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GREEN INFRASTRUCTURE OPTIMIZATION TO ACHIEVE PRE-DEVELOPMENT CONDITIONS OF A SEMIARID URBAN CATCHMENT

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The introduced hydrologically comprehensive Green Infrastructure design approach shows that using a Pre-Development Condition nearness metric as a GI design goal leads to more common Environmental Benefits, as compared with the conventional stormwater management goal of runoff reduction. In addition, this study shows that diversifying the types of employed GIs in a catchment would lower Life Cycle Costs.

Green Infrastructure Optimization to Achieve Pre-Development Conditions of a Semiarid Urban Catchment

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Abstract

One challenge facing sustainable cities is managing stormwater in urban catchments. Of particular interest is mitigating the negative impacts of urbanization on hydrologic variables to a sustainable level. In this context, "sustainable" could be defined as mimicking the Pre-Development Conditions (PDC) of an urban catchment by implementing Green Infrastructure (GI). Nevertheless, common stormwater management standards do not necessarily maintain the PDC of a region. They often prioritize site suitability and reduction of runoff volumes that can be used to partially meet the PDC of the area. However, a goal could be to get closer to PDC in maximum extent possible, in all hydrologic variables, not just runoff; following the primary purpose of designing GIs. Although studies show GI techniques can significantly contribute to approaching PDC, no comprehensive methods incorporate multiple hydrological components and reveal compatible types of GI with the PDC of a catchment. To introduce a comprehensive GI design approach based on PDC nearness, a systematic Multi-Objective Optimization (MOO) framework was developed and is presented in this paper. This framework employs the recently introduced PDC nearness metric known as Water Budget Restoration Coefficient (WBRC), and includes

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comparison of two different sets of tradeoffs based on two independent optimization sets: (i) the first optimizes candidate GIs in terms of Life Cycle Cost (LCC) and Runoff Volume (RV), and represents common practice, and (ii) the second one optimizes GIs in terms of LCC and WBRC, representing a more comprehensive hydrologic goal. The selected candidate GIs were i) Permeable Pavements (PP), (ii) Green Roof (GR) and (iii) Bio-retention Cells (BC), because of their diverse hydrological benefits. The optimum results of the two MOO sets were compared in terms of environmental and stormwater management benefits to reveal the overall performance of both approaches. The results suggest that considering WBRC criteria in the optimization process outperforms conventional practice in terms of common benefits. Specifically, 50% more evapotranspiration, which can be translated to having more plants and eventually better air quality; 30% more reduction in the duration of flood events; 2% more total suspended solids removal; and about the same level of performance in groundwater recharge and flood volume reduction.

Keywords: Hydrologic-Hydraulic Modeling, Green Infrastructure, Stormwater Management, Water Budget Restoration, Multi-Objective Optimization, High Throughput Computing.

1. Introduction

Urbanization significantly impacts the water budget and water quality components of catchments by increasing the amount of impervious surfaces such as roads, parking lots and roofs (Guan et al., 2016; Jacobson, 2011; Powell et al., 2008; Shuster et al., 2005). These impacts can have negative consequences on urban ecosystems, human health, and water resources. Depending on varying spatial and climatological factors, the specific effects of urbanization can vary among different catchments, although typically infiltration decreases, stormwater runoff increases, and runoff to streams and waterways is accelerated as urbanization grows (Haase, 2009; USGS, 2003;

Wu, 2015). Therefore, the magnitude of other water budget components such as evapotranspiration (ET), infiltration, and groundwater recharge decrease (Barron et al., 2013; He and Hogue, 2012; Jeppesen et al., 2011; Kaufmann et al., 2007). Thus, higher surface runoff with reduction of other components of the hydrologic cycle are typical results of urbanization, and controlling such intensifying impacts remains an area of concern as land development takes place.

Studies have shown that impacts of urbanization on hydraulic and hydrologic characteristics contribute to major problems in wastewater management, sediment erosion and stream quality degradation, water-borne diseases, and acidification of water bodies (Astaraie-Imani et al., 2012; Narain, 2012; Nie et al., 2011; Tavakol-Davani et al., 2016; Xiao et al., 2012). Since the passage of the Clean Water Act (CWA) in 1972, which originally focused on point source pollution in the United States, public policies have led to the development of best management practices that have helped control runoff-based water quality problems (U.S. EPA, 2000). After the CWA, by construction of so-called grey infrastructure, the extent of point source pollution has significantly decreased. However, today, given urban expansion and the limited control of runoff, the fraction of point to nonpoint pollution is almost exactly converse from the 1970s: 85% of current water quality impairments are associated with nonpoint source urban or agricultural stormwater runoff (Ruckelshaus, 2010).

It is important to restore and maintain other hydrological components besides runoff since each of them contributes to at least one type of environmental benefit. For instance, increasing infiltration can result in higher Ground Water Recharge (GWR), and since groundwater is one of the most important natural resources for drinking and irrigation (USGS, 2018), it contributes to more water provision. Likewise, increases in evapotranspiration (ET) contributes to a variety of environmental benefits as follows: (i) ET controls the amount of water to be percolated to the ground (Ellis, 2013; Wong and Jim, 2015); (ii) ET reduces Urban Heat Island (UHI) intensity (Alexandri and Jones, 2008; Shashua-Bar et al., 2009; U.S. EPA, 2008a); (iii) plants generate cool air through the ET process, alongside increasing carbon sinks, which can eventually contribute to better air quality near roads (Baik et al., 2012); and (iv) under certain weather conditions, higher ET leads to enhanced precipitation caused by higher moisture in the atmosphere (Shepherd and Burian, 2003; Spracklen et al., 2012). Therefore, maintaining a well-balanced hydrological cycle in which each hydrological component is able to make its own contribution could potentially lead to higher environmental benefits and a more sustainable design.

Modern techniques in preventing the negative impacts of urbanization improve upon the traditional approaches in terms of costs, nearness to Pre-Development Condition (PDC) and environmental benefits. The traditional approaches to managing stormwater were flood-control and mitigation-based and focused on structural methods such as pipe and channel networks to prevent surface water from ponding (Burian et al., 1999; Riverlink, 2018). However, such a purely structural approach has certain limitations in terms of providing adequate storage (Hinman et al., 2005). Plus, it is not able to control stormwater pollution and therefore leads to downstream flooding and water quality issues (Carson et al., 2014). Later, Best Management Practices (BMPs) such as detention basins were used to compensate for storage shortage, although they were still costly and energy-intensive. Modern Low Impact Development (LID) techniques as source reduction approaches are engineered to control the impacts of urbanization in an environmentally friendly fashion (Burian and Pomeroy, 2010; EPA, 2018). Moreover, it has been shown that by incorporating GI plans it is possible to restore PDC (Feng et al., 2016). Other studies have shown practices such as Bio-Retention (BR) not only enhance the value of ecosystems and increase resiliency, but also provide water-management services at a lower cost and with a greater overall economic benefit in many aspects (Horinko Group, 2015). For instance, an urban neighborhood in Seattle, Washington, reduced wet-season runoff by 98% (Horner et al., 2002) by incorporating vegetated swales, native plants in the street right-of-way, and narrowing street width.

Rather than a comprehensive approach in LID design, current practice is based on site suitability and capital cost analysis towards merely managing runoff (Lee et al., 2012; Martin-Miklea et al., 2015). There is a distinct gap in the literature for a comprehensive and hydrologically diverse LID design approach that incorporates all hydrological components and includes all candidate GIs to compete fairly with one another. GIs are capable of bringing the water budget components closer to the predevelopment condition by mimicking the natural hydrology of a catchment (U.S. EPA, 2018). However, current LID design manuals and regulations usually focus on runoff control as the goal (e.g., Hinman et al. 2005), ignoring the rest of the hydrological components such as ET and infiltration enhancement. For instance, it is common to set a certain amount of capture volume to promote water quality and flood protection in downstream areas without quantifying the watershed-scale benefits. However, having diverse control plans, especially in the context of GI plans, may help get closer to PDC, provide more environmental benefits, and, ultimately, reach a more sustainable level while meeting all of the existing regulations regarding stormwater quality and quantity.

In an attempt to introduce holistic GI design approaches, there have been several GI optimization studies in the literature (Alves et al., 2016; Damodaram et al., 2013; Heidari et al., 2016; Lee et al., 2012; Tavakol-Davani, 2016; Yang and Chui, 2016). These studies typically made substantial simplifications because of the huge computational time required for such analyses. For instance, Damodaram et al. (2013), by using a single objective optimization technique and considering 2-year, 10-year and 100-year events, introduced a method in strategically placing the

LIDs where they could efficiently manage peak flow alterations. Others have used Multi-Objective Optimization (MOO) platforms to determine a range of solutions; for example, BMPs were optimized in terms of runoff quantity and quality by linking EPA SWMM to NSGA-II (Oraei et al., 2012), but only a 5-year 24-hour design storm was considered for this analysis. In another work, Zhang et al. (2013) linked the epsilon-NSGA-II to a SWMM model to identify cost-effective solutions of LIDs in response to the 10-year 24-hour design storm of the area of analysis. In a more recent study, an EPA SWMM model was linked to NSGA-II, to assess the reduction of Combined Sewer Overflows (CSOs), but because of the huge computational time, instead of an extended simulation period, only single storm events were considered for the analysis (Alves et al., 2016). On the other hand, studies have shown decentralized stormwater management techniques such as GIs are more efficient in capturing more frequent storms and thus more appropriate to be designed based on continuous long term analyses. Consequently, there remains the need for an approach to overcome the computational burden of MOO processes while being able to run extended period models of stormwater as detailed as usual GI performance models.

Given the lack of a hydrologically comprehensive approach in selecting and designing appropriate LIDs in a long term rainfall-runoff analysis, this study strives to evaluate a more hydrologically comprehensive GI design goal that could lead to more environmental and stormwater management benefits. Specifically, it uses two sets of optimization runs for the candidate GIs to determine optimum configurations and compare results between RV-LCC versus WBRC-LCC in terms of environmental benefits. To accelerate the optimization process, the framework is linked to a High Throughput Computation (HTC) tool to allow implementation of a long term GI analysis.

2. Method

2.1 Studied area

A small urban catchment located in the northeast of Salt Lake City (SLC), Utah, was selected for this analysis (Figure 1). The total catchment area is 11 hectares, and the stormwater runoff for this area is collected by a small drainage network, which directs runoff into the Red Butte Creek. The site consists of a variety of potential candidates for different types of GI plans because it encompasses parking lots, roofs, and curbside-vegetated areas. Therefore, three different GIs have been selected for this site: Permeable Pavements (PP), Green Roofs (GR), and Bio-retention Cells (BC). They were selected because of their separate implementation locations (rooftops versus parking lots versus landscapes) and diverse hydrological benefits.

The climate of SLC is categorized as semiarid (Bair, 1992; Russell and Cohn, 2012), and the average annual temperature is 11.5 ^{0}C. Also, based on the 1981 to 2010 record, the SLC average annual precipitation is 16.1 in (NOAA, 2013). The primary soil type of the catchment is Bingham gravelly loam (NRCS, 2018). For this type of soil, the hydraulic conductivity is approximately 8.99 mm/h, porosity is 0.46, and wilting point and field capacity are 0.15 and 0.3, respectively (Merrell, 2013). The water table was measured as 38.25 m below the land surface by a U.S. Geological Survey (USGS) groundwater station near the study site (USGS, 2015).

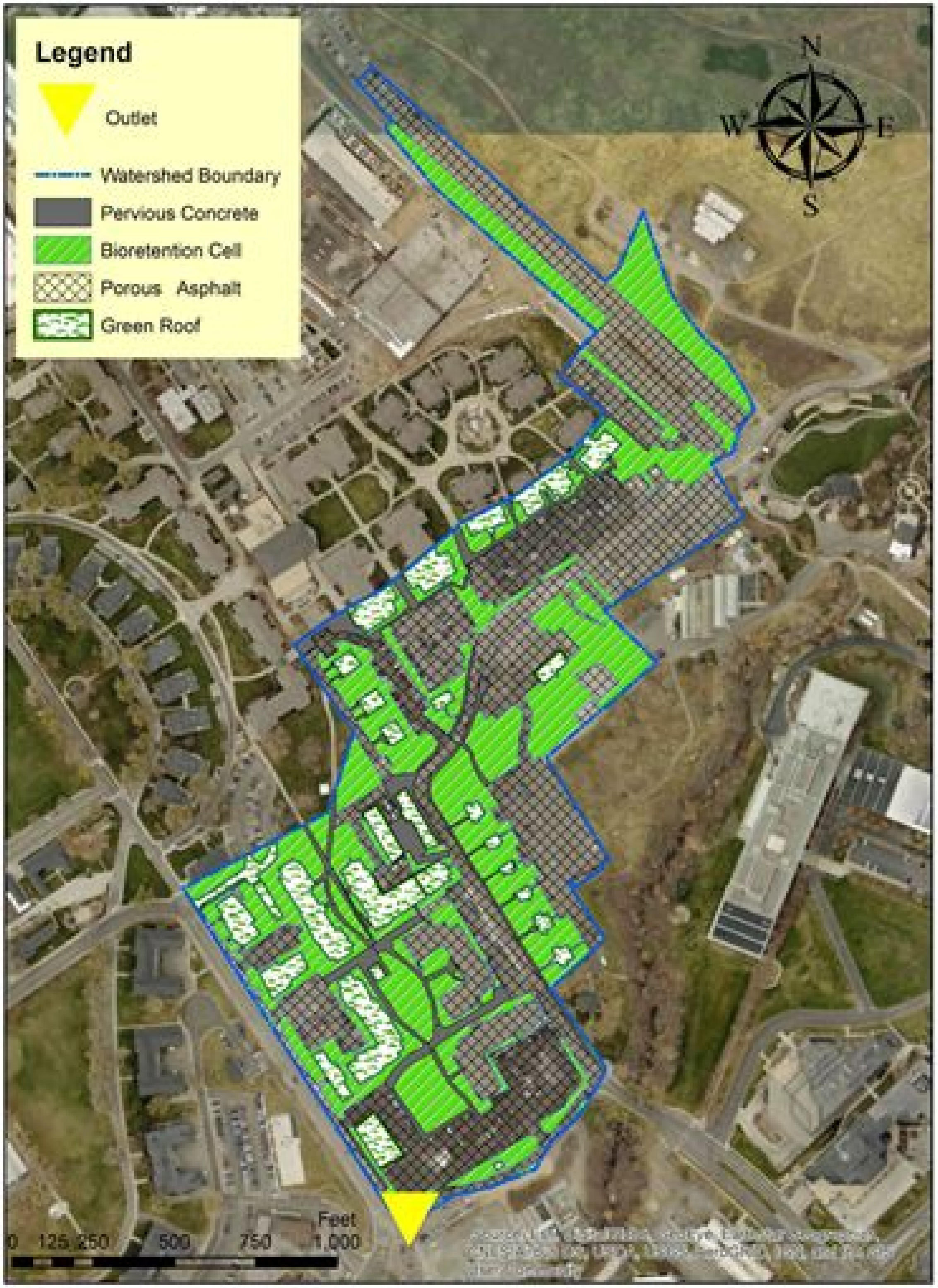

Figure 1. The studied area as well as the possible location of the candidate GIs

2.2 Hydraulic and hydrologic modeling

2.2.1 Model

EPA SWMM was selected as the hydraulic and hydrologic modeling platform, due to its ability to simulate the performance of the LIDs of interest. The drainage catchment was delineated and further subdivided into 51 subcatchments based on terrain, locations of storm drain inlets, and other hydraulic features (e.g., curb and gutters). Through GIS data analysis (calculating areas confined by buildings, streets, parking lots, lawns, etc.), the percentage of imperviousness in each subcatchment was determined. Then, all required hydraulic and hydrologic (slope, percent of impervious area, Manning's n, etc.) characteristics of the area, were introduced to the model. More details on the schemes of the GI plans are presented in Section 2.3. The Green-Ampt method was employed as the infiltration model, and the dynamic wave approach was used for flow routing, resulting in a flow routing error of less than 5% for all runs, based on the SWMM reports.

2.2.2 Rainfall data

The precipitation data for the year 2014 assuming to represent a normal water year for the Salt Lake area (Feng et al., 2016) was used for this study. 2014 has a total rainfall depth of 482 mm, and it is relatively close to the annual average of 409 mm. The rainfall data was obtained in 5-min intervals through MTMET (Mesowest, 2015) and embedded in the EPA SWMM input file.

2.2.3. Model calibration

The model was calibrated, based on five different rainfall events in 2014, by the use of a flow measuring device installed at the outlet of the catchment. A 2150 Area Velocity Flow Module (Teledyne Isco, USA) was installed in May 2014 in the storm drain at the outlet of the catchment to measure the flow rate in 1-min increments. Precipitation data, in 5-min intervals, have been collected from the weather station located within the studied catchment, namely Mountain Met (MTMET) operated by the Department of Atmospheric Science at the University of Utah (Mesowest, 2015). Then, in an attempt to match the modeling results to the five rainfall events in May 2014, slope, width, Manning's n, imperviousness, and depression storage were manually adjusted in the calibration process. The root of mean square errors (RMSE) and the coefficient of determination (R^2) ranged from 2.57 to 10.56 L/s and from 0.37 to 0.87, respectively.

2.2.4 ET and other hydrologic variables

Monthly potential evapotranspiration (PET) rates were calculated using the Penman-Monteith equation (Monteith, 1965) by following the standard practice in the literature (Kingston et al., 2009; Sherwood and Fu, 2014; Thompson et al., 2014). These values were entered in the SWMM model. Also, the contribution of deep GW to ET amounts was assumed to be negligible for this study. This is because a test simulation with deep percolation in SWMM showed that it would affect the ET values only by 0.22% of the rainfall amount, which is negligible.

2.3 Green infrastructure design

Specific GI units selected were PP, GR, and BC, based on the characteristics of the site and the diverse hydrologic benefits of these GIs. While runoff reduction is considered to be the core benefit of all GIs, the combination of these three types of GIs can increase ET and improve aesthetics, stormwater quality, and infiltration. An optimum configuration of the selected GIs can be determined by the NSGA-II method, as discussed in Section 2.6.

A detailed vertical layer configuration is defined for each selected GI (Table 1), to facilitate comparison of the competing GI plans. Considering varying stormwater management benefits of the selected GIs, numerous configurations can lead to successful runoff capture to meet the standards, but a critical question is which configuration provides an appropriate compromise among cost and efficiency in terms of ES provision. Thus, the GIs were compared to determine which plan was more effective and less costly.

2.4 Life cycle cost estimates

To estimate and compare the 50-year LCC associated with each plan, a few consistent assumptions were required. It was assumed that engineering-planning and contingency-corrective costs would be 10 and 20% of the capital cost, respectively. In addition, the facilities would be installed by experts, and the level of maintenance would be moderate for all of them. Moderate maintenance is defined by the following assumptions: (i) frequency of maintenance events is every 12 days, (ii) time spent per visit is 2 hours, (iii) labor crew number is 1, (iv) labor compensation rate is \$31 per hour; (v) machinery costs is \$0 material, and (vi) visit fee is \$10; these assumptions would lead to a grand total of 72\$ per visit. According to the available resources in the literature (Belan and Otto, 2004; City of Lincoln, Nebraska, 2008; Edgewood College, 2003; Kassulke, 2003; Maryland Department of the Environment (MDE), 2000; Rain Garden Guide, 2008; U.S. EPA, 2008b), an estimator tool was developed and used to generate LCC per square foot for each GI type. Table 2 summarizes the final present value of a 50-year LCC per square foot of each unit.

Table 1. GI vertical scheme and parameters for each LID design in SWMM.

Properties		Green infrastructure		
		PP	GR	BC
Surface layer	Berm height (cm)	15.2	2.5	10.2
	Vegetation volume Fraction	0	0.4	0.4
	Manning's n	0.014	0.15	0.24
Pavement layer	Thickness (cm)	15.2	N/A	N/A
	Void ratio	0.18		
	Permeability (cm/hr)	254		
	Clogging factor	0		
Soil layer	Thickness (cm)	10.2	25.4	61.0
	Porosity	0.3	0.58	0.43
	Field capacity	0.2	0.48	0.21
	Conductivity (cm/hr)	7.62	8.1	3.9
Storage layer	Thickness (cm)	66	N/A	61
	Void ratio	0.15		0.6
	Seepage rate (cm/hr)	1.27		1079
	Clogging factor	0		0
Storage drain	Flow coefficient	0	N/A	0.6
Drainage mat	Thickness (cm)	N/A	2.54	N/A
	void ratio		0.6	

2.5 Pre-Development Condition closeness metric

In 2016, Feng et al. (2016) introduced a metric quantifying the closeness of a catchment to its PDC. The equation (Eq.1) includes a deficit term that is subtracted from unity, to ultimately calculate the closeness to PDC (dimensionless; fraction). In this equation, *f'i* is the fraction of the water budget component in predevelopment condition, and *fi* is the fraction of the water budget component in the existing or designed condition. A goal of this study was to maximize the WBRC or approach PDC, necessarily minimizing the deficit term. In other words, as the deficit term approaches zero, the WBRC will approach unity, manifested mathematically as

$$\mathrm{WBRC} = 1 - \sum_{i=1}^{n} \left(fi \left| f'i - fi \right| \right) . \tag{1}$$

Table 2. Summary of assumptions in LCC estimates.

Item	GI Type		
	Pervious concrete	GR and BC	Porous asphalt
Life cycle cost/square foot (USD/m^2)	565.1	49.5	47.4
Level of maintenance	Moderate	Moderate	Moderate
Implementation by	Experts	Experts	Experts
Contingency-corrective costs	10% of capital cost	10% of capital cost	10% of capital cost
Engineering and planning	20% of capital cost	20% of capital cost	20% of capital cost

2.6 NSGA-II set up

NSGA-II was employed as the optimization tool for this study. It is an improved version of NSGA, a powerful MOO framework that was initially developed in 1994 (Srinivas and Deb, 1994). NSGA-II addresses the computational complexity of NSGA and also provides an explicit mechanism for preservation of diversity (Deb et al., 2002). NSGA-II has been successfully applied in different engineering studies, especially, as discussed in the introduction, in the stormwater management domain.

The details of the NSGA-II set up for this study are as follows. The variables were the area of each defined GI in all 51 subcatchments. In other words, the NSGA-II was used to optimize the areas of different GIs in the study area by minimizing RV, LCC and WRBC deficit. Because some subcatchments include more than one type of GI, the total number of variables equaled 92. Upper bound values matching 90% of the total possible areas for GI implementation were considered, to prevent the creation of unrealistically high GI areas. Each generation has eighty individuals forming the population, and 1000 generations were considered to ensure convergence of the objective functions. In other words, each "individual" is a complete GI plan for the entire site and has 92 variables (or 92 GI units); the individuals compete to one another to indicate the optimum ones in terms of the objective functions. The objective functions for this study were (i) minimization of RV and (ii) minimization of LCC, and (iii) minimization of WBRC Deficit. The objective functions (i) and (ii) form the first MOO and (ii) and (iii) form the second MOO set.

2.7 High throughput calculation

A parallel processing resource, HTCondor (HTCondor, 2018), was used for high throughput calculations, to accelerate the large number of SWMM runs. HTCondor was chosen among other available distributed computing resources, including supercomputers and Graphics Processing Unit (GPU) algorithm implementation, because of its significantly lower setup costs, platform-independent structure (cloud-based computing) and high unit processing speed. Another advantage is that HTCondor is an open-source HTC workload management software framework amenable to clusters of distributed and common computer resources (HTCondor, 2018). It consists of a set of software tools that implement and deploy HTC on distributed computers. Distributed computing powers can be effectively integrated through HTCondor into one computing environment for simulation-based optimization tasks, such as NSGA-II. Furthermore, the distributed ownership and low price make HTC environment more convenient for users than supercomputers (Yang et al., 2014).

For this study, the platform-independent structure of HTCondor allowed different operating systems to join the pool, even without installing the US EPA SWMM or MATLAB (the NSGA-II platform software in this study), and it decreased the simulation time from months of analysis to less than a week. MATLAB software was used to run the NSGA-II, and link it to SWMM and HTCondor. The executable version of the US EPA SWMM was transmitted through the pool during the simulations, and the results of the analyses were stored in the master computer hosting the pool. A total of five computers provided an average of 40 nodes available for this study. Figure 2 depicts a flowchart for the framework used to distribute the optimization process.

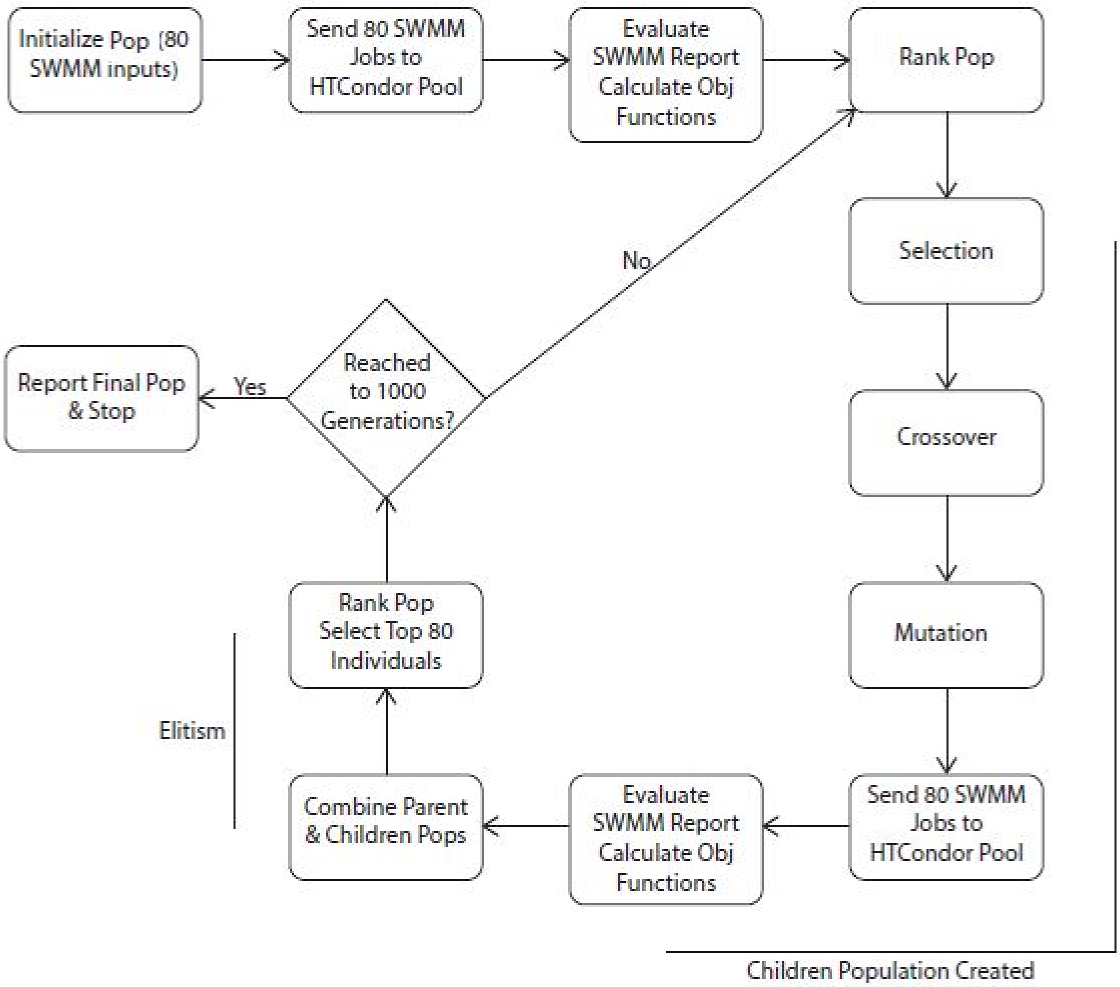

Figure 2. Flowchart showing the parallelized NSGA-II process. Note that Pop stands for the word "population".

2.8 Stormwater management indices

Four stormwater management categories were considered in the analysis because of their direct relevance and importance including ET provision, flood protection, Ground Water Recharge (GWR) and stormwater quality. ET provision accounts for the air quality aspect of environmental benefits. Flood protection analysis covers the flood protection category of environmental benefits and consists of (i) flood volume and (ii) flood duration. These metrics were associated with flooding of each node in the SWMM model and summation of the total time and volume of flood for them. Groundwater recharge represents the fresh water provision aspect of environmental benefits, calculated with simulated aquifer storage in SWMM. Lastly, the stormwater quality improvement aspect of environmental benefits was assessed based on the ability of GIs with respect to removing Total Suspended Solid (TSS) from stormwater.

3. Results and Discussion

3.1 Convergence of results

The results of the two optimization sets suggest that, after around 700 generations, the objectives converged to fairly constant values. For instance, based on the results of the first optimization set (i.e., RV vs. LCC), after around 500 generations (Figure 3), the fluctuation of the minimum and average of LCC curves both substantially decreased and effectively converged to constant values. Therefore, the number of generations employed in the optimization process appears sufficient.

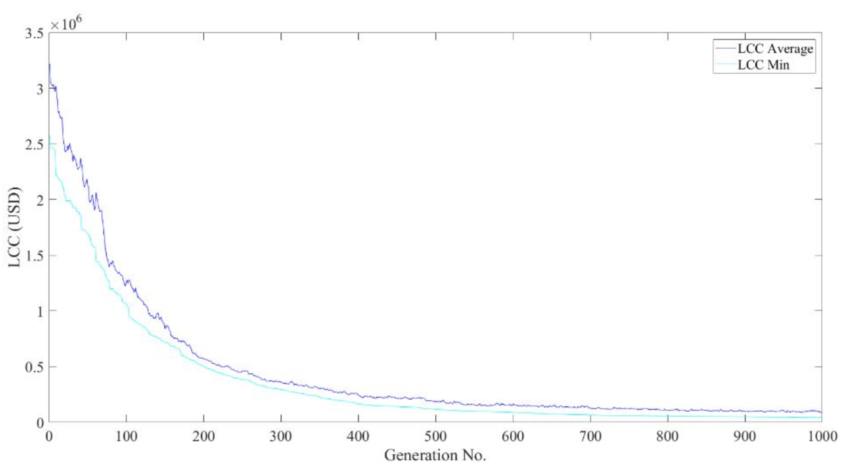

Figure 3. The average and minimum of LCC for all of the population for each generation.

3.2 Development of the Pareto front

Figure 4a-d and Figure 5a-d illustrate how the Pareto fronts formed through the generations for the two MOO sets. By following the optimum GI designs, the average LCC was significantly decreased for both MOO sets. These results corroborate the importance of GI optimization practice. The last generation of results corresponds to the Pareto front for the two optimization sets. Specifically, the first Pareto front (Figure 4d) illustrates the tradeoff between RV and LCC, and the second one (Figure 5d) shows the tradeoff between WBRC Deficit and LCC. To compare the performance of these two optimization sets, they are depicted on the same axes and discussed in the next section.

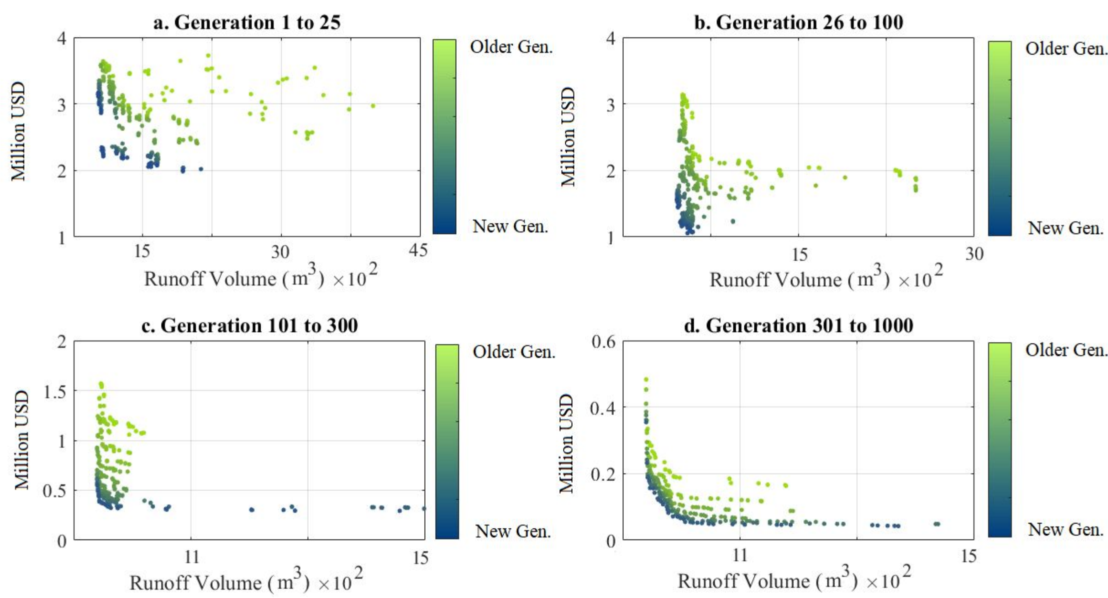

Figure 4. Shows the development of Pareto front **for the RV vs. LCC optimization set**. In all plots, lighter colors correspond to older generations, and dark blue ones are associated with new generations. Subfigure a) delineates generation 1 to 25; b) generations 26 to 100; c) major generations in 101 to 300; and d) major generations in 301 to 1000.

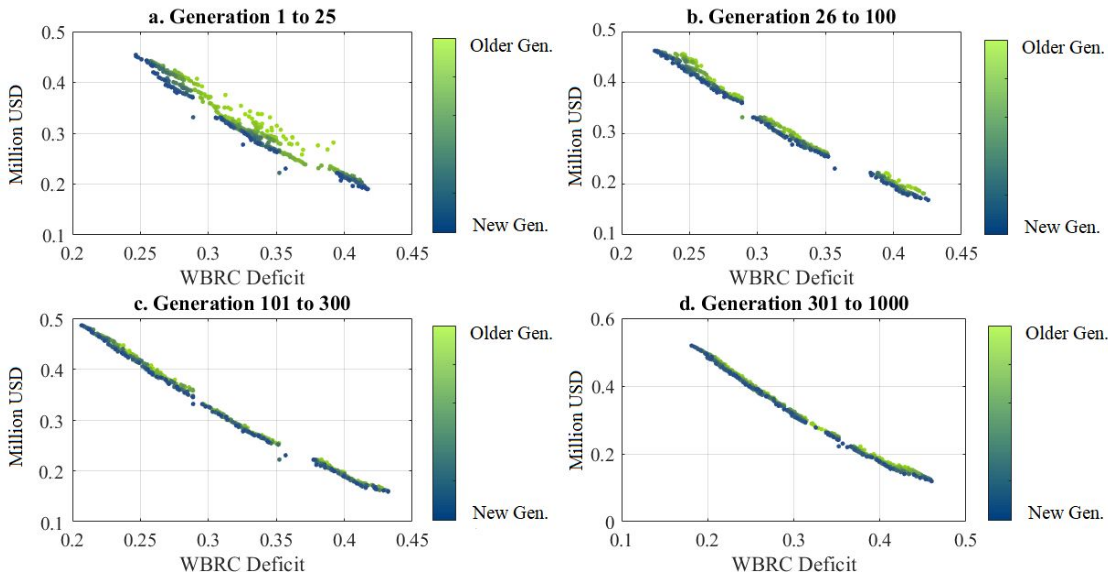

Figure 5. Shows the development of Pareto front **for the WBRC vs. LCC optimization set.** In all plots, lighter colors correspond to older generations, and dark blue ones are associated with new generations. Subfigure a) delineates generation 1 to 25; b) generations 26 to 100; c) major generations in 101 to 300; and d) major generations in 301 to 1000.

3.3 Comparison of two Pareto fronts

In order to compare the two Pareto fronts, the results should be calculated (and plotted) based on the same objectives. Therefore, based on the characteristic of the individuals, WBRC Deficit values were calculated for RV based optimization set. Using the same vertical axis scale as the LCC of the individuals, Figure 6 plots both optimization results for WBRC Deficit. In addition, this plot includes the No-GI results to depict the end of the continuum of the tradeoffs.

Comparison in terms of LCC between the two Pareto fronts reveals that both optimization sets cover nearly the same range of LCC values. However, the fact that in Figure 6, RV-based solutions cover a shorter range in terms of LCC values does not mean that they are inherently less costly. This could be simply because more expensive

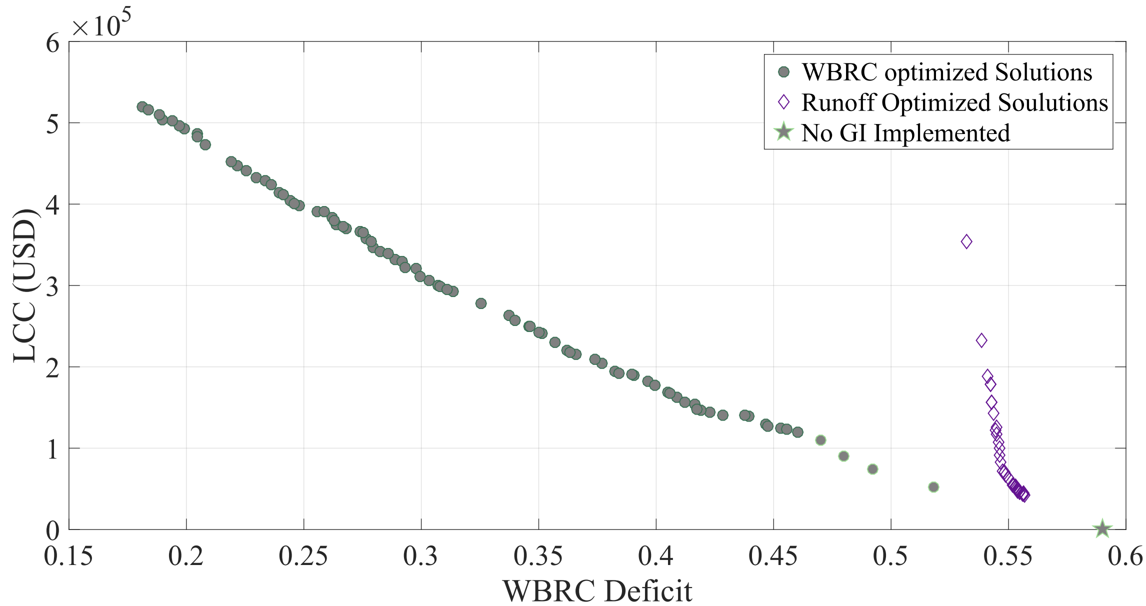

Figure 6. Pareto fronts on a WBRC Deficit versus LCC scale for both optimization sets.

RV-optimum solutions are not showing in the RV-based Pareto front. In fact, the two Pareto fronts show two different paths of getting away from the No-GI condition: (i) decreases runoff and (ii) increases WBRC. Since the two Pareto fronts are in the approximate same LCC range, there are several individuals with the same cost, but different performance. Nonetheless, considering the lower part of the curves, it can be concluded that WBRC-based individuals, for the same amount of money, produce significantly more WBRC values.

The RV-based optimum solutions did not generate a broad range of WBRC Deficit (Figure 6), and they revolve around a value of 0.55 WBRC deficit. It is evident that the WBRC-optimized solutions cover a range of WBRC Deficit values of 0.18 to 0.52, corresponding to 48 to 82% restoration of PDC (Figure 6). On the other hand, RV-based optimum results do not cover a wide range and do not seem to achieve promising results with respect to closeness to PDC. One possible explanation for this is that the RV-based optimization process does not include other hydrological components in the WBRC equation, but only focuses on runoff reduction. For instance, in the RV-optimized solutions, although ET values may be far from the PDC condition, if the RV of an individual is quite low then that individual survives and joins the Pareto front.

The form of the curves in Figure 6 indicate both the nondominance state of the WBRC-based solutions and the relative accuracy of both optimization sets. Specifically, all of the RV-based solutions reside above the hypothetical line connecting the WBRC-based solutions and No-GI point (Figure 6). This suggests that all of the individuals belonging to the WBRC-based Pareto front are nondominated, or in other words can dominate the RV-based solutions in terms of WBRC. This validates the accuracy of the employed nondominated sorting MOO. In addition, the fact that these two curves get closer to each other around the No-GI point suggests that for the lower LCC, which corresponds to lower implementation of GIs, both optimization sets generate nearly the same results. Since lower LCC corresponds to lower area of GIs, the curves approach each other as WBRC Deficit decreases. However, for all points, the WBRC-based solutions dominate the RV-based solutions in terms of WBRC Deficit, which is consistent with our expectations.

3.4 Environmental benefits provision

Because it is evident the two optimization sets generate different solutions, the Pareto fronts should be compared with respect to the main environmental and stormwater management benefits indices discussed in the previous chapters. An ensemble approach was employed, meaning all of the individuals for both Pareto fronts were used one by one to calculate the environmental benefits metrics of desire. The following subsections compare and discuss the results associated with the four environmental benefits indices of interest.

3.4.1 Evapotranspiration

As expected, the WBRC-based optimum results significantly dominate the RV-based solutions in ET restoration. Specifically, ET values for WBRC-based solutions form a coherent curve (Figure 7), despite the clustered RV-based individuals. A possible explanation for this trend is that ET was part of the optimization process in WBRC-based optimization and was not in the RV-based process. In the WBRC-based set, the ET values ranging from 15.5 to 29 ac-ft distinctly show a better performance than RV-based set by having approximately twice the average ET provision.

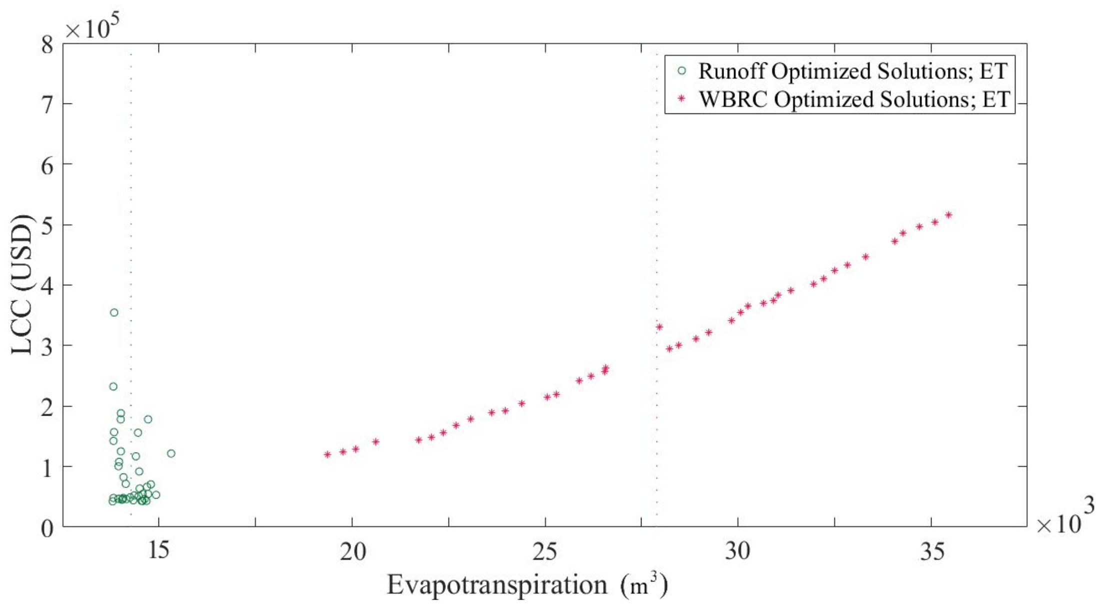

Figure 7. The total amount of evapotranspiration associated with each individual for the both Pareto fronts (dashed lines show the average evapotranspiration values).

3.4.2 Flood protection

The flood protection level is almost the same for both optimization sets, with a slightly better performance from WBRC-based results. The volume of flooded nodes of the drainage system in the RV-based solutions cover a wider range and exhibit an average of more than twice that compared to WBRC-based results. Based on Figure 8a, it is evident that RV-based solutions cover a range of results from near 0 to 6056 litters, and the WBRC-based solutions range from 757 to 3596 litters. However, considering the length of the box and the average line (Figure 8a), it may be concluded that the WBRC-based solutions provide greater protection on average. It should be noted that, because the catchment area was fairly small, and only optimum results are compared, flood values are relatively low.

Likewise, results suggest that RV-based solutions generate a wider range of results (i.e., 0 to 250 hours; Figure 8b). However, the WBRC-based results are concentrated around a smaller range with having approximately 50 hrs less flooded nodes than the average of RV-based results. Overall, the WBRC-based solutions show an acceptable level of performance in comparison to the RV-based results.

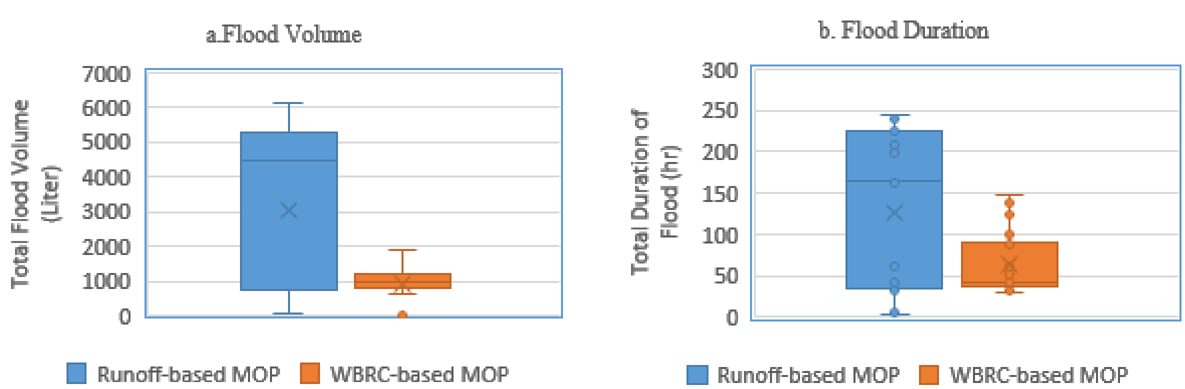

Figure 8. Flood protection analysis: a) the total **volume** of the flood for all flooded nodes for both Pareto fronts; and b) the total **duration** of the flood for all flooded nodes for both Pareto fronts.

3.4.3 Ground water recharge

Focusing on the fresh water provision aspect of the ES categories, it seems that both optimization sets provide the same extent of groundwater recharge, with RV-based results performing slightly better. The GWR percentage of WBRC-based solutions exhibit a range of 2 to 4% (Figure 9); however, the RV-based solutions form a cluster around a constant value of 5.5%. The fact that WBRC-based optimum results formed a range rather than a constant value may be attributed to this variable being part of the goal of the optimization process. Additionally, the greater GWR (1-2% more) for RV-based results may be because catchment infiltration was only 14% of the water budget, preventing greater GWR values. On the other hand, the optimization process for RV-based solutions clearly did not involve GWR or infiltration, and the goal of decreasing runoff as much as possible resulted in higher GWR percentage. Both optimization sets exhibit what may be considered acceptable ranges of GWR contribution.

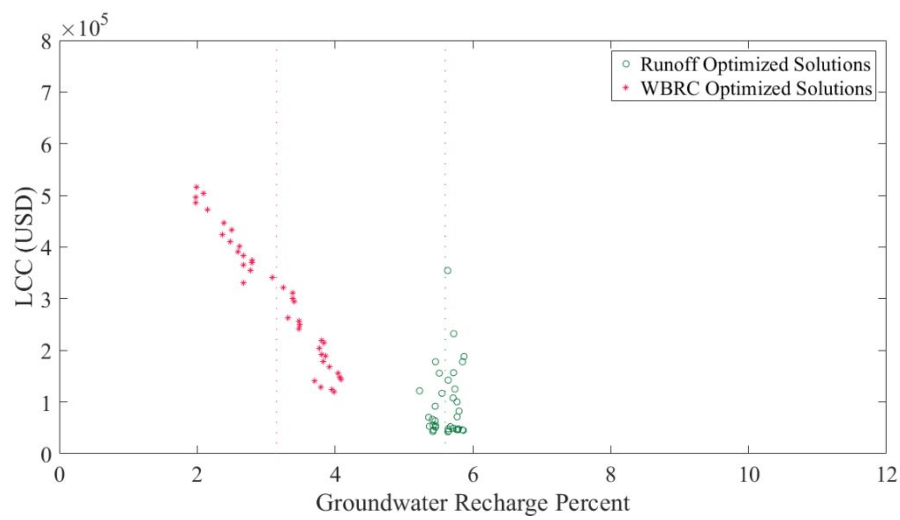

Figure 9. Ground Water Recharge percentage for both Pareto fronts (dashed lines show the average groundwater recharge values)

3.4.4 Stormwater quality (TSS)

WBRC-based optimum solutions captured slightly more TSS than the RV-based solutions. Although the RV-based solutions cover a wider range of TSS removal percentage, the minimum, median, mean and maximum of results exhibit better performance in WBRC-based solutions (Figure 10). Furthermore, running an unpaired two-tailed *T*-test revealed that the results are significantly different, with *p*-value as small as 9.6x10-7. Although the average percentage removal varies by less than 2%, WBRC-based results show better performance than RV with respect to TSS removal.

3.5 WBRC optimum configuration of GIs

All results suggest that WBRC-based optimum solutions provide more diverse and comprehensive hydrological and environmental benefits. The relative role of configuration of GIs is also important. To compare configurations, all optimum solutions were included, and percentage of each three candidate GIs (i.e., PP, BC and GR) were calculated to assess whether any particular GI outperforms others.

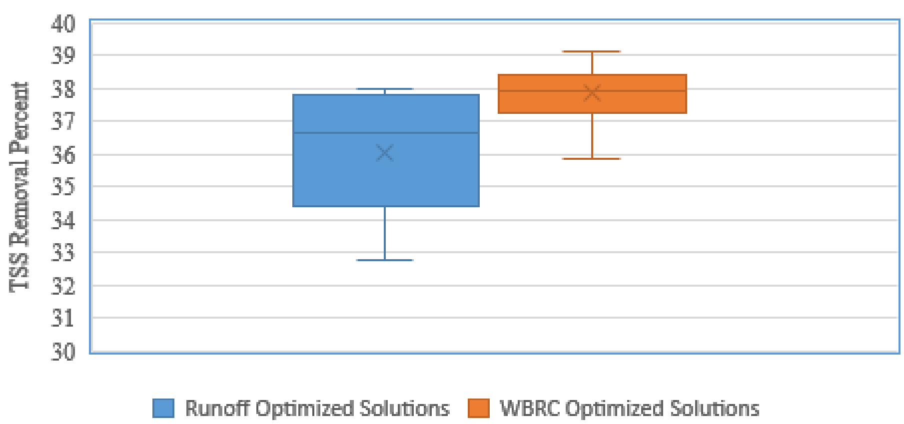

Figure 10. TSS removal percentage by the GIs for both WBRC-based and RV-based optimum solutions.

For all of the WBRC-optimum solution set, an approximately constant contribution of the three selected GIs was observed (Figure 11). Specifically, the results suggest that an average permutation consisting of 72% PP, 13% BC and 15% GR can lead to effective GI plans that provide diverse hydrological benefits. Based on the LCC associated with each GI plan, the LCC of GI plans forming the Pareto front range approximately from 119,000 to 519,000 United States Dollar (USD). Taking the average of LCC values, it can be concluded that the average scenario of 72% PP, 13% BC and 15% GR would cost roughly 304,000 USD. Based on the average GI contribution percentage calculated from the WBRC-optimum solutions, Figure 12 provides an approximate map of the GIs in the studied urban catchment. No significant GIs can be found in the upstream part of the subcatchment, and almost all relatively bigger GIs are concentrated

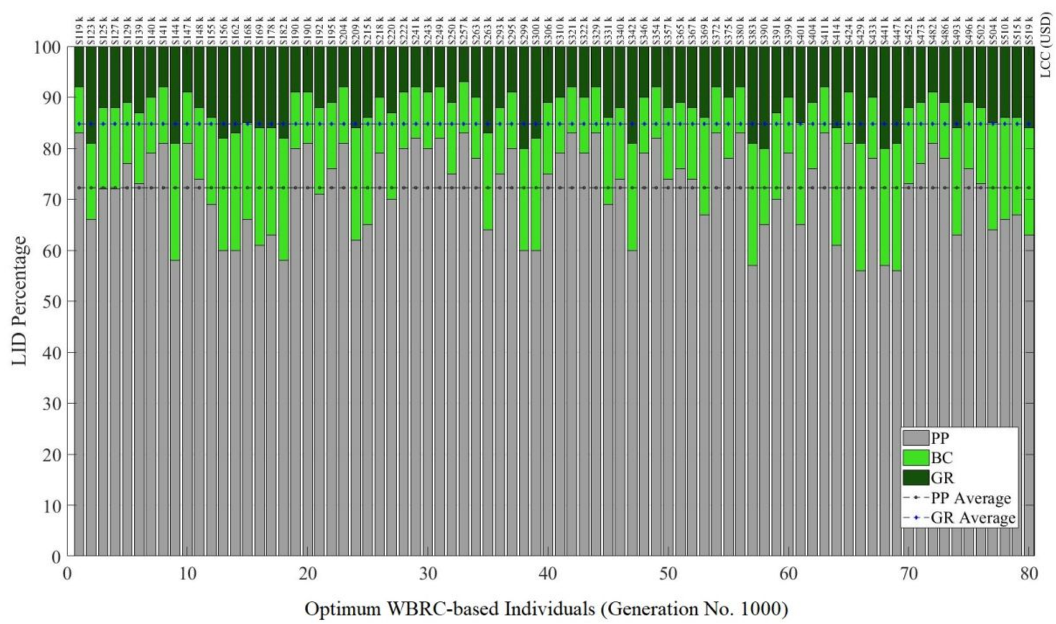

Figure 11. GI configuration of the optimum WBRC-based individuals. Each bar represents an optimum GI plan. Bars are sorted ascending based on LCC.

in the downstream part. By summing up the GI areas and comparing the value to the total area of the catchment, it can be concluded that for this subcatchment, placing GIs in the range of 1.5 to 2% of the subcachment area and more concentrated around the outlet would lead to more ES provision (Figure 12).

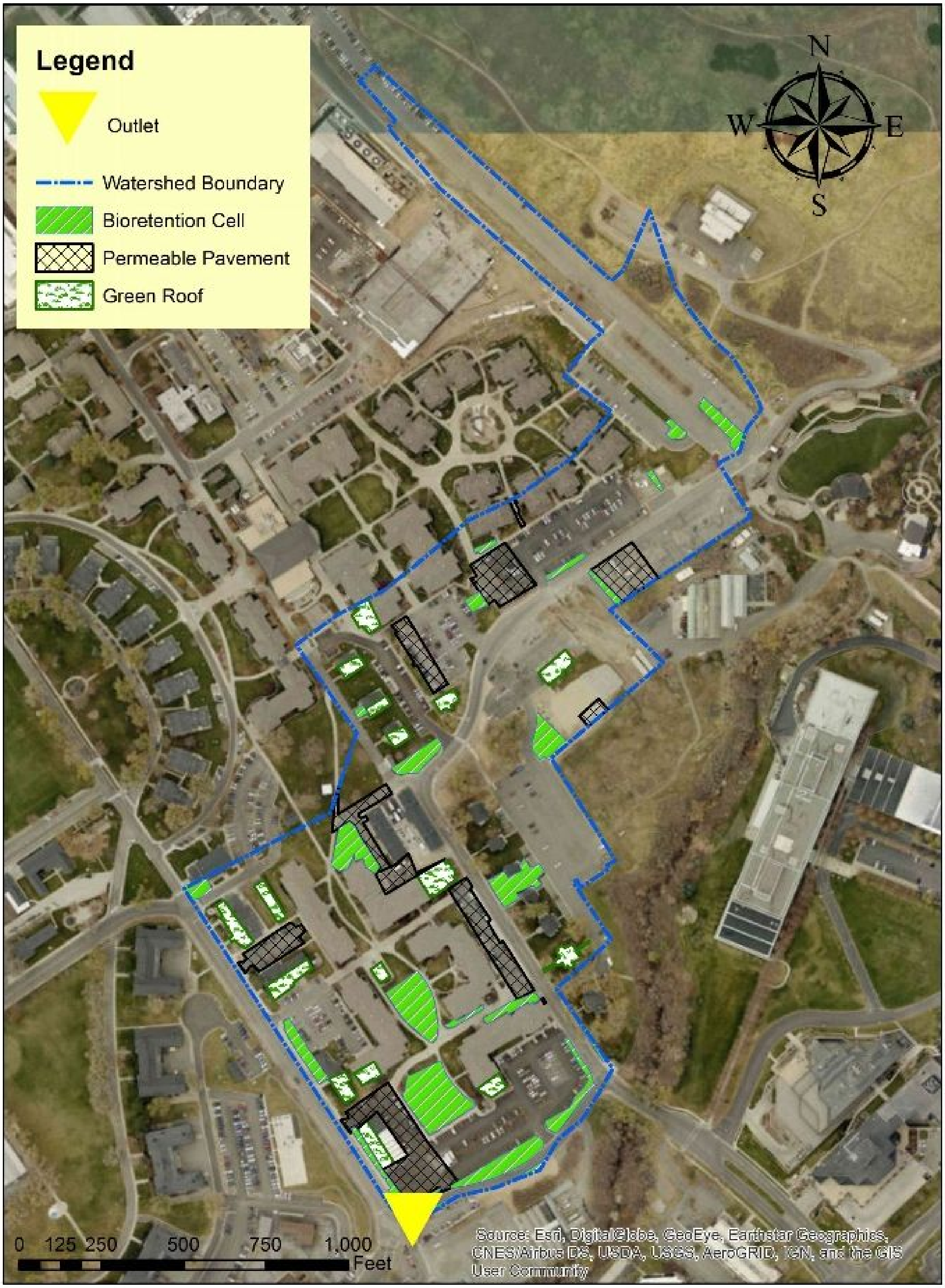

Figure 12. The configuration and distribution of GIs in the WBRC-optimum results.

4. Summary and Conclusions

A major goal of this study was to introduce a novel GI optimization approach utilizing a PDC metric as the objective rather than just runoff reduction. Two independent MOO sets were developed by linking EPA SWMM to NSGA-II in a MATLAB platform: (i) LCC versus WBRC and (ii) LCC versus RV. Then, optimum results were compared in terms of four different yet common categories of environmental and hydrological benefits: ET provision, flood protection, Ground Water Recharge (GWR), and stormwater quality improvement. To accelerate the optimization process, an HTC tool was employed to parallelize the MOOs on a network of computers, which decreased the computation time from months to a few days.

Results showed that WBRC was able to generate 50% more ET than the typical RV goal. This can be eventually translated to improved air quality, reduced heat island intensity, etc. Also, WBRC decreased the average flood duration by 30%, and provided statistically significant more TSS removal. However, WBRC-based optimum GIs showed almost the same level of acceptable performance for flood volume and GWR in comparison to the typical RV-based results. Moreover, WBRC-based optimum solutions suggest that for the studied region, by implementing GIs in the 1.5 to 2% of the entire catchment area and having 72% PP, 13% BC and 15% GR as GI units, it is possible to get closer to PDC, and eventually obtain more hydrologic and environmental benefits out of implemented GIs. The real-world application of the introduced approach may include conducting a similar analysis for an urban catchment, and come up with the diversity distribution of candidate GIs, which have been optimized based on WBRC and LCC; then providing incentives for land developers to implement their required BMPs in a fashion that leads to the desired percentage of GIs, to be able to obtain more hydrologic and environmental benefits. For example, for the studied urban catchment, if the existing implemented GIs are all BCs and GR, incentives should be provided for the developers to implement PPs to reach to the suggested equilibrium values (72% PP, 13%BC and 15%GR).

Future work on this topic may include further investigating the performance of WBRC on a different climate, or in a different scale, by running a similar MOO comparison. Specifically, such a study may consider one or more of the following topics: (i) similar research on the same climate and region, but in a different and possibly bigger urban catchment (ii) on a different geographical location with the same semiarid climate, (iii) in a totally different climate, (iv) inclusion of different LID types, e.g., having only PP and BR, or having Rainwater Harvesting cisterns, (v) performing an uncertainty analysis on the design of GIs in SWMM, specifically having different soil characteristics and climate conditions, (vi) considering societal and other weighting factors to water budget components, (vii) inclusion of more environmental benefits categories, e.g., food provision, erosion control, etc., and lastly (viii) creating a simplified model that has the same level of accuracy as the existing SWMM model to overcome the burden of accelerating the optimization process by HTCondor.

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The introduced hydrologically comprehensive Green Infrastructure design approach excels conventional stormwater runoff reduction goal in terms of common Environmental Benefits.