roughness coefficient (n = 0.05), channel slope (0.01), and rectangular cross-section assumptions. Event scale runoff volumes (10^3 m^3) averaged 348.9, with maximum, minimum, and median values of 1,280.8, 0.001, and 204.6, respectively.

Out of the 22 monitored storm events, six events with rainfall exceeding 15 mm and complete 15 minute rainfall runoff records were selected for model verification to ensure adequate hydrologic response for assessing municipal water supply potential. The largest of these events occurred on August 13, 2011, corresponding to an estimated 25~50 year return interval, and was used to place additional emphasis on matching simulated and observed peak flows.

During calibration, key hydrologic parameters were adjusted within physically realistic bounds to improve agreement between simulated and observed hydrographs. Manning's n, depression storage values, and infiltration parameters were iteratively refined while maintaining the surveyed channel geometry to ensure physically consistent model behavior.

The water quality module was calibrated by adjusting buildup and washoff coefficients for Total Suspended Solids (TSS), Total Phosphorus (TP), Total Nitrogen (TN), and 5day BOD (BOD_5) so that simulated event mean concentrations matched those measured by the ISCO 6712 automatic sampler. The resulting calibrated parameter set was then uniformly applied to all six verification events to maintain consistency across simulations.

Peak flow, total runoff volume, MRE (Eq. 1), R^2 (Eq. 2), and NSE (Eq. 3) (Nash and Sutcliffe, 1970) were used to evaluate the agreement between measured and simulated hydrographs (**Table 1**).

$$\mathrm{MRE} = \frac{1}{n}\sum_{i=1}^{n}\frac{Q_{i,obs} - Q_{i,sim}}{Q_{i,obs}} \tag{1}$$

$$\mathrm{R}^2 = \left(\frac{\sum_i^n \left(Q_{i,obs} - \bar{Q}_{i,obs}\right)\left(Q_{i,sim} - \bar{Q}_{i,sim}\right)}{\sqrt{\sum_{i=1}^n \left(Q_{i,obs} - \bar{Q}_{i,obs}\right)^2}\sqrt{\sum_{i=1}^n \left(Q_{i,sim} - \bar{Q}_{i,sim}\right)}} \right)^2 \tag{2}$$

$$\mathrm{NSE} = 1 - \frac{\sum_i^n \left(Q_{i,obs} - Q_{i,sim}\right)^2}{\sum_i^n \left(Q_{i,obs} - \bar{Q}_{i,obs}\right)^2} \tag{3}$$

Where $Q_{i,obs} = \text{observed flow}$, $\bar{Q}_{i,obs} = \text{mean of observed flow}$; $Q_{i,sim} = \text{simulated flow}$, $\bar{Q}_{i,sim} = \text{mean of simulated flow}$, and N = number of data points

Table 1. Comparison of Measured and Simulated Runoff Characteristics at a Monitoring Site

Storm Events	**1**		**2**		**3**		**4**		**5**		**6**	
Date (mm/dd/yyyy)	**8/24/2010**		**6/21/2011**		**8/13/2011**		**10/8/2011**		**1/24/2012**		**2/16/2012**	
	Measured	**Simulated**	**Measured**	**Simulated**	**Measured**	**Simulated**	**Measured**	**Simulated**	**Measured**	**Simulated**	**Measured**	**Simulated**
Total Rainfall (mm)	46.99	-	19.81	-	114.81	-	79.50	-	49.28	-	57.40	-
Mean Runoff (m^3/s)	0.95	1.16	0.47	0.52	2.35	2.79	0.68	0.95	0.36	0.28	0.43	0.28
Runoff S.D (m^3/s)	1.50	1.57	0.66	0.44	4.22	4.92	1.05	1.21	0.48	0.30	0.63	0.49
Runoff Median (m^3/s)	0.15	0.31	0.14	0.35	0.81	0.37	0.15	0.34	0.12	0.16	0.22	0.11
Peak Flow (m^3/s)	5.41	5.56	2.28	1.74	19.33	18.73	5.15	5.55	2.19	1.27	3.27	2.51
Total Volume (m^3)	22,271	48,003	10,950	12,284	114,801	139,845	57,994	81,005	44,084	33,943	75,570	50,128
MRE	0.22	0.12	0.19	0.40	-0.23	-0.34						
R^2 Value	0.87	0.84	0.90	0.80	0.88	0.90						
NSE Value	0.76	0.79	0.92	0.59	0.80	0.88						

In this study, verification metrics including MRE, R^2, and NSE were computed using rainfall–runoff data collected by ISCO 6712 automatic samplers from July 2010 to March 2012. Six storm events with rainfall exceeding 15 mm and complete 15 minute monitoring records were selected to ensure meaningful hydrologic response during model verification. Although a formal parameter by parameter sensitivity analysis was not performed, hydrologic sensitivity was assessed through scenario-based simulations that varied the initial storage volume of the proposed retention pond (0%, 25%, 50%, and 100%) and the orifice release sizes (0.5%, 1%, and 2% of total pond storage). These scenario evaluations provide insight into the model's responsiveness to operational conditions and complement the verification analysis.

Runoff to precipitation ratios for the six verification events ranged from 33.03% to 92.17% for observed data and from 43.22% to 84.90% for simulated data. These ranges indicate that the Green-Ampt infiltration model is appropriate for representing infiltration behavior in the study watershed, consistent with the applicability of the Green-Ampt formulation to semi-arid soils. Based on MRE values, four storm events from 2010～2011 were slightly overpredicted, whereas two events from 2012 were underpredicted. Differences between simulated and observed peak flows ranged from -3.1% (storm event 3) to +41.8% (storm event 5). R^2 varied from 0.80 (storm event 4) to 0.90 (storm events 3 and 6), and NSE values ranged from 0.59 (storm event 5) to 0.92 (storm event 3), indicating generally strong model performance.

After completion of the hydrologic verification, the water quality component of the SWMM model was developed using the Event Mean Concentration (EMC) approach. Monitoring data were available in the form of EMCs for TSS, TP, TN, and BOD_5; therefore, these values were used as direct inputs for pollutant buildup and washoff simulations. Because no BMPs capable of pollutant removal were present during the monitoring period, the predicted concentrations represent untreated stormwater and are expected to be similar to the measured EMC values. **Table 2** summarizes the concentration data for the six storm events used in this study.

The largest pollutant loads were observed during the August 13, 2011 storm event, which produced 18.71 tons of TSS, 1.09 tons of BOD_5, 0.34 tons of TN, and 0.083 tons of TP across the two monitoring stations. Across all sampled events, the average BOD_5 concentration was 15.65 mg/L (ranging from 7.5 to 27.1 mg/L), whereas the mean TSS concentration was 105 mg/L (ranging from 31 to 163 mg/L). These results provide the baseline pollutant loads against which the performance of the proposed retention pond BMP scenarios can be evaluated.

Table 2. Comparison of Measured and Simulated Water Pollutants at a Monitoring Site.

Storm Events	1		2		3		4		5		6	
Date (mm/dd/yyyy)	8/24/10		6/22/11		8/13/11		10/10/11		1/26/12		2/19/12	
	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
Concentration (mg/l)												
TSS	31	31	137	133	163	163	105	102	125	116	69	69
TP	0.38	0.37	0.73	0.71	0.73	0.73	0.36	0.35	0.25	0.23	0.14	0.14
TN	2.39	2.34	4.25	4.14	4.08	4.08	2.23	2.16	2.09	1.94	2.94	2.93
BOD_5	21.3	21.0	27.1	26.4	9.5	9.5	9.8	9.5	18.7	17.3	7.5	7.5

4. Best Management Practice (BMP) Evaluation

The recommended structural control facility at this site is designed to manage runoff from a 1 year frequency storm and provide approximately 0.23×10^6 m³ of active storage to support supplemental municipal water supply. The system is configured as a wet retention pond incorporating a controlled release weir and spillway. The total storage capacity is 0.36×10^6 m³ at the spillway elevation and 0.23×10^6 m³ at the controlled release elevation, allowing staged outflow management under varying hydrologic conditions.

It is important to clarify that the storage values of 0.23×10^6 m³ and 0.36×10^6 m³ reported by UCRA (2013) represent long-term, system scale storage capacities for the entire COSA watershed, intended to enhance drought resilience and municipal water supply security. These volumes incorporate multi facility, basin-wide water management objectives and do not reflect the geometric capacity of any single retention structure. In contrast, the 14.324×10^3 m³ used in this study represents the event-based design volume of the proposed retention pond for the 1 year, 12 hour design storm at Subcatchment II(a). Because these values describe fundamentally different spatial and temporal design scales system level versus single facility, long-term versus event-based they are not contradictory but instead complementary within the broader BMP planning framework.

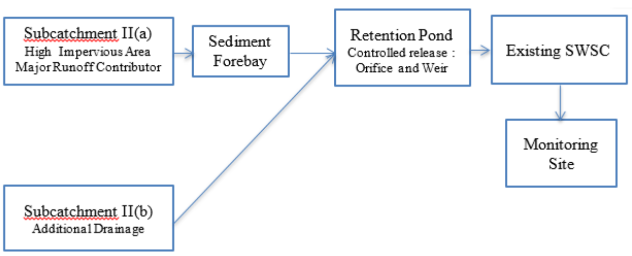
The proposed retention pond is positioned at the outlet of subcatchment II(a), directly upstream of both the existing stormwater structural control facility and the downstream monitoring station. This location was selected because subcatchment II(a), owing to its substantially higher impervious area, contributes the dominant portion of runoff reaching the monitoring point.

Table 3. Simulation Results for Different Initial Storage Volume Conditions.

Initial Storage Volume	Storm Water Quantity		Storm Water Pollutant Loadings			
Condition	**Peak Flow**	**Total Volume**	**TSS**	**TP**	**TN**	**BOD_5**
	m^3/s	**m^3**	**kg**	**kg**	**kg**	**kg**
			Existing Condition (No Retention Pond)			
No Storage Volume	3.92	12099.2	2039.55	10.02	86.45	592.53
			Recommended Condition (Retention Pond, Volume or Load)			
Dry Condition	3.79	7305.9	730.55	4.50	38.86	212.24
25% Full Condition	3.79	8476.5	743.08	4.91	42.34	215.88
50% Full Condition	3.79	9647.1	755.30	5.31	45.81	219.43
75% Full Condition	3.79	10832.4	768.77	5.63	48.58	223.34
Full Condition	3.81	11987.0	785.52	5.74	49.51	228.21
			Recommended Condition (Retention Pond, Percentage)			
Dry Condition	3%	40%	64%	55%	55%	64%
25% Full Condition	3%	30%	64%	51%	51%	64%
50% Full Condition	3%	20%	63%	47%	47%	63%
75% Full Condition	3%	10%	62%	44%	44%	62%
Full Condition	2.75%	0.93%	61.49%	42.73%	42.73%	61.49%

For the 1 year, 12 hour Type II design storm, the calibrated SWMM model produced a peak flow of 3.92 m^3/s and a total runoff volume of 12.099×10^3 m^3. These values informed the design of a 14.324×10^3 m^3 retention pond equipped with a sediment forebay. Operational storage capacities of 0.23×10^6 m^3 at the controlled release elevation and 0.36×10^6 m^3 at the spillway elevation were established. The controlled release system - consisting of an orifice and a weir - was designed to provide hydraulic retention times of up to 11 hours, improving both flow attenuation and pollutant removal efficiency.

A schematic layout depicting the spatial configuration of the retention pond relative to subcatchment II(a), the existing SWSC, and the downstream monitoring station has been added as **Figure 3** to enhance clarity and support interpretation of the system design.



Figuire 3. Layout of Retention Pond Relative to Existing SWSC

Model simulations were conducted under varying operational conditions, including four initial storage states (dry: 0%, 25%, 50%, and full: 100% of storage capacity) and three orifice sizes. According to UCRA (2013), the precipitation input corresponded to the 1 year, 12 hour design storm (42.2 mm total rainfall, 13.34 m^3/s peak flow, and 0.35×10^6 m^3 of runoff).

The BMP evaluation represented the proposed retention pond as a storage unit placed immediately upstream of the existing SWSC. Each simulation scenario paired an initial storage condition (0%, 25%, 50%, or 100%) with a specific orifice size to reflect alternative operational strategies. For each scenario, peak flow, total runoff volume, and pollutant loads (TSS, TP, TN, BOD_5) at the downstream monitoring station were extracted and compared against existing condition results. These metrics served to quantify both hydraulic attenuation and pollutant reduction benefits provided by the retention pond.

The proposed retention pond is expected to reduce peak flows, improve downstream water quality, and increase the availability of stormwater for municipal or irrigation use. This is consistent with previous BMP evaluations and optimization studies demonstrating that wet detention and retention ponds can simultaneously attenuate peak flows and enhance sediment and nutrient removal (Abduljaleel *et al.*, 2023; Qi *et al.*, 2024; Yang *et al.*, 2023). Subcatchment II(a), which generates most of the runoff due to its higher imperviousness relative to subcatchment II(b), supports the justification for locating the SWSC at this outlet (UCRA, 2013). The retention pond design was based on peak flow and runoff volume estimates derived from the 1 year, 12 hour Type II design storm at 15 minute intervals (Hershfield, 1961; Frederick *et al.*, 1977).

Flow regulation is achieved through a combined orifice weir system (Brandes & Barlow, 2012). According to UCRA (2013), pollutant removal performance for TSS, BOD_5, TP, and TN was simulated using removal equations that reflect improved treatment efficiency at hydraulic retention times up to 11 hours. Separate equations were applied to solids related parameters (TSS, BOD_5) and nutrient related parameters (TP, TN), as shown in Eqs. (4~5).

$$R = 0.903+0.0049\times HRT \quad \text{(for TSS/ BOD}_5\text{, for HRT > 1 hour)} \tag{4}$$

$$R = 0.511+0.00935\times HRT \quad \text{(for TP/TN, for HRT > 1 hour)} \tag{5}$$

Where, R = fraction removal and HRT= hydrologic retention time (hour). For the wet and dry ponds, HRT was greater than 1 hour for the simulations, therefore the equations were focused on removal for HRT > 1 hour.

Peak flow, total runoff, pollutant loads, and concentrations were evaluated across all scenarios to assess the effectiveness of the proposed retention pond (**Table 3**). Simulations were conducted for initial storage volumes of 0%, 25%, 50%, 75%, and 100% to determine how available storage influences hydraulic and water quality performance. As expected, the dry pond condition (0%) provided the greatest reductions in peak flow and pollutant loads due to the maximum available storage. Even under full storage conditions, modest reductions were still observed because simultaneous inflow and outflow increased hydraulic retention time and enhanced pollutant treatment. Overall, the scenarios demonstrated (1) reduced peak flows and associated flood risk mitigation, (2) improved water quality, and (3) increased stormwater availability for supplemental water supply.

Table 4 summarizes the combined influence of initial storage volume (0%, 25%, 50%, 75%, and 100%) and orifice size (0.5%, 1%, and 2% of the total pond storage) on peak inflow, total runoff volume, and pollutant loadings at the monitoring station. Across all scenarios, peak inflow consistently decreased relative to existing conditions, indicating that the proposed retention pond provides measurable hydraulic attenuation regardless of its initial storage condition. For the dry and 50% initial storage scenarios, the percentage reduction in peak flow was nearly identical across the three orifice sizes, suggesting that available storage volume exerts a stronger influence on peak flow mitigation than the specific orifice diameter when sufficient freeboard is present.

Under the full storage condition, however, the 0.5% orifice resulted in a greater reduction in peak flow compared to the 1% and 2% orifices. This is attributed to the extended hydraulic retention time associated with the smaller outlet, which slows the discharge rate and delays the timing of downstream peak flow, even when minimal storage volume is initially available. As expected, total runoff volume was not significantly affected by orifice size in any scenario, because the orifice controls outflow rate rather than volumetric capture. Pollutant loadings (TSS, TP, TN, and BOD_5) followed a reduction pattern similar to peak flow, reflecting increased retention time and associated settling and treatment processes within the pond.

Table 4. Simulation Results for Different Orifice Sizes.

Retention Pond with Orifice									
Orifice Size	**0.50%**			**1%**			**2%**		
Storage Volume	**Empty(0%)**	**50%**	**Full(100%)**	**Empty(0%)**	**50%**	**Full(100%)**	**Empty(0%)**	**50%**	**Full(100%)**
Peak Flow	3.3%	3.3%	2.9%	3.3%	3.3%	2.8%	3.3%	3.3%	2.6%
Total Volume	37.6%	20.2%	1.8%	36.7%	18.8%	0.9%	36.3%	18.4%	0.4%
TSS	64.3%	63.4%	62.2%	63.8%	62.7%	61.2%	63.5%	62.3%	60.8%
TP	54.7%	47.8%	43.9%	53.6%	46.2%	42.2%	53.1%	45.4%	41.4%
TN	54.7%	47.8%	43.9%	53.6%	46.2%	42.2%	53.1%	45.4%	41.4%
BOD_5	64.3%	63.4%	62.2%	63.8%	62.7%	61.2%	63.5%	62.3%	60.8%

5. Summary and Conclusions

This study evaluated the impact of a proposed retention pond located downstream of an existing stormwater structural control on both stormwater quantity and quality. The results show that the pond can increase water availability and reduce peak flows as well as pollutant loads such as TSS, TN, TP, and BOD_5.

The SWMM model was verified using six stormwater events, yielding MRE values of -0.23 to 0.40, R^2 values of 0.80 to 0.90, and NSE values of 0.59 to 0.92. The impact of the recommended retention pond was then evaluated under different initial storage volumes and three outlet orifice sizes in terms of peak flow, total runoff volume, and pollutant loads. Depending on the initial storage condition, the pond provided reductions of 2.6~3.3% in peak flow, 0.4~40% in total runoff volume, and 41.4~64.3% in pollutant loads. In particular, when the initial storage was full, the 0.5% orifice size yielded slightly greater peak flow reductions than the larger orifices under the 1 year design storm.

In conclusion, the simulation results indicate that the recommended retention pond located between the main flow path and the existing stormwater structural control can serve multiple purposes, including peak-flow reduction for flood control, increased water availability for water conservation, and improved water quality as part of urban stormwater management.

Despite the effectiveness demonstrated in this study, several limitations should be acknowledged. First, the SWMM calibration and verification were based on six event-based storm observations, which may not fully capture long-term hydrologic variability. Second, the performance of the proposed retention pond was evaluated under assumed initial storage conditions and outlet configurations; actual field operations may differ depending on maintenance frequency, sedimentation, and real time inflow dynamics. Third, pollutant removal efficiency was assessed primarily through hydraulic retention time and not through detailed water quality modeling that includes chemical or biological processes. Lastly, climate variability and future land use changes were not incorporated into the simulations, which may influence long-term BMP performance. These limitations present opportunities for future studies to incorporate continuous simulations, real time operational data, and expanded water quality modeling frameworks.

The numerical findings of this study are consistent with results reported in previous BMP and SWMM based assessments. For mid-range initial storage conditions (25–50%), the modeled peak flow reduction of 18～32% falls within the range of 15～35% documented in prior retention pond evaluations. This mid-range comparison is presented to align with literature values; however, across all simulated scenarios - including dry and full storage conditions - the full range of peak flow reductions observed in this study spans from 2.75% to 74%. Similarly, the simulated reductions in runoff volume and the extended hydraulic retention time (up to 11 hours) are comparable to values documented in earlier studies of storage based BMPs in semi-arid watersheds. These consistencies reinforce the validity of the modeling approach and demonstrate that the proposed retention pond performs within or above the efficiency range commonly reported in the literature.

The modeling framework developed in this study also provides a basis for future research and real time implementation. Because the SWMM configuration can incorporate continuous rainfall input and real time sensor data, the proposed retention pond design can be adapted for operational decision support during storm events. Future studies may integrate continuous simulations, climate change projections, and automated control strategies (e.g., real time gate or orifice adjustments) to improve hydraulic performance under variable conditions. Furthermore, linking the model with IoT based monitoring networks or data-driven forecasting tools could support real time pond operation, optimize storage availability, and enhance pollutant removal efficiency. These potential extensions demonstrate that the proposed approach is suitable not only for planning level evaluation but also for real time stormwater management applications.

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Data Availability Statement

The data that supports the findings of this study are available from the UCRA. Restrictions apply to the availability of these data, which were used under license for this study.

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