Optimization of pollution control performance of wet detention ponds in tropical urban catchments using particle swarm optimization

Salisu Dan'azumi, Supiah Shamsudin and Azmi Aris

ABSTRACT

Wet detention ponds are the best management systems for the control of urban stormwater. The objective of this study is to develop optimum pollution control performance of wet detention ponds using an analytical probabilistic model (APM) and particle swarm optimization (PSO). An urban catchment, in a tropical region, was selected as a case study and APM parameters were developed using long-term rainfall data. Firstly, the active storage was kept constant while the permanent pool was varied and PSO simulations conducted. Secondly, PSO simulations were conducted, keeping the permanent pool constant and varying the active storage. The pollution control increased with increasing detention time, reached a peak value and thereafter declined. However, the pollution control was more sensitive to permanent pool than active storage as higher pollution control is attained at a shorter time using the former. The PSO captures the optimum detention time and the corresponding peak pollution control performance by five iterations and the computational time required for the PSO is much shorter than the APM which has to be exhaustively enumerated. The optimum detention time in tropical climates is found to be shorter than temperate regions and recommendations given in existing literature cannot be applied to tropical regions.

Key words | active storage, detention pond, particle swarm optimization, permanent pool, pollution control, wet pond

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INTRODUCTION

Urban runoff resulting from stormwater is the second major flow of concern to drainage engineers, and the second largest source of impairment to lakes and estuaries, eclipsed only by runoff from agricultural sources as the most important source of water pollution (NRDC 1999). Urban stormwater runoff gathers a variety of pollutants as it passes over roads, roof-tops, and parking lots in domestic, commercial and industrial areas causing deterioration in streamwater quality. Safe and efficient removal of stormwater is particularly important in maintaining public health and safety and to protect the receiving water environment. Stormwater consists of that portion of rainfall that runs off from urban surfaces, and hence its properties, in terms of quantity and quality, are inherently linked to the nature of the rainfall, as well as the catchment characteristics (Butler & Davies 2004). As stormwater runoff passes through a properly designed pond, it is detained and suspended solids and other pollutants carried by the stormwater settle thereby improving the quality of the outflow, and this also helps prevent flooding and pollution of the downstream waters (Toet *et al.* 1990; Färm 2002). In this context, pollution control performance of a detention pond is defined as its ability to capture and treat pollutants, in terms of total suspended solids (TSS) carried by stormwater. The TSS is used as a surrogate measure for other water quality parameters as the removal of other pollutants was found to be positively correlated to the removal of TSS and hence it is used as a primary performance measure

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(Adams & Papa 2000; Chen & Adams 2006). Although there is a great deal of literature on the design optimization of detention ponds, most of the studies were carried out in temperate regions (Papa *et al.* 1999; Adams & Papa 2000). Therefore, similar studies need to be extended to cover tropical regions due to the marked difference in meteorological characteristics which affects the rainfall pattern, thus playing an important role in the estimation of the optimum detention time that gives highest pollution control performances at the detention facilities. Thus, the range of optimum detention time that yields the highest pollution control in wet ponds, designed for temperate regions, may not apply to tropical regions, due to the frequent rainfall experienced in the regions.

Many articles on optimization in detention pond design exist. Rao (2009) defined optimization as the process of finding the conditions that give the maximum or minimum value of a function. Behera *et al.* (1999) presented a methodology for the determination of the optimum pond design parameters of storage volume, release rate, and depth in a multiple parallel catchment system. The method considers designing smaller ponds at different locations within the catchment such that the overall discharge at the catchments' outfall does not violate the runoff quantity and quality constraints. Yeh & Labadie (1997) applied dynamic programming and genetic algorithms to the integrated watershed level planning of a stormwater detention system. Reservoir and channel routing algorithms were embedded into the dynamic programming and the least cost combination of input corresponding to the desired downstream peak flow attenuation were simulated. Papa *et al.* (1999) studied the trade-off between improved pollutant removal efficiency in a detention facility, over a longer detention time, and decreased volume of runoff captured and treated to develop a methodology for the design of stormwater quality control ponds. Xiao *et al.* (2004) coupled the heuristic optimization technique (Scatter search) with the Agricultural Nonpoint Source Pollution model to develop an optimization framework that can be used to find the least-cost optimal placement and design of stormwater basins at a watershed scale. Travis & Mays (2008) applied discrete dynamic programming for the optimization of sizing and location of a network of flood control retention basins within a watershed. The method determines the ideal pond location while satisfying constraints such as infiltration, basin geometry, stormwater volume, water quality, construction and land costs. This method was found to produce significant cost savings over traditional methods.

Many different techniques are used in operations research discipline and swarm intelligence techniques have been found to give promising results in the optimization of various systems (Rao 2009). Particle swarm optimization (PSO) is a stochastic optimization algorithm based on social simulation models. It is a swarm intelligence algorithm developed by Kennedy & Eberhart (1995), simulating the choreographed motion of schools of fish, flocks of birds and herds of animals while attempting to find a rich source of food and avoid predators. The algorithm employs a population of search points that moves stochastically in a multi-dimensional search space. If a particle finds a best position, that position is retained in its memory. Its experience is communicated to the whole population, biasing its movement towards the most promising regions detected so far. The communication scheme is determined by a fixed or adaptive social network that plays a crucial role on the convergence properties of the algorithm (Parsopoulos & Vrahatis 2010). Since its introduction in 1995, PSO applications have grown exponentially, researchers have developed new applications and many PSO variants appear in the literature (Poli *et al.* 2007; Poli 2008). PSO researchers have produced results that are very encouraging (Dorigo 2007; Fallah-Mehdipour *et al.* 2011; Sedki & Ouazar 2011).

Despite the amount of literature on PSO, applications in the water sector are very few and are mostly on reservoir operational management. Kumar & Reddy (2007) derived reservoir operation policies using elitist mutated PSO algorithm where the worst particle solutions are replaced by the best solution, after performing mutation on the best particle. The approach was tested on a multi-reservoir system (hypothetical and real) and promising results were obtained. Similarly, multi-objective PSO was applied to the operation of multi-reservoir system in order to maximize reliability, minimize vulnerability, maximize resiliency of the reservoir system, while satisfying the downstream demand. The PSO algorithm was compared with a traditional method (weighting method) and results show that the multi-objective PSO algorithm is successful in finding near-optimal, Pareto-front solutions (Fallah-Mehdipour *et al.* 2009). Multi-objective PSO was implemented in the evaluation of two water resources problems: a multipurpose reservoir operation problem, with up to four objectives; and a problem of selective withdrawal from a thermally stratified reservoir with three objectives. The multi-objective PSO solver was found to easily generate solutions that are very close to Pareto sets compared with the non-linear programming method. The multi-objective PSO was further tested with two standard test functions reported in the literature and performed very well with respect to both the two test functions (Baltar & Fontane 2008).

Shourian *et al.* (2008) coupled the river basin network flow model MODSIM, with PSO to develop a methodology for optimized design and operation in the Sirvan River basin of Iran. In the PSO-MODSIM algorithm, the design variables (i.e. size of planned dams and water transfer systems), and the operational variables (i.e. relative priorities for meeting reservoir target storages), were varied and evolved using PSO algorithm. The MODSIM simulates the system performance and evaluates the fitness of each set of those design and operational variables. The PSO maximized the total net benefit consisting of benefits due to supplying water to different types of water uses, construction costs of dams, water transfer and pumping systems. Despite its numerous applications; PSO literature applied to detention pond's performance optimization do not seem to exist. This study used analytical probabilistic models (APM) to develop PSO algorithm applicable to optimization in wet detention ponds design.

APM are mathematical expressions of a system's output performance derived from the probability distribution of the system's input variables. In APM of urban storm water management, the input variable is rainfall and the output is the catchment's response to the rainfall input. The probability distributions of the input variables (storm depth, duration, inter-event time) are transformed into the probability distribution of output performances using derived probability distribution theory. The APM of the systems output can be used to derive various systems performance such as probability of spill per rainfall event, runoff capture efficiency, fraction of pollution control, average annual number/volume of spills, etc. Since the APM are computationally efficient models their implementation into an optimization framework is straightforward and easy (Adams & Papa 2000). Figure 1 shows the steps involved in the development of the APM. The APM models for urban storm water management were found to yield good results comparable to design storm and continuous simulation modeling (Guo & Adams 1999, 2009). In this work, APM for pollution control performance were used to develop PSO algorithms for the optimization of detention time in wet ponds. The meteorological rainfall data for a tropical urban catchment, in Peninsular Malaysia, was used as a case study. The APM developed in Papa *et al.* (1999), Adams & Papa (2000), Chen & Adams (2005, 2006) were used and applied under tropical conditions, and the approach was incorporated into the PSO-based optimization framework. The combination of APM with PSO is unique and novel and is one of the major contributions of this study.

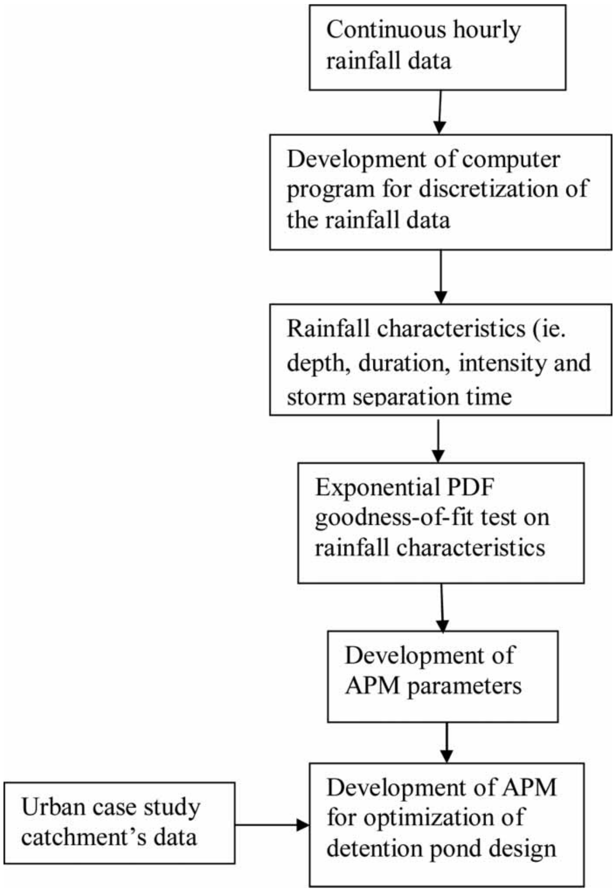


Figure 1 | Flowchart of APM.

METHODS

Rainfall data collection and analysis

Long-term hourly rainfall data were collected from a rain-gauge station (Station ID 3116006) located about 3 km from the case study catchment in Kuala Lumpur. In various studies a number of different criteria for choosing the minimum storm separation time were used (Dunkerley 2008). In this study we discretized data into individual events using a storm separation time of 6 hr as in similar studies (Guo & Urbonas 2002; Guo 2002). Rainfall characteristics of average rainfall depth (v), average rainfall duration (t), average rainfall intensity (i) and average storm separation time (b) were derived from the long term rainfall statistics. In order to apply the APM; the rainfall characteristics must fit an exponential distribution (Adams & Papa 2000) and therefore, a goodness-of-fit test was conducted and the exponential distribution was found to fit the data. The APM parameters include: inverse of average duration of rainfall event λ (hr^{-1}), inverse of average depth of rainfall event ζ (mm^{-1}), inverse of average inter-event time ψ (hr^{-1}) and average annual number of rainfall events (θ). The parameters were derived from the rainfall characteristics. These parameters, along with catchment characteristics, were used to determine the pollution control performances. Table 1 gives values of the rainfall characteristics, alongside the APM parameters, for the case study catchment in Kuala Lumpur, Malaysia.

Determination of catchment characteristics of the case study area

The case study catchment selected is Taman Sri Serdang, an urban area in a typical tropical climate, located in Kuala-Lumpur , Malaysia. The catchment consists of 283 units of single-storey houses. The average slope of the catchment varies between 0.23 and 0.31%. The total drainage length, including the minor drains, was 3,836 m and the existing imperviousness was calculated as 83% (Al-Mamun 2005).

The runoff coefficients (φ) of the catchment was obtained from the imperviousness ratio using the relationship proposed by Guo & Urbonas (2002). The pervious area depression storage and impervious area depression storage of the catchment were estimated using the equation proposed by Butler & Davies (2004) and the total catchment's depression storage (S_d) is the area weighted depression storage of the pervious and impervious areas. Table 2 gives the physiographic characteristics of the catchment.

Determination of pollution control performance

Equations (1)–(7) describe the steps involved in the determination of pollution control performance of wet ponds. In its condensed form, the pollution control performance is given by Equation (1) (Adams & Papa 2000):

$$C_P = E_q[1 - e^{\zeta S_p/\varphi}] + E_d \frac{(P_u - P'_u)}{R} \qquad (1)$$

Table 1 | APM parameters for the nearest rain gauge station (Station ID 3116006)

		Analytical probabilistic model parameters								
Station location	**Station ID**	***t* (hr)**	**λ (hr^{-1})**	***v* (mm)**	**ζ (mm^{-1})**	***i* (mm/hr)**	**β (hr/mm)**	***b* (hr)**	**ψ (hr^{-1})**	**θ (#/yr)**
Kuala-Lumpur	3116006	4.09	0.25	14.29	0.07	3.88	0.26	40.13	0.03	198

Table 2 | Catchment characteristics of Taman Sri Serdang

Catchment	Slope (%)	Imperviousness ratio (%)	Impervious area depression storage (mm)	Pervious area depression storage (mm)	Total depression storage S_d (mm)	Runoff coefficient (φ)
Tmn Sri Serdang	0.27	82.7	1.35	5.39	2.05	0.63

where the analytical expressions for the various terms used in the Equation (1) are presented in Equations (2)–(7) below. In Equation (1); E_q is the overall fractional TSS removal efficiency in the permanent pool under quiescent settling, E_d is the overrall fractional TSS removal efficiency in active storage under dynamic settling, S_p is the permanent pool volume, P_u and P'_u are the average annual volume of runoff spilled from the permanent and active storage, respectively, R is the average annual volume of runoff entering the pond, and φ is the runoff coefficient of the catchment. The quiescent and dynamic settling efficiencies (E_q and E_d) are given by Equations (2) and (3), respectively (Adams & Papa 2000):

$$E_q = \sum_i F_i \left[\frac{V_{si}}{\psi h_p} \left(1 - e^{-\psi h_p / V_{si}} \right) \right] \tag{2}$$

$$E_d = \sum_i F_i . \left\{ 1 - \left(1 + \frac{V_{si}}{n h_A} \frac{S_A}{z\Omega} \right)^{-n} \right\} \tag{3}$$

where F_i is the fraction of total mass contained in the ith size fraction of the stormwater particles, V_{si} is the average settling velocity of typical stormwater particles (m/h), n is the pond settling performance factor, where a value of $n = 3$ (i.e. good performance is assigned) (Adams & Papa 2000) and h_A is the depth of active storage (m), h_p is the depth of permanent pool (m), S_A (mm) and $\Omega\,(\text{mm/hr})$ are pond parameters of active storage and outlet capacity, respectively.

The average annual volume of runoff entering the pond (R) is given by Equation (4):

$$R = \theta \frac{\varphi}{\varsigma} e^{-\varsigma S_d} \tag{4}$$

where θ is the average annual number of rainfall events, and φ and S_d are runoff coefficient and depression storage of the catchment, respectively.

P_u and P'_u are given by Equations (5) and (6), respectively (Adams & Papa 2000):

$$P_u = \theta \frac{\varphi}{\varsigma} e^{-(\varsigma/\varphi)} S_p e^{\varsigma s_A} \tag{5}$$

$$P'_u = \theta \frac{\varphi}{\varsigma} G_p(0) \tag{6}$$

where S_p is the permanent pool volume and $G_p(0)$ is the probability per rainfall event of any spill occurring from the detention pond. The probability per rainfall event of any spill occurring is given by Equation (7) (Chen & Adams 2005):

$$G_P(0) = \left[\frac{\lambda/\Omega}{\lambda/\Omega + \varsigma/\varphi} \right] \left[\frac{(\psi/\Omega) + (\zeta/\varphi) e^{-(\psi/\Omega + \varsigma/\varphi) S_A}}{\psi/\Omega + \varsigma/\varphi} \right] e^{-\varsigma S_d} \tag{7}$$

The detention time can be calculated by considering the two extremes, under which the pond operates (Papa *et al.* 1999). Firstly, when the rate of pond's inflow is less than or equal to the rate of pond's outflow, the pond is empty and detention time is zero. Secondly, when the rate of inflow is greater than the rate of outflow and the pond is full, the detention time is equal to S_A/Ω, where S_A is the active storage capacity of the pond and Ω is the pond outflow rate. The average steady state detention time can be obtained as the average of these two conditions given by Equation (8) (Papa *et al.* 1999):

$$t_d = \frac{1}{2} \frac{S_A}{\Omega} = \frac{1}{2} t_{dd} \tag{8}$$

where t_d is the detention time and t_{dd} is the drawdown time.

Posing the optimization problem and selecting the algorithm to solve it

The objective function for the single-objective optimization is a maximization of Equation (1), herein formulated as follows:

$$\begin{aligned} &\text{Maximize } C_p = E_q (1 - e^{-\varsigma S_p/\varphi}) + E_d \, {}^{(P_u - P'_u)}_{R} \\ &\text{Subject to constraint } S_A/\Omega > 0 \end{aligned} \tag{9}$$

where S_A, S_p and Ω are decision variables that must be combined in a certain fixed ratio in order to yield the peak pollution control. Note that the variables have already appeared in Equations (2)–(7) and these equations are simply the analytical expressions of the various terms used in Equation (9). The detention time relates the decision variables S_A and Ω as already shown in Equation (8).

PSO algorithm was selected for the optimization of detention time in wet detention ponds which corresponds to the peak pollution control (C_p). In PSO algorithm, each particle represents the pollution control performance. Figure 2 shows the general flowchart of PSO.

The steps in the above PSO flow can be mathematically represented as follows:

1. Initialization of swarm position and velocity: The PSO simulation was started with swarm distributed in the design space. The initial swarm position and velocity are given by Equations (10) and (11), respectively.

$$x_0^i = x_{\min} + \text{rand}(x_{\max} - x_{\min}) \tag{10}$$

$$v_0^i = \frac{x_{\min} + \text{rand}(x_{\max} - x_{\min})}{\Delta t} = \frac{\text{position}}{\text{time}} \tag{11}$$

where x_0^i and v_0^i are the initial swarm position and initial velocity. ($x_{\max}$–$x_{\min}$) is the range of the design space for the decision variable (x), rand is a random number uniformly distributed in [0, 1] and Δt is the time increment.

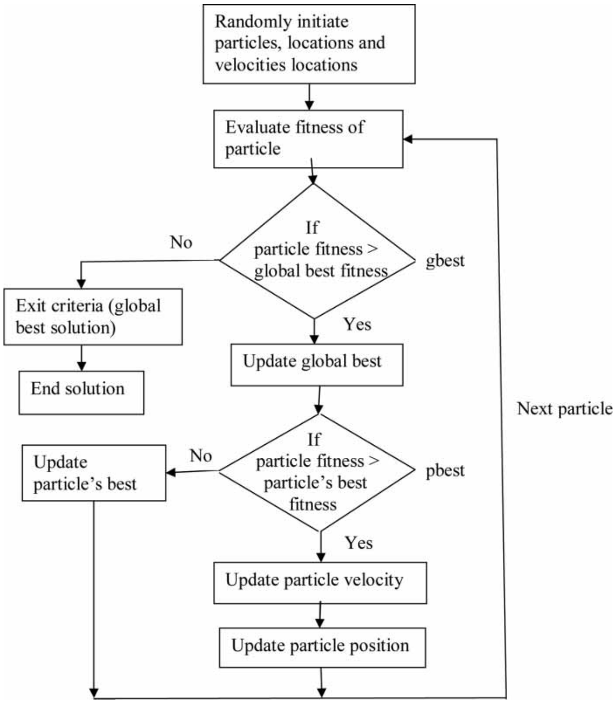


Figure 2 | Flowchart of PSO.

2. Evaluation of position of swarm and quality: A velocity vector ($v_{k+1}^i \Delta t$) was added to the swarm and the new swarm position (x_{k+1}^i) evaluated, Equation (12):

$$x_{k+1}^i = x_k^i + v_{k+1}^i \Delta t \tag{12}$$

3. Updating the global best: The global best was updated with respect to the objective function.
4. Updating the personal best: The personal best was updated with respect to the objective function.
5. Velocity update: The velocity of swarm is updated with reference to its best previously visited position (x_i^*) as well as with the position of the global best (g^*). Some random component (rand), inertia (w) and correction factors (c_1 and c_2) were added to the swarm at this point, Equation (13):

$$v_{k+1}^i = w v_k^i + c_1 \, \text{rand} \frac{(x_i^* - x_k^i)}{\Delta t} + c_2 \, \text{rand} \frac{(g^* - x_k^i)}{\Delta t} \tag{13}$$

The PSO simulation was conducted and PSO parameters of inertia (w), correction factors (c) and number of swarm (N) were calibrated. The inertia was varied while keeping the correction factors and number of swarm constant. The correction factor was varied while keeping the inertia and number of swarm constant. Similarly, the number of swarm was varied while keeping the inertia and correction factor constant. The particles were observed to be stable at inertia (w) range of 0.2–0.7, correction factors (c) of 1.0–1.6, and number of swarms (N) of 10–30. A median value of 0.5 for inertia, 1.5 for correction factor and 30 swarms were therefore selected. This is with a view to increasing the exploitation and exploration capability of the swarms (Rao 2009; Parsopoulos & Vrahatis 2010). In this work, $c_1 = c_2 = c$.

RESULTS AND DISCUSSION

Tables 3 and 4 give quantitative results of the variables used as intermediate steps in the calculation of the pollution control performance of wet detention ponds. Wet detention ponds have two regions, the permanent pool and the active storage zone (Figure 3). The runoff quantity control occurs at the active storage and pollutants removal occurs mainly

Table 3 | Quantitative values of intermediate variables used in the calculation of pollution control performance. Case 1: S_P changing, S_A constant

t_d	E_d	E_q	R	P_u				P'_u				$G_p(0)$			
	$S_A = 2$ to 8 mm			$S_p =$ 2 mm	$S_p =$ 4 mm	$S_p =$ 6 mm	$S_p =$ 8 mm	$S_p =$ 2 mm	$S_p =$ 4 mm	$S_p =$ 6 mm	$S_p =$ 8 mm	$S_p =$ 2 mm	$S_p =$ 4 mm	$S_p =$ 6 mm	$S_p =$ 8 mm
0.5	0.20	0.97	1,543.8	1,236.2	989.8	792.6	634.7	352.3	282.1	225.9	180.9	0.20	0.16	0.13	0.10
1	0.35	0.97	1,543.8	1,236.2	989.8	792.6	634.7	520.6	416.9	333.8	267.3	0.29	0.23	0.19	0.15
2	0.55	0.97	1,543.8	1,236.2	989.8	792.6	634.7	685.0	548.5	439.2	351.7	0.38	0.31	0.25	0.20
4	0.76	0.97	1,543.8	1,236.2	989.8	792.6	634.7	816.2	653.6	523.4	419.1	0.46	0.37	0.29	0.24
6	0.86	0.97	1,543.8	1,236.2	989.8	792.6	634.7	874.6	700.3	560.8	449.0	0.49	0.39	0.31	0.25
8	0.91	0.97	1,543.8	1,236.2	989.8	792.6	634.7	909.0	727.9	582.8	466.7	0.51	0.41	0.33	0.26
10	0.94	0.97	1,543.8	1,236.2	989.8	792.6	634.7	932.6	746.8	598.0	478.8	0.52	0.42	0.34	0.27
12	0.96	0.97	1,543.8	1,236.2	989.8	792.6	634.7	950.3	761.0	609.3	487.9	0.53	0.43	0.34	0.27
14	0.97	0.97	1,543.8	1,236.2	989.8	792.6	634.7	964.5	772.3	618.4	495.2	0.54	0.43	0.35	0.28
16	0.98	0.97	1,543.8	1,236.2	989.8	792.6	634.7	976.3	781.8	626.0	501.2	0.55	0.44	0.35	0.28
18	0.98	0.97	1,543.8	1,236.2	989.8	792.6	634.7	986.5	789.9	632.5	506.5	0.55	0.44	0.35	0.28
20	0.98	0.97	1,543.8	1,236.2	989.8	792.6	634.7	995.4	797.0	638.2	511.1	0.56	0.45	0.36	0.29

Table 4 | Quantitative values of intermediate variables used in the calculation of pollution control performance. Case 2: S_A changing, S_p constant

t_d	E_d	E_q	R	P_u	P'_u				$G_p(0)$			
	$S_A = 2$ to 8 mm				$S_A = 2$ mm	$S_A = 4$ mm	$S_A = 6$ mm	$S_A = 8$ mm	$S_A = 2$ mm	$S_A = 4$ mm	$S_A = 6$ mm	$S_A = 8$ mm
0.5	0.20	0.97	1,543.8	1,236.2	352.3	171.8	99.0	62.0	0.20	0.10	0.06	0.03
1	0.35	0.97	1,543.8	1,236.2	520.6	283.5	172.3	111.5	0.29	0.16	0.10	0.06
2	0.55	0.97	1,543.8	1,236.2	685.0	420.9	274.4	186.0	0.38	0.24	0.15	0.10
4	0.76	0.97	1,543.8	1,236.2	816.2	559.0	393.2	282.3	0.46	0.31	0.22	0.16
6	0.86	0.97	1,543.8	1,236.2	874.6	631.2	463.0	344.5	0.49	0.35	0.26	0.19
8	0.91	0.97	1,543.8	1,236.2	909.0	677.5	511.1	389.9	0.51	0.38	0.29	0.22
10	0.94	0.97	1,543.8	1,236.2	932.6	711.1	547.6	425.8	0.52	0.40	0.31	0.24
12	0.96	0.97	1,543.8	1,236.2	950.3	737.3	577.0	455.7	0.53	0.41	0.32	0.26
14	0.97	0.97	1,543.8	1,236.2	964.5	758.8	601.9	481.4	0.54	0.43	0.34	0.27
16	0.98	0.97	1,543.8	1,236.2	976.3	777.1	623.4	504.2	0.55	0.44	0.35	0.28

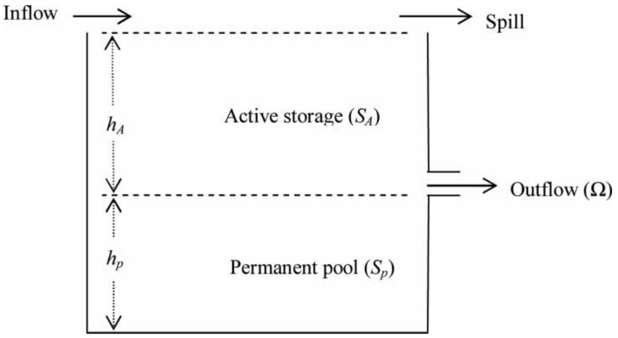


Figure 3 | Schematic diagram of a wet detention pond.

at the permanent pool. Though over a longer inter-event dry period, the permanent pool may also act in controlling the runoff quantity. However, longer inter-event dry period is not common in tropical climates. Pollutant removal occurs in the active and permanent pools due to dynamic settling and quiescent settling, respectively. TSS removal efficiency has been selected as representative of all pollutants as many pollutants are adsorbed to the TSS, resulting in a strong positive correlation between the TSS and other pollutants (Rossi *et al.* 2006; Opher & Friedler 2010). In this work, TSS with median size diameter ($60\ \mu m < x \leq 0.13$ mm) were selected and their average settling velocity of 0.4572 m hr^{-1} was used (Athayde 1986; Adams & Papa 2000). Brodie & Dunn (2009) also classified particles of median size to be in the range of $63\ \mu m < x \leq 500\ \mu m$ which also falls within our classification. The pollution control performance of wet detention ponds was investigated for two cases.

In order to investigate the effect of variations in active and permanent pools on pollution control performance, a sensitivity analysis was carried out. It is a technique used to determine how different values of an independent variable will impact on a particular dependent variable under a given set of assumptions (Investopedia 2012). Sensitivity is also defined as the study of how uncertainties in model output can be apportioned to different sources of uncertainties in model input (Saltelli *et al.* 2008).

In the first case, the sensitivity of pollution control performance to permanent pool volume was investigated by exhaustively enumerating all the possible values from the APM. The active storage was kept constant while the permanent pool was varied and the pollution control observed. It was noted that, for each combination of active and permanent pool volume, the pollution control performance curves begin at a finite value, when the detention time was very low, and increased with increasing detention time reaching their peak values at 4 hr of detention and then declined as the detention time becomes longer (Figure 4).

Figure 5 shows the result of fitness of the PSO parameters when the active storage was kept constant and the permanent pool was varied. It was observed that, in each case, a constant fitness value was attained at the 5th iteration and beyond. Thus, the fitness values from the PSO simulation were 39.5, 51.0, 60.2 and 67.6%, which are in good agreement with the peak pollution control given by the APM values in Figure 4. Referring to Figure 4, the optimum detention times corresponding to the peak pollution control was 4 hr in each case. If the optimum detention time is known; the detention pond's outlet can be designed appropriately as the ratio of pond's storage capacity to the detention time.

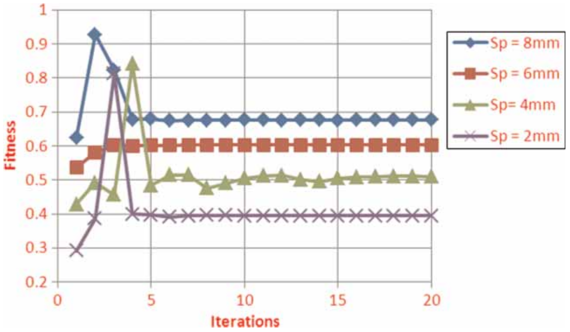


Figure 5 | PSO simulation result of pollution control at varying volumes of permanent pool (S_p) ($h_A = 0.5$ m, $h_p = 1$ m and $S_A = 2$ mm).

In the second case, the sensitivity of pollution control performance to active storage was investigated using the same procedure as in the first case. But in this case, the permanent pool was kept constant while varying the active storage volume and Figure 6 shows the result. It should be noted that, at a very low detention, unlike the previous case, the pollution control performance curves started from a common point and increased to reach their maximum value after which they declined. Comparing Figure 6 with Figure 4 also shows the pollution control is more sensitive to permanent pool than active storage. In Figure 4, highest pollution control is attained in relatively shorter

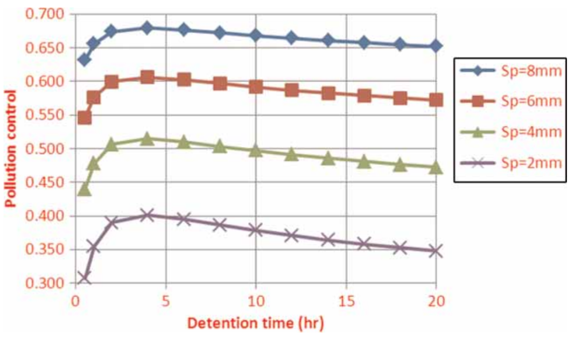


Figure 4 | Sensitivity of pollution control performance of wet ponds: S_A constant, S_p changing ($S_A = 2$ mm, $h_A = 0.5$ m, $h_p = 1$ m).

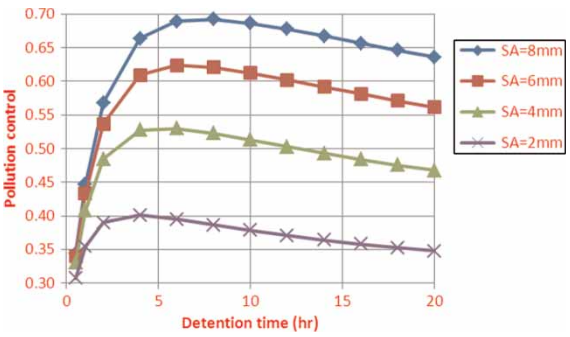


Figure 6 | Sensitivity of pollution control performance of wet ponds: (S_A changing, S_p constant $S_p = 2$ mm, $h_A = 0.5$ m, $h_p = 1$ m).

detention time (4 hr) as compared with Figure 6 (4–8 hr) indicating the effectiveness of increasing the permanent pool.

The PSO simulation was conducted and Figure 7 shows the fitness result when the permanent pool was kept constant while varying the active storage. It was observed that, in each case, a constant fitness value was attained at the 5th iteration and beyond. Thus, the fitness values from the PSO simulation were 40.1, 53.0, 62.3 and 69.2% which are in consonance with the peak pollution control given by the APM in Figure 6. Referring to Figure 6, the optimum detention corresponding to the peak pollution control of 40.1, 53.0, 62.3 and 69.2% were 4, 6, 6 and 8 hr, respectively. Therefore, the detention pond's outlet can be designed by taking the ratio of the pond's volume to the detention time.

Sensitivity analysis of APM parameters to pollution control performance

Figure 8 shows the effect of APM parameters on the optimum detention time and on the corresponding peak pollution control performance of the wet detention ponds. Firstly, the APM parameters ζ, ψ and θ were kept constant while varying λ (Figure 8(a)). Secondly, ζ was varied and the remaining parameters λ, ψ and θ were kept constant (Figure 8(b)). Thirdly, the parameters λ, ζ and θ were kept constant while varying ψ (Figure 8(c)). Finally λ, ζ and ψ were maintained constant and θ was varied (Figure 8(d)).

In the first case, it was observed that the pollution control performance increased with a decrease in λ parameter but the optimum detention time corresponding to peak pollution control remains constant (Figure 8(a)). In the second case, both the optimum detention and the corresponding peak pollution control are affected by the ζ parameter. The optimum detention time and the corresponding peak pollution control performance increased with an increase in ζ parameter (Figure 8(b)). In the third case, it was observed that the pollution control performance increased with a decrease in ψ parameter, but the optimum detention time corresponding to the peak pollution control decrease with an increase in the ψ parameter (Figure 8(c)). Lastly, both the optimum detention time and the corresponding peak pollution control performance were found to be insensitive to the θ parameter (Figure 8(d)).

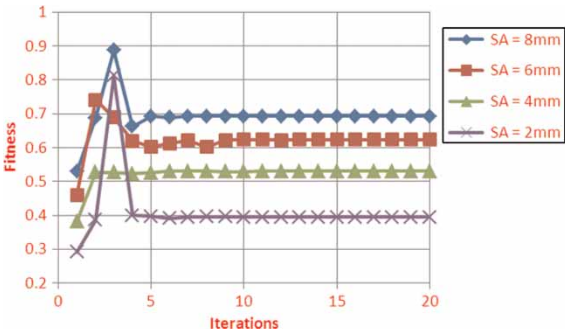
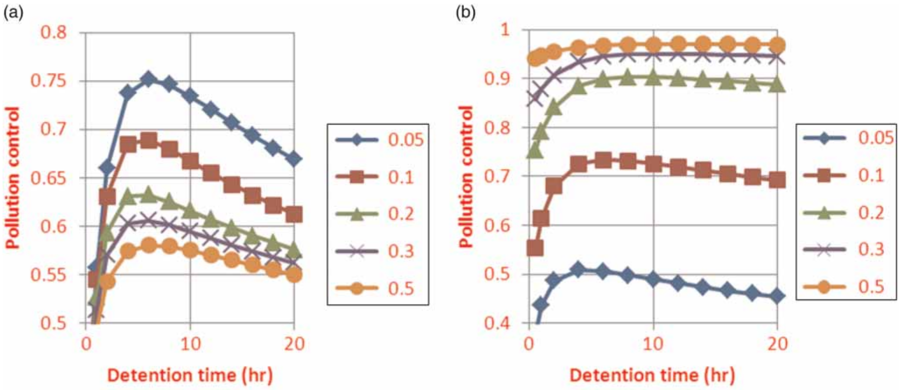


Figure 7 | PSO simulation of pollution control at varying volumes of active storage (S_A) ($h_A = 0.5$ m, $h_p = 1$ m and $S_p = 2$ mm).

Finally, results from this work indicate that, given a combination of active and permanent pool in wet detention ponds, the peak pollution control performance occurs at a certain detention time which is highly dependent on the meteorology of the catchment. Rainfall characteristics affect the APM parameters of the catchment, which in turn affect the optimum detention time. Thus, the optimum detention time in temperate regions, which is of the order of tenth of hours, could not apply to tropical regions. Ponds designed in the tropical regions are prone to a greater risk of overflow compared with those in non-tropical regions. It was also noted that larger ponds give higher pollution control performance compared with smaller ponds given the same detention time. Other factors that affect the optimum detention time include the size of the suspended sediments carried by the stormwater, as well as the pond settling performance factor, all of which influence the settling efficiency of the stormwater particles in the pond. It is important during hydrologic design of wet detention ponds to target the detention time that gives the highest pollution control in order to maximize the removal of TSS from the urban stormwater. Hydraulic considerations also need to be to be given due consideration during design of the facility (Buren *et al.* 1996; Persson 2000).

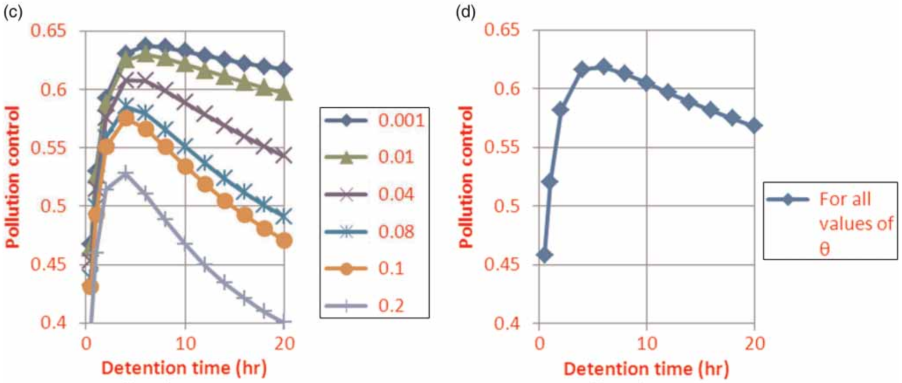
CONCLUSIONS

In this paper, a PSO algorithm for the optimization of detention time in wet detention ponds that gives highest pollution control performance for tropical urban catchments has been developed. The pollution control performance was investigated by varying the permanent and active storage volumes.



Effect of λ parameter

Effect of ζ parameter



Effect of ψ parameter

Effect of θ parameter

Figure 8 | Sensitivity of pollution control performance to APM parameters: (a) inverse of average duration of rainfall event λ (hr^{-1}), (b) inverse of average depth of rainfall event ζ (mm^{-1}), (c) inverse of average inter-event time ψ (hr^{-1}), and (d) average annual number of rainfall events (θ).

In the first case, the pollution control curves begin at a finite value and increased with increasing detention time reaching their peak value and then declined. In the second case, the pollution control performance started from a common point and increased to reach maximum values after which the performance declined. In both cases, results from the PSO and APM were compared and the PSO gave peak pollution control performance in a relatively shorter time period compared with the APM. The PSO was able to capture the peak pollution control performance in just a few seconds compared with the APM which needs to be exhaustively enumerated in order to obtain the peak value. It was also shown that the pollution control is more sensitive to increases in permanent pool than active storage. Highest pollution control is attained in relatively shorter detention time when the permanent pool is increased relative to the active storage. Result also shows that rainfall characteristics of the area play an important role in the determination of the optimum detention time. To design detention facilities for optimum benefits, points of highest pollution control should be targeted in the design, as well as the other conditions that may also need to be met.

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