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Development of Simulation-Optimization Model for Stormwater Treatment Measure Optimization (Case Study: Gold Coast City, Australia)

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ABSTRACT: Urbanization and urban development builds large amounts of impervious areas, stopping the infiltrating of rainfall into soil process and consequently, requiring of the construction of large stormwater treatment measures. A new tendency in storm water management endorses 'source control' whereby small distributed water sensitive urban design systems are built throughout the subdivision to alleviate the effects of land use changes, and protect downstream water quality. Source control practices include use of water sensitive urban design practices like rainwater Tanks, vegetated swales, bio-retention systems, infiltration basins, and constructed wetlands in order to disconnect impervious areas from each other. These elements have different roles and costs. This paper presents a rule based method, to reduce the costs of urban stormwater management. For this purpose, two simulation and optimization model are linked together in the MatLab integrated development environment. Linking the simulation model (MUSIC) and the optimization model (Genetic Algorithm), allowed this simulation and optimization model (MUSIC-GA) to minimize the costs of various treatment devices. Results of usage of MUSIC-GA model on optimizing of urban stormwater treatment systems in about 1.7 hectares residential areas in Gold Coast City, Australia showed that optimized post development is at least 45 percent effective means for removal of pollutants from urban stormwater runoff. Also, small coefficient of variation (0.005) of the results of different runs indicated that there is a proper convergence of MUSIC-GA results toward the global optimal solution.

Keywords: Urban stormwater, Water sensitive urban design, MUSIC, Constructed wetland, Genetic algorithm.

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INTRODUCTION

Urbanization is a common process in most parts of the world which replaces natural vegetation such as forest and grassland with impervious surfaces including roads, driveways, parking areas, and building roofs (Hudson, 1994).

A variety of pollutants which are produced on these surfaces are removed by wash-off with the stormwater runoff and transported by the stormwater runoff loading to receiving water bodies (Goonetilleke and Thomas, 2005).

Due to the severity of the problem of polluted stormwater runoff, mitigation actions on stormwater pollutants are became to an essential concerns in all over the world. Traditionally, storm water management practices considered runoff as a waste to be removed quickly from developments.

Thus, the runoff from urban and suburban developments used to be collected and conveyed by drainage system into lakes and streams. The result, apart from impacts on water quality, was increased occurrence of flooding, a rise in flood elevations, and spread of flood prone areas that adversely impacted properties along and adjacent to streams and lakes.

Since 1990 there have been an increasing number of initiatives to manage the urban water cycle in a more sustainable way. The new tendency is trying to control the runoff at its source rather than collecting and conveying it by a drainage system into a detention or retention basin (Davis et al., 2001). The integration of management of the urban water cycle with urban planning and design is known as Water Sensitive Urban Design (WSUD). (Davis et al., 2001; Hunt et al., 2006). This approach distributes WSUD systems throughout subdivision to alleviate the effects of land use changes, and protect downstream water quality (Parker, 2010).

Decision making in urban stormwater treatment always contains maximizing the treatments in stormwater runoff quantity and quality while minimizing the total treatment cost (Zhang et al., 2006). Cost effective implementation of WSUD treatment methods, allowing this pattern to be widespread applied (Donofrio et al., 2009). Although this approach endorses low cost treatment methods, the cost of design and construction of stormwater treatment systems and evaluating of their treatment performance has always been one of the restriction factors in developing of these treatment devices. Following this, several theoretic and hydrological

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models for stormwater calculations have been proposed. Although many hydrologic models have been developed over the years, most of the fundamental mathematical equations that are used in these models are related to rural or natural catchments rather than urban areas. Compared to the hydrologic processes in rural areas, there are obviously different processes in urban catchments, especially infiltration and depression storage because of the presence of impervious surfaces.

In order to meet the requirements of simulating urban catchments, modifications are incorporated in hydrologic models replicating rural areas so that they can model urban areas as accurately as possible (Liu, 2011). Following this, several theoretical models for urban stormwater modelling have been proposed. Model of urban stormwater improvement conceptualization (MUSIC) developed in Australia, estimates pollutant transport from catchments and stormwater treatment through different systems (Imteaz et al., 2013). MUSIC also enables users to evaluate conceptual design of stormwater management systems and estimate their life cycle costs through cost functions which eWater CRC team provided them (Imteaz et al., 2013).

Previous studies in attempting to develop a model for determining the optimal storage properties of stormwater treatment systems and reduction of the pollutants concentrations through them mostly used a gradient model based on search procedure of focused on single point of urban stormwater treatment. Elliott (1998), used a gradient model based on search procedure to identify effective and efficient control measures to meet goals of chemical quality of the streambed sediments, groundwater recharge and flood control in the city of Christchurch, New Zealand. He considered the spatial location of potential control measures throughout the catchment and concluded that stormwater treatment ponds and infiltration are of little benefit in relation to improving sediment quality. Therefore contaminant source abatement measures are required to control the long-term cumulative toxic effects of stormwater. Also there were studies that used integrated simulation and optimization models for optimization of and land use stormwater treatment devices. Lee et al. (2005) used scatter search method for developing an optimization model for wet weather control to determine the most cost effective strategies for the combination of centralized storage release systems and distributed on site wet weather control alternatives. They used data which are generated by running process of simulation models for developing the production function that provided estimates of performance for specified decision variables.

Despite the helpfulness of these studies and optimization methods, in discontinuous cases or in cases with abrupt changes of the objective function, the traditional optimization algorithms cannot be used. Also traditional algorithms are effective in small problems with limited number of variables and by a large number of decision variables they will not work properly. Due to the ability of evolutionary algorithms in solving such problems, usage of these algorithms is increased in recent years. GA, which is invented by Holland (1975) , is a special type of evolutionary algorithm that is better known as a stochastic optimization method. Later this method developed by Goldberg et al. (1989) and nowadays, this method due to its abilities has an appropriate position along the other methods. Harrell and Ranjithan (2003), used a modelling approach via a genetic algorithm based search procedure to generate cost-effective pond configurations that meet system targets for removal of pollutant loadings, including TSS, TP, and TN in the City Lake watershed in North Carolina. Their results showed that the cost improvements happen when land management considered simultaneously with the decisions for pond locations and sizes. Zhang et al. (2006), used the Epsilon-Dominance Non- Dominated Sorted Genetic Algorithm II to carry out the optimization of low impact development (LID) designs on an urbanizing watershed. They used United States environmental protection agency (USEPA) stormwater management model with considering both infiltration and the detention types of integrated management practices to reach the optimal control. They found that the optimization model can be a very useful tool in urban stormwater related decision makings, especially for optimizing LID scenarios. Reichold et al. (2010) presented a methodology to identify optimal watershed management strategies with minimal impact on flow regime using a simulation-optimization framework. In this application, long-term hydrologic alteration is analysed using continuous runoff simulation and a hybrid optimization approach, based on genetic algorithm and downhill simplex method which is invented by Nelder and Mead (1965), for different urban land use strategies. Lee et al. (2012) described a watershed-scale design optimization model for stormwater best management practices (SUSTAIN) using a case study in Kansas City with observed rainfall and flow data. The SUSTAIN model developed two bmp cost-effective curves for flow volume and pollutant load reductions.

In series of water resources studies, especially urban stormwater treatment, reducing of the costs of stormwater treatment measures is considered as an important part of studies (Bozorg Haddad et al., 2013). This paper presents a rule-oriented method, to significantly reduce the computational parts for obtaining this object and in turn, increases the accuracy of the computations. Therefore in the present study treatment devices are used for urban stormwater management with the usage of a simulation-optimization model in a way that minimizes the costs. This goal is achieved by using of MUSIC as a simulator and GA as an optimization tool. These two models are linked together in the MatLab integrated development environment (IDE), so that the properties of treatment system, due to the high performance of both models, will lead to a higher confidence levels.

MATERIAL AND METHODS

Development of impervious areas, causes an increment in runoff volume and decrement in time to peak, and consequently leads the urban areas to have higher flood frequency (Masamba and Mazvimavi, 2008). Urbanization also results in the growth of runoff pollutants concentration (Barron et al., 2011). As a response, for developing a more sustainable urban environment, stormwater treatment technologies have been instigated (Zingera et al., 2013).

Among stormwater treatment devices, constructed wetlands (CWs) are becoming an increasingly popular technique, in part due to their effectiveness and adaptability. Implementing CWs mitigates the negative effects urbanization has on the hydrological cycle by aiming to re-introduce pre-development processes into the urban environment.

Constructed wetlands

CWs are artificial wetlands developed in areas where they do not occur naturally. There are several definitions of CWs but Brix (1994) defined them as systems that may act as efficient water purification systems and nutrient sinks with long retention times, with an extensive amount of sediment surface area in contact with the flowing water to provide for effective removal of particulate matter.

CWs offer effective, reliable treatment of wastewater in a simple and inexpensive manner (Matamoros et al., 2005). In addition, CWs offer several additional advantages compared to natural wetlands, including site selection, flexibility in sizing, control over the hydraulic pathways and retention time. The pollutants in such systems are removed through a combination of physical, chemical and biological processes including sedimentation, precipitation, adsorption to soil particles, assimilation by the plant tissue and microbial transformations. In recent decades, this treatment device has been grown in popularity due to its flexibility in sizing and preferred for stormwater management as proper treatment device(Greenway, 2010).

MUSIC

MUSIC is the model for urban stormwater improvement conceptualization, first developed by Wong et al. (2002), and now enhanced by the eWater cooperative research centre. MUSIC provides the ability to simulate both quantity and quality of runoff from catchments ranging from a single house block up to many square kilometres. One of the great strengths of MUSIC is the ability to model the treatment processes that occur with stormwater treatment devices (Wong et al., 2006). MUSIC enables users to evaluate conceptual design of stormwater management systems to ensure they are appropriate for their catchments. It simulates the performance of a group of stormwater management devices (measures), configured either in series or in parallel form (Imteaz et al., 2013).

Genetic algorithm

Genetic algorithm (GA) is a random approach for search and optimization. This algorithm starts its search with using of random points set which are called population. Each member of the population is called a chromosome. Chromosomes are evolving in the each iteration (generation). Every chromosome indicates one of the optimization problem's answers. In this algorithm, a chromosome is composed of several genes that they transform the parental characteristics to the children.

Application of genetic and evolution operations ensures GA to progress to the different responses. Genetic operators contain four different operators which are mutation, and crossover. Mutation operator can make changes in one or more genes in the one or more chromosomes. In addition, crossover operation, which is the most important genetic operator, composes one or more chromosomes of parents to produce their children. Evolutionary operators like roulette wheel and selection process can be noted as the policy of parent selection for creation of next generation's population. Based on this rule, each chromosome, according to its fitness function value, allocates a particular surface area of the roulette wheel. This surface operates like dartboard; whenever the fitness function of the chromosome gets higher value, the probability of collision between dart and the chromosome's area will be increased and vice versa.

The GA model performance is highly depends on the selection of its parameter values. Therefore, achieving to the ideal solution requires an accurate selection of these values.

The simulation and optimization model (MUSIC-GA)

This paper has used GA for finding proper storage properties of urban stormwater treatment measures. The total life cycle costs of treatment devices are taken as the objective function:

$$f = Minimize \sum_{i=1}^{n} life\, cycle\, cost_i \qquad (1)$$

Where the life cycle cost for each stormwater treatment system is the sum of all discounted costs including acquisition, establishment, operation, maintenance, and decommission costs over the span of analysis for the stormwater treatment system. The life cycle costing module in MUSIC allows users to generate a cumulative life cycle cost estimate for any point in a stormwater treatment train. Therefore in this study a connection established between the simulation model (MUSIC) and the optimization model (GA) in the MatLab IDE. After communicating between simulation and optimization models, initial values which are generated with GA, are placed in to the storage properties of the treatment measures. Consequently, the treatment train efficiency and the life cycle cost of each treatment system are evaluated by running the simulation model (MUSIC). In addition, according to the amounts of treatment train effectiveness and the total life cycle costs of treatment measures, fitness functions are calculated. This process is continued in the loop until the stop criterion is satisfied. Figure 1 shows the flowchart of overall procedure.

Case study

The case study which is used in this paper includes 17 residential lots communal areas, as well as a central road, access roads, driveways and parking areas on 1.7 hectares in Gold Coast City, Australia. Figure 2 shows an overview of the study area. Gold Coast City is one of South East Queensland's most rapidly growing areas. With increasing development pressure and population growth in the City, continued implementation of traditional urban water systems will result in increased pressure on natural water systems and degradation to Gold Coast waterways and beaches.

Compounding these issues are drought conditions which have created issues in the delivery and assurance of a sustainable water supply.

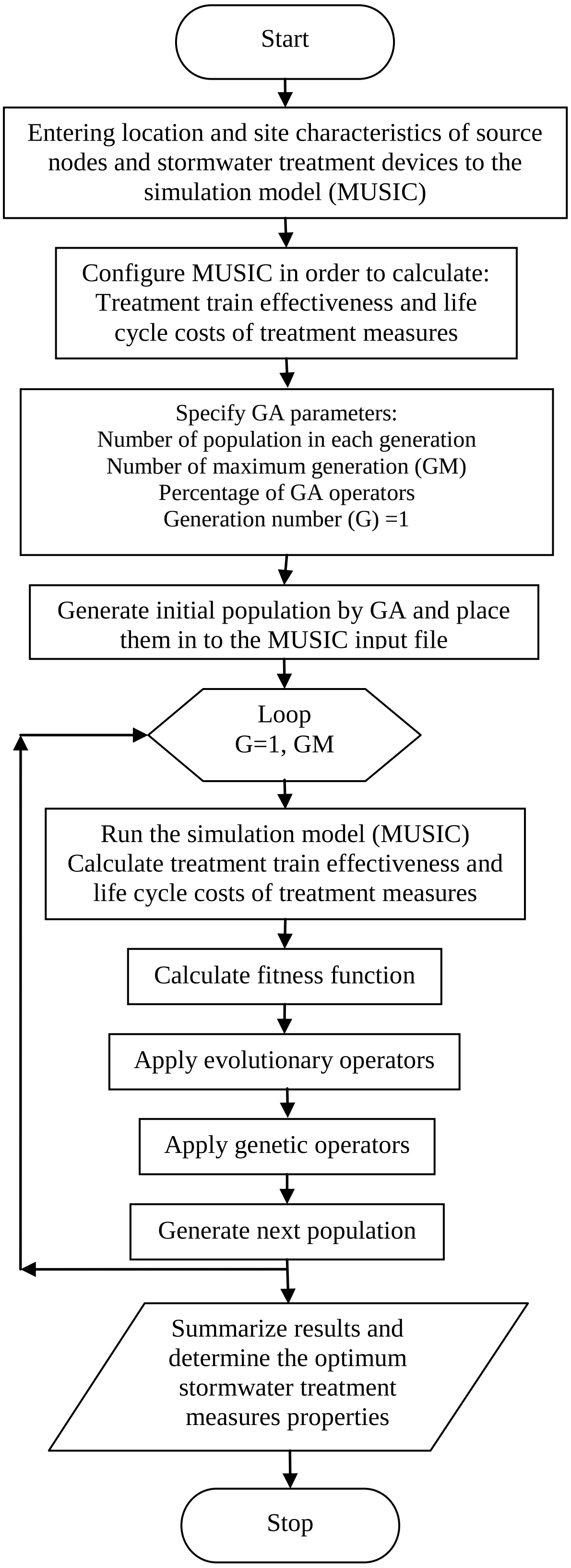

Figure 1. Flow chart of MUSIC-GA model

The runoff pollutants of the site will be lead to a river. For this reason, stormwater's pollutant concentration should not exceed the specified amount. In accordance to Gold Coast City Council (2005) land development guidelines, application of WSUD practices should reduce environmental pollution based on a total suspended solids (TSS) reduction of 80%, a total phosphorus (TP) reduction of 60%, and a total nitrogen (TN) reduction of 45%. Therefore, the concentrations of the pollutants including TSS, TP, and TN are taken as the constraints for the optimization model. The site is essentially cleared and there are no major constraints other than the site slope that is toward to the north east. Neither the soils nor the climate are major constraints, however, the landscape of the developed areas provided some challenges for the location of CW.

In addition, the site characteristics involve previous and impervious areas, the base flow and storm flow pollutant concentrations due to Fletcher (2004) study, and also rainfall-runoff parameters due to MacLeod et al. (2008) study are summarized in Tables 1 and 2 respectively. Also, the serial correlation in pollutant estimation is considered to be 0, so that the pollutants are assumed to be fully independent. Moreover, rainfall and evaporation data are taken from central Gold Coast (Hinze Dam) data that has been placed in MUSIC by developers of this simulation model.

For the post-development scenario it was assumed that the roofs have 100% effective impervious area. However this amount for paved pathways was assumed to be 50%. And finally 5 percent of vegetated areas are as an effective impervious area.

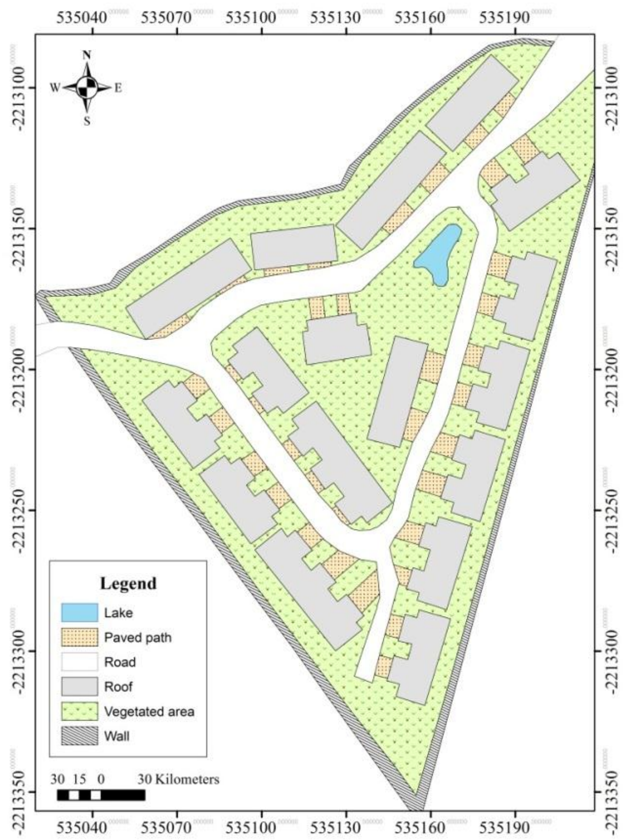

Figure 2. Case study in Gold Coast City, Australia

Moreover for simplification of modelling, the urbanized areas were aggregated and consequently, residential lots reduced to 1 urban source node with 70 percent impervious area. Also, due to landscape areas, the maximum surface area of CW is considered to be equal with 2000 square meters. Consequently, by multiplying this amount to 1 meter (extended detention depth), the maximum amount of volume that CW could take is

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assumed to be 2000 cubic meters. Therefore, the storage properties of the CW are taken as the decision variables in MUSIC-GA model. The cost functions of CW, which are taken from (Taylor, 2005) study, are listed in table 3. Furthermore, according to the MUSIC default options, year 2014 considered to be the base year. Also annual inflation rate and real discount rate are considered to be 2 and 5.5 percent respectively. And finally, 25 years are taken as the amount of life cycle years.

Table1. Rainfall-Runoff properties of urban source nodes

Urban source node	**1**
Total area (Ha)	1.7
Percent of pervious area	30
Percent of impervious area	70
Rainfall threshold (mm/day)	1
Soil storage capacity (mm)	400
Initial storage (% of capacity)	10
Field capacity (mm)	200
Infiltration capacity coefficient-a	50
Infiltration capacity exponent-b	1
Initial depth (mm)	50
Daily recharge rate (%)	25
Daily baseflow rate (%)	5
Daily deep seepage rate (%)	0

Table 2. Base flow and Storm flow pollutant concentration properties

Pollutant	**TSS (log mg/L)**		**TP (log mg/L)**		**TN (log mg/L)**	
	Mean	**Std. dev**	**Mean**	**Std. dev**	**Mean**	**Std. dev**
Base flow concentration	1.1	0.34	-0.97	0.31	0.2	0.2
Storm flow concentration	2.18	0.39	-0.47	0.31	0.26	0.23
Estimation method	Stochastically		Stochastically		Stochastically	
Serial correlation (R squared)	0		0		0	

Where: “Std. dev” is the abbreviation for “Standard deviation”

Table 3. Costing algorithms for Constructed wetland

Cost type	**Costing algorithm**
Total acquisition cost (TAC)/kL ($2004/kL)	$1911A^{0.6435}$
Typical annual maintenance cost ($2004)	$6.831(TAC)^{0.8634}$
Annualized renewal/adaptation cost ($2004)	0.52% *of TAC p.a.*
Decommissioning cost ($2004)	42% *of TAC*

Where: “A” is the surface area of the treatment zone in square meters. and “p.a.” is the abbreviation for “per annum”

RESULTS AND DISCUSSION

By the results of sensitivity analysis on the optimization model, the amount of crossover and mutation probabilities are considered to be 60 and 40 percent respectively. Also, the amount of elitism is considered to be one chromosome in the each iteration. Moreover, 1000 generations is considered as the maximum amount of generations for the stop criterion.

Using CW near to major sources of runoff and pollutants, worked effectively in mitigating urban stormwater runoff and downstream water quality protection. However, because of costs of this treatment system, in this paper, parameter settings of this treatment measure are optimized in a way that minimizes the costs of this device.

The optimization model for optimizing of treatment train measures ran for 5 times. Results of each run and their differences are shown in table 4. According to the five runs for optimizing of treatment train devices, it is necessary to analyse the results of different runs. The value of coefficient of variation (CV) between the results of 5 runs, one of good measures for this analysis, is equalled to 0.005. The low value of CV for different results presents an appropriate convergence between results of optimization model and the global optimal solution. Due to table 4, it can be seen that the optimized value of surface area of CW is equalled to 1948 square meters. Therefore by multiplying this value to 1 meter extended detention depth, the volume of the CW is calculated to 1948 cubic meters.

For evaluating of the performance of MUSIC-GA model in optimizing of surface area of CW, the simulation model is also ran for additional points around the optimum value. The results of different runs of simulation model are presented in Figure 3. In accordance to Figure 3, it can be seen that the developed simulation-optimization model has a significant efficiency in optimizing of stormwater treatment measures; As by considering the surface area of CW with 1500 square meters, not only the runoff pollutants concentrations reduction (based on 80% reduction of TSS concentration, 60% reduction of TP, and 45% reduction of TN) are established but also the minimum amount of life cycle cost of CW is selected.

By utilizing of GA as an optimization model, optimized post-developed scenario ran with the best parameter sets in the simulation model (MUSIC).

The modelled annual pollutant loads (TSS, TP, TN, and GP) for both pre-developed and post-developed scenarios are presented in Table 5. Also, Table 5 contains the improvement percentages of pollutant concentrations in the post developed scenario. The efficiency of constructed wetland is calculated through division of pollutant loads difference among both scenarios by the pre-developed scenario’s pollutant loads. Additionally the comparative cumulative frequency curves for pollutant concentrations are provided in Figures 4 to 6.

The table 5 indicates that, there is a significant reduction in all pollutant loads. In addition, treatment train effectiveness shows that with the optimized constructed wetland, TSS, TP, and TN load reductions are achieved to 80, 76, and 65 percent respectively. In addition, as is illustrated by the Figures 4 to 6, 0^{th} to 82.3^{th} percentiles of TSS, 0^{th} to 82.6^{th} percentiles of TP, and 0^{th} to 50.2^{th} percentiles of TN concentrations for the post-development scenario are lower than the pre-development condition. This confirms that, by using of simulation-optimization model and running the optimized setting of the stormwater treatment devices, at the mentioned percentages of rainfall-runoff process the post-development scenario will meet a neutral or beneficial effect on water quality.

Table 4. The objective function value of different performances

Run	Number of runs	Decision variable	Fitness function ($)	Percentage of TSS reduction	Percentage of TP reduction	Percentage of TN reduction
1	62	1983.9096	446995.02	88.780427	77.493958	45.667155
2	112	1956.5398	442707.05	88.466661	77.108169	45.161233
3	67	1948.644	441466.4	88.371997	76.992712	45.010084
4	117	1949.9923	441678.38	88.388275	77.012536	45.036021
5	72	1948.7055	441476.08	88.372741	76.993618	45.011269
Maximum	117	1983.9096	446995.02	88.780427	77.493958	45.667155
Mean	86	1957.5582	442864.59	88.47602	77.120199	45.177152
Minimum	62	1948.644	441466.4	88.371997	76.992712	45.010084
Coefficient of Variance	0.30599296	0.0077072	0.0053405	0.0019734	0.0027789	0.0062186

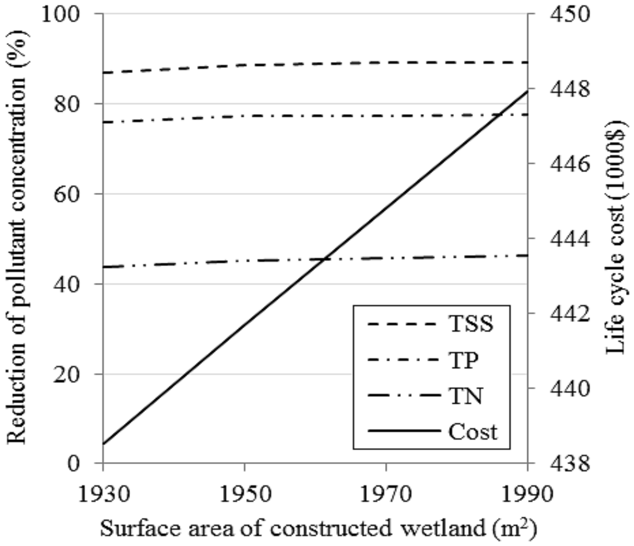

Figure 3. Results of different runs around the optimum point of CWs properties

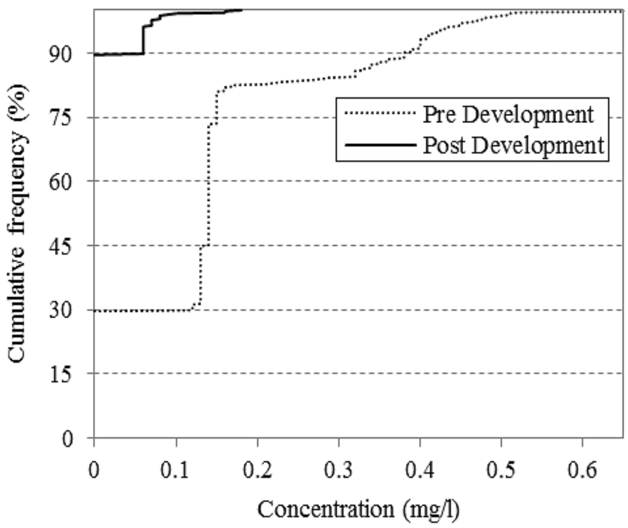

Figure 5. Pre and post development cumulative frequency graphs for daily TP concentrations

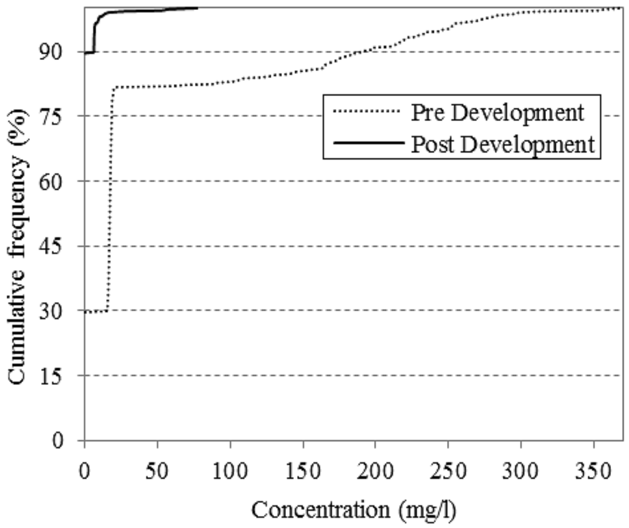

Figure 4. Pre and post development cumulative frequency graphs for daily TSS concentrations

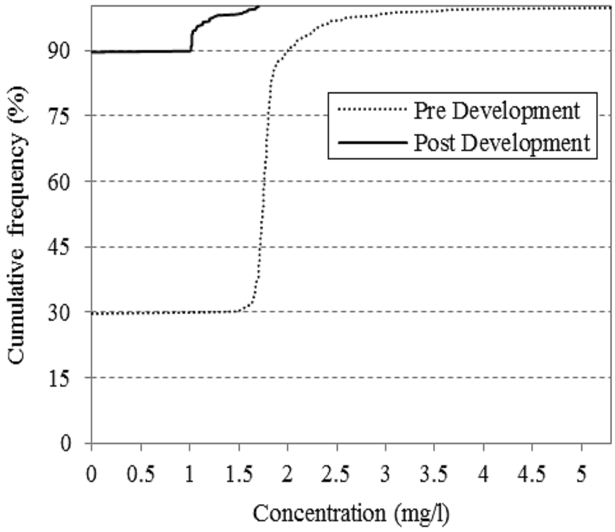

Figure 6. Pre and post development cumulative frequency graphs for daily TN concentrations

Table 5. MUSIC modelling pollutant load results

Scenario	Annual pollutant loading (kilogram/year)		
	TSS	TP	TN
Pre development	4340	8.97	42.2
Post development	503.44	2.07	23.21
Percentage of improvement	88.4	76.9	45.0

CONCLUSION

The purpose of this study was to optimize the post developed scenario of urban areas, by changing the size of treatment devices in a way that the site meet neutral or beneficial effects on water quality and consequently the costs are being minimized. So that MUSIC and GA are linked together in the MatLab IDE for optimizing the amount of storage properties of stormwater treatment measures.

The study considered two developed conditions including pre-development and post-development scenarios. 88 percent removal of TSS, 76 percent removal of TP, and 45 percent removal of TN concentrations in the post-development scenario confirmed that optimized treatment devices are effective means for removal of pollutants from urban stormwater runoff. Also, calibrating of optimization model showed that when it is calibrated in terms of number of generations, mutation and crossover percentages, it has more ability to reduce the costs urban stormwater treatment devices.

As a final point, this paper was based on a specific physical and topographical region in Gold Coast City, Australia consisting residential lots. So, the results would change in different land uses or in different circumstances. However, using of GA in comparison to the other studies indicated that, the optimization model generally makes it easier to achieve the desired points of treatment systems storage properties for reducing of pollutants concentrations.

RECOMMENDATION

It can be recommended that for getting better results in developing of such simulation-optimization models, it is better to use and test more optimization methods. In this way, specific case studies with different developed scenarios and land uses have to be tested in various simulation and optimization models. And by comparing the results of different optimization methods in optimizing of those specific case studies, the best and complete simulation-optimization model from the terms of reach time to solution and the solution's accuracy will be determined.

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