Sub-catchment Prioritization in a Tropical Watershed for Stream Health Improvement and Low Impact Development Application Using Multi-Criteria Decision Analysis: A Case in Palo, Leyte, Philippines

Sergi Garbanzos
Department of Civil Engineering, De La Salle University

Gessel Mae Abordo
Department of Civil Engineering, De La Salle University

Arvel Art Alde
Department of Civil Engineering, De La Salle University

Janecee Gavan
Department of Civil Engineering, De La Salle University

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Sub-catchment Prioritization in a Tropical Watershed for Stream Health Improvement and Low Impact Development Application Using Multi Criteria Decision Analysis: A Case in Palo, Leyte, Philippines

Sergi Garbanzos[1], Gessel Mae Abordo[1], Arvel Art Alde[1], Janecee Gavan[1], Jaren Kirby Larraga[1], Alyssandra Janine Baylon[1], Kent San Pedro[1], Jayson Cayetano[1], and Marla Maniquiz-Redillas[1]
[1]Department of Civil Engineering, De La Salle University, 2401 Taft Avenue, Malate, Manila 1004, Philippines
sergi.garbanzos@dlsu.edu.ph

Abstract:
The adverse impacts on streams due to rapid development have prompted the development of sustainable urban drainage design such as low impact development (LID). Still, the prioritization of its application remains a challenge. This research aims to create a sub-catchment prioritization scale in a tropical watershed using Multi Criteria Decision Analysis (MCDA) for stream health improvement and LID application in Palo, Leyte, Philippines. Ten sub-criteria under three clusters were assessed under the physical, hydrologic-quantity, and hydrologic-quality groups based on site conditions and benefits of LID. Results from each cluster show different priorities depending on location and parameter: the upstream-midstream is characterized by high slopes and sediment accumulation (5,014 g), while midstream-downstream has high runoff (20.03 mm) and heavy metal concentrations and low infiltration (2.21 mm). The two weight scenarios and performance assessment dictate that the downstream areas should be prioritized, although the initial treatment at the upstream can also prevent degradation downstream.

Keywords: low impact development; multi criteria decision analysis; sediment; stream health; water quality

1. INTRODUCTION

Urbanization is known to have numerous impacts on the stream's hydrology, geomorphology, and even ecology. [1]. Land cover and precipitation have relationships that could adversely affect stream health, causing numerous instances of flooding, bank erosion, and pollutant transport from hazardous chemicals and excess deposited sediments [2]. Untreated diffuse pollution from several sources can impact stream health and even later challenge modern water conservation practices [3]. Due to the changing climatic conditions and rapid anthropogenic development, adaptive urban drainage and sustainable drainage networks have been suggested to handle future risks [4]. Nature-based solutions (NBS), also called low-impact development (LID), are innovative small-scale decentralized measures that aim to mimic the hydrological conditions of pre-developed environments [5], promoting multiple benefits ranging from runoff reduction, improvement of infiltration, and even the treatment of pollutants. LIDs can also capture sediments containing additional contaminants that have a transformative effect on the stream's ecosystem and function [6].

While multiple studies have comprehensively detailed the numerous benefits of NBS and LID controls, knowing the optimal placement is a challenge in implementation. Each site's spatial and climatological variability requires additional assessments, especially if the budget and possible application areas are limited. Various topographic, anthropogenic, and climatological factors need to be considered in assessing each watershed; therefore, prioritization processes may need to be applied first. This also applies to the optimal composition of LID application, which remains an issue. Zhang and Chui [7] state that strategic LID planning is a product of multiple components, from selecting the LID type, sizing of the practices, and determining the location of the application. Comprehensive frameworks that consider numerous factors and optimization methods are still needed to quantify their effectiveness fully [8]. Multicriteria decision analysis (MCDA) was then incorporated into LID-related research for site selection and watershed prioritization [9]. Song and Chung [10] utilized the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to get the priority sub-catchments across ten social, hydrological, and physical-geometric criteria. Wang et al. [11] also used a similar framework considering LID performance, including hydraulic performance, pollution control, cost, and structural resilience. Suitability mapping has also been performed using MCDA methods [12].

There has been an ongoing rise of LID related research over the past decade, but its application on tropical regions is still lacking [13]. Tropical regions experience high rainfall and temperature variability [14], making LID application challenging. Rapid development and the lack of NBS research in these countries would also make LID implementation trickier, considering that their impacts are different from regions with different climates. This research aims to create a sub-catchment prioritization scale in a tropical watershed using MCDA for stream health improvement and LID application in Palo, Leyte, Philippines. Since LID research is still an ongoing topic in the country, the sub-catchments from the upstream to downstream regions were first assessed in the site area regarding their topographic and hydrologic conditions. The prioritization process employed in the study uses both digital and monitored data to reflect physical, sediment, and water quality data, and it also serves as a preliminary assessment of the site's environmental concerns. This study initiates the application of MCDA in LID-related studies in the tropical countries such as the Philippines, which could be used for future research and pilot implementation for optimal placement. The inclusion of additional parameters in the study can help create a comprehensive framework for future manuals for the widescale application of LID controls in the country.

2. MATERIALS AND METHODS

2.1 Study Site

The selected study site is the Palo watershed in Palo, Leyte, the downstream area on the eastern side of the province. The Palo watershed is under a Type IV Philippine tropical climate, which is characterized by even distribution of rainfall throughout the year. The region experiences an average temperature of 24°C to 32°C and annually receives a rainfall of 2,216 mm, which commonly peaks in the months of December to January. A Japan International Cooperation Agency (JICA) report in 2017 [15] has highlighted the flooding that could occur in the catchment's largest stream, Bangon River, although very few studies have tackled issues surrounding the impacts of urbanization on streams in the region.

Five sites near the stream have been assessed, namely Malirong Bridge (MB), Palo West Bypass Road (PWBR), San Salvador Street (SSS), Bernard Reed Bridge (BRB), and Bernard Reed Bridge II (BRB2), a representation of the upstream to downstream regions of Bangon River (see Fig. 1). All locations are classified under transportational land uses, although the downstream regions BRB and BRB2 were also classified under industrial and commercial uses. BRB2 and PWBR were also classified as secondary roads compared to the rest which are primary roads. The monitoring areas have distances ranging from 0.52 to 2.43 km and were selected based on the ease of sediment and stream samples.

Fig. 1. The site areas located in the Palo Watershed

2.2 Criteria Selection

The selection of the criteria was dependent on the site conditions and the components that the application of LID can mitigate and resolve upon application [5]. Ten different criteria were selected based on physical characteristics that could alter hydrologic conditions and parameters that could impact stream quality, from sediment loads and heavy metal concentrations. The criteria further categorized depending on the cluster that they fit into: the physical category containing the sub-catchment slope imperviousness, and location (upstream – downstream), the hydrologic – quantity category relating to the potential runoff and infiltration values during precipitation events, and the hydrologic - quality category depicting the existing stream quality conditions and possible contaminants, particularly sediments and heavy metals (see Table 1). The use of both physical and hydrologic – quantity parameters were based on previous research that also prioritized watersheds [10], while the selection of heavy metals and sediments were based on the potentially toxic metals (PTM) and their sources dictated by Hong et al. [16], and Mehmood et al [17] expounds how it can be treated by LID controls.

Table 1. Selected parameters and their respective categories for MCDA

Category	Parameter
Physical	Slope
	Imperviousness
	Location
Hydrologic - Quantity	Runoff
	Infiltration
Hydrologic - Quality	Sediment Size
	Sediment Amount
	Zinc (Zn)
	Lead (Pb)
	Copper (Cu)

Physical parameters were determined based on locally collected data from government units and were analyzed using QGIS. The hydrologic quantity parameters were estimated based on a rainfall analysis and modeling in Stormwater Management Model (SWMM), a tool for modeling single-event or long-term rainfall simulations in urban and non-urban landscapes for stormwater planning [18]. Results have been focused on the total accumulated runoff and infiltration in each sub-catchment. Manual methods were employed to collect data for the quality component, and laboratory analysis was used to quantify it. Grab sampling was conducted on the stream during dry days and tested in a nearby laboratory to determine the amount of pollutants in the river. Zinc (Zn), lead (Pb), and copper (Cu), which have defined as common contaminants in surface water and runoff [19], were the selected heavy metals for this study and they were tested in the laboratory using Microwave plasma atomic emission spectroscopy (MP-AES). On the other hand, sampling using brooms and pans was used to collect road-deposited sediments in a 1x1 m plot, and sieve analysis was used to determine the grain size distribution. The Spearman correlation analysis was then performed using heavy metal concentrations and sediment weights and their relationship to their respective location. Their relationship was defined by Spearman's rank correlation coefficient r_s, where a value of 1 would indicate that there's a completely positive correlation, while a value of 0 would imply that there's no correlation between the two variables. [20]

2.3 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS method is one of the most widely used MCDA methods, and it has been selected among other known methods as it has the lowest deficit in ranking alternatives [21]. The concept of TOPSIS is based on the minimum and maximum Euclidean distance from the most important and least important ideal values from the other alternatives. These show the positive and negative ideal solutions (see Eq. 1 and 2), and the closeness coefficient of each alternative (see Eq. 3).

$$d_i^{+} = \left(\sum_{j=1}^{m} \left(a_{ij} - a_j^{+}\right)^2 \right)^{1/2} \quad (1)$$

$$d_i^{-} = \left(\sum_{j=1}^{m} \left(a_{ij} - a_j^{-}\right)^2 \right)^{1/2} \quad (2)$$

$$C_i^{*} = \frac{d_i^{-}}{d_i^{+} + d_i^{-}} \quad (3)$$

where d_i^{+} is the Euclidean distance between alternative i and the positive ideal solution, d_i^{-} is the Euclidean distance between alternative i and the negative ideal solution, a_{ij} is the performance value of the jth criterion of alternative i, a_j^{+} and a_j^{-} are the maximum and minimum values of a_{ij}, respectively, and C_i^{*} is the closeness coefficient.

The analysis also adopted two weight determinations for comparison: the entropy weight method and an equal weights scenario. The entropy weight method objectively measures values' dispersion in decision-making processes, creating a degree of differentiation between compared factors [22]. The equal weights scenario, on the other hand, is a representation of the results if all criteria are placed under the same importance. These weights were then multiplied with the respective scores for each category before the relative performance score is obtained. The results from TOPSIS, considering the two weights, were compared with one another, and higher calculated performance scores were deemed sites needing more prioritization.

3. RESULTS AND DISCUSSION

3.1 Hydrologic Analysis

An initial topographic assessment of the site area was first conducted using collected map data from the local government units. Watershed delineation was performed on the site using QGIS to identify the tributaries at each selected site (see Table 2). Slope values were relatively high in the region as the area is mountainous in the upstream to midstream region, and there is a gradual increase in slope as it reaches the coastal regions. High rates of impervious cover were observed along the midstream to downstream areas, peaking at the BRB site, reaching 56.6%. Priority was given to areas with higher average slopes and higher impervious cover, as these could facilitate the build-up and movement of sediments to the stream [23]. For the location criterion, these were numbered from 1 to 5 since these were qualitative, where 1 is the downstream (DS), 3 is the midstream (MS), and 5 is the upstream site (US), with more priority to the upstream regions to prevent the conveyance of pollutants to the downstream areas [24].

Table 2. Sub-catchment characteristics

Site	Area (km^2)	Slope (%)	Impervious-ness (%)	Location
MB	0.49	9.58	11.8	US
PWBR	1.21	3.35	18.6	US-MS
SSS	1.07	6.42	30.1	MS
BRB	0.40	6.31	56.6	MS-DS
BRB2	0.34	2.76	4.33	DS

Rainfall analysis was then conducted by collecting historical data from the site from 1990 – 2012. Since the data collected was represented as cumulative daily data, a probability analysis was used to determine the rainfall percentiles. The Weibull Probability Distribution was utilized in this study to rank the rainfall as used in other studies [13, 25], which uses the highest values in the assessment to prevent underestimation (see Fig. 2). The 90th percentile of rainfall, which was approximately 22.2 mm, and this was further disaggregated into 24 hours for modeling.

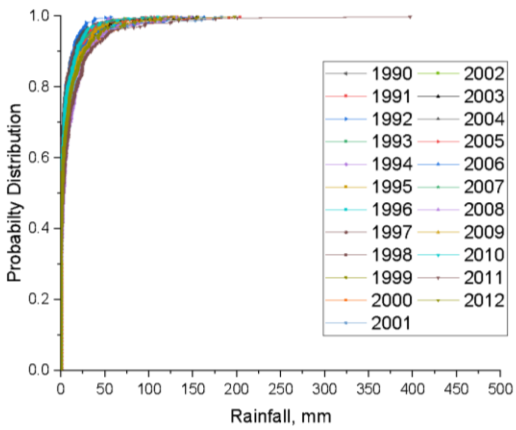

Fig. 2. Weibull probability distribution of historical rainfall

Hydrologic analysis was then performed on the delineated sub-catchments using the disaggregated rainfall data and simulating them in SWMM. This study used Horton's Infiltration Method to compute the infiltration values and used the overland flow computation by Randall [26] and Duarte-Lopez [27]. Due to the empirical nature of the calculation, results favored the regions with higher slopes and impervious cover (see Table 3). The highest runoff values were observed in the BRB site, which had the largest impervious cover, and they also yielded the smallest infiltration rates among all sites. Due to the similar area, slope, and imperviousness of most other sites, the modeled values appeared to be identical. In the MCDA, the highest runoff rates were deemed the best application locations, while areas with the lowest infiltration were set as the priority sites.

Table 3. SWMM simulation results

Site	Runoff (mm)	Infiltration (mm)
MB	17.02	5.28
PWBR	16.22	5.83
SSS	17.83	4.46
BRB	20.06	2.21
BRB2	17.61	4.68

3.2 Sediment Analysis

Sediment analysis in this study focused on assessing collected sediments, in terms of their volume and nominal sizes, in a small plot near the stream areas. Four visits have been conducted in the five site areas for collecting, weighing, and sieving, and the average results have been used in the TOPSIS analysis (see Fig. 3). Collected samples have high variation in each site; some sediment weight samples could be as low as 570 g, as observed in the SSS site, or could reach as high as 9,207 g, as observed in the BRB2 site. Despite being secondary roads, BRB2 and PWBR attained the highest average sediment amounts, at around 3,640g and 5,014g respectively, which could indicate that these locations lack sweeping and monitoring policies, which contributes to sediment build-up. Applying Spearman's correlation to the sediment amount versus the distance from the upstream to downstream areas reveals a non-significant positive correlation between the two variables, generating a r_s equal to 0.0928 and a p-value of 0.7421.

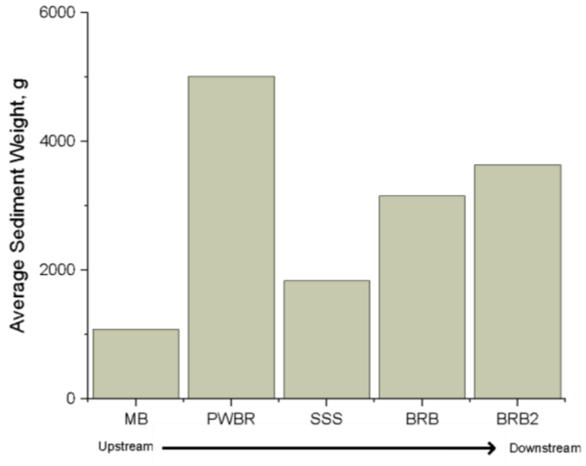

Fig. 3. Average sediment weight per site

The application of grain size distribution analysis (GSDA) on the collected sediment data represents the particle sizes in each site, which could potentially be washed off and contribute to the pollutants in the stream [23]. The characteristics of the road-deposited sediments could be an essential factor in particle mobility and pollutant concentrations, although the environment could also influence these [28]. The collected sediment particles during each of the four visits were taken cumulatively in the GSDA for assessment (see Fig. 4). In determining the critical sediment size, this study adopts the results of Zhao et al. [29], which indicates that the critical size of the sediment particles is <100 µm as they contain more concentrations of metals and other pollutants. This was supported by other studies [28, 30]. However, other research has varying critical size values, such as the findings of Tillinghast, Hunt, and Jennings [31], which dictates that d_{65} is the critical sediment size to limit stream erosion in a watershed in North Carolina as it had the best relationship between sediment size and unit discharge.

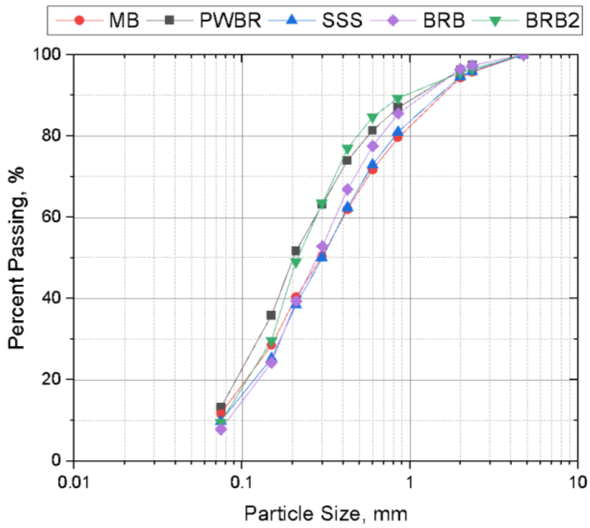

Fig. 4. Grain size distribution of road deposited sediments

In this research, the higher percentage of passing Sieve #100 (0.15 mm passing) would be the priority as it would imply that more pollutants could be transported there. The collected samples' passing percentages were estimated to be 28.51%, 35.84%, 25.25%, 29.63%, and 24.20% for the MB, PWBR, SSS, BRB, and BRB2 sites, respectively. Results here suggest a greater risk of pollutants in the PWBR site than the rest due to the high amount of fine sediments collected, although testing the samples could give a better understanding of the values. The selection of critical sizes in each selected site area is a research gap that could be addressed in future research. Likewise, since sediment may contain additional pollutants that could impair downstream regions and streams [32], analyzing the elemental composition of these sediments may also be researched further.

3.3 Stream Water Quality

Riverine metals such as Zn, Pb, Cu, Cr, Cd, and Ni [16] are commonly found in urbanized streams due to various building materials, and the three focused metals are widely found in traffic-associated land uses [33]. Studies have also indicated that some of these heavy metals come from road deposited sediments [28], which contribute to the heavy metal concentrations in rivers. Testing has shown that there were instances of each selected heavy metal in each portion of the river (see Fig. 5). The largest metal concentration among the three was the Zn metal, which could have come from tire wear in traffic [34]. The protective coating of steel materials such as galvanized pipes and castings also contain Zn [35]; therefore, nearby construction and built-up areas in the region could have contributed to the incoming pollution as well. This was followed by copper, whose source could have been from agricultural land uses [36]. Huang et al. [33] also mention that Zn and Cu could have come from automatic brake pads. While Pb had higher average concentrations than Cu, some samples did not exhibit the presence of Pb after testing as they were below detection limits, and therefore were equated to zero in the assessment. Pb has mainly been associated with gasoline combustion, although literature suggests that all examined elements come from various vehicular sources [34].

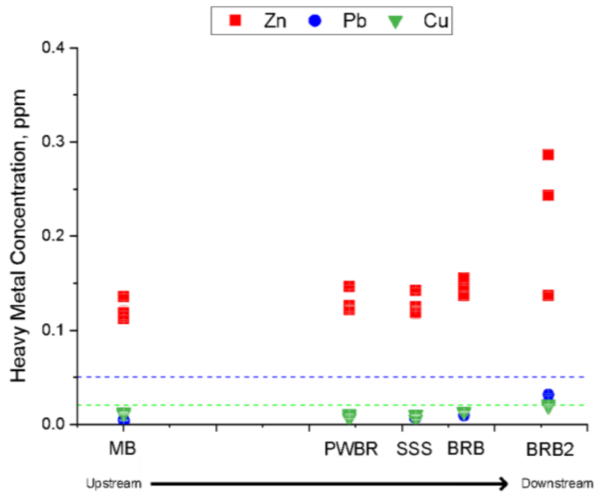

Fig. 5. Heavy metal concentration along various parts of Bangon river

According to the Department of Environment and Natural Resources of the Philippines [37], all sampled values appear to be within safe values. While the zinc concentration is the highest among all tested contaminants, it has a relatively safe value of 2 ppm, whereas the sampled values only range from 0.12 – 0.2 ppm. Lead concentrations are also within safe levels, although copper concentrations have reached the acceptable limit in BRB2 or the downstream region. All observed average values appeared to peak as they reached the downstream areas, which could imply that most of the diffuse pollution upstream is conveyed to the downstream regions. Statistical analysis using Spearman correlation has shown that Zn was the element that had a very strong positive relationship with distance, attaining a r_s of 0.8735 and a p-value of 0.00004. This was followed by the moderate correlation of Cu, having a r_s of 0.5247 and a p-value of 0.05403, and lastly by Pb, having a r_s of 0.4736 and a p-value of 0.08712.

3.4 Multi-criteria Decision Analysis

The computation of the entropy weights was first performed, and these were compared with the equal weight scenario, wherein all ten criteria were given a 0.1 value (see Table 4). Computations have shown that the entropy weights only had slight differences from the equal weight scenario. The highest values were observed in the imperviousness percentage of the site and lead concentration in the stream due to the high variation of data, while other factors maintained a value close to 0.1 also. This could be due to the small number of alternatives presented in the study and from the dataset collected, which could be increased in the following studies. The usage of other subjective decision-making tools such as analytical hierarchy process as used by Wu, Chen, and Lu [38] can also be adopted to show a difference in the weight distribution, which could also affect the final performance scores.

Table 4. Comparison of weights across the ten criteria

Weight Classification		Equal Weights	Entropy Weights
Hydrological - Quality	Copper (Cu)	0.100	0.099
	Lead (Pb)	0.100	0.154
	Zinc (Zn)	0.100	0.097
	Sediment Amount	0.100	0.108
	Sediment Size	0.100	0.095
Hydrological - Quantity	Infiltration	0.100	0.094
	Runoff	0.100	0.093
Physical	Location	0.100	0.109
	Imperviousness	0.100	0.129
	Slope	0.100	0.108

Using the calculated weights, the performance scores were calculated (see Fig. 6). Scores generally had higher values in the downstream region compared to the upstream region, and for both weight scenarios the BRB2 and BRB sites garnered the highest numbers. The high performance of BRB2 was attributed to its relatively high impervious cover compared to the rest of the sites and, consequently, its low infiltration due to the development. While the scores for most parameters were low, BRB also attained the largest score using the entropy weights as they had the highest average water contamination values from Pb, Cu, and Zn, significantly raising their overall priority from the computation. For the other sites, PWBR only dominated in the sediment amount category, while the MB site upstream only attained the best values in terms of its slope and location.

While MCDA results have denoted that the downstream areas are the areas of priority in the site, few studies have recorded the impact of downstream LIDs in controlling runoff and peak flows. Upstream applications based on previous studies have had better results in reducing runoff and treating pollutants, which alleviates the potential impacts on the downstream catchments [24, 39]. The large heavy metal concentrations could be treated in the upstream regions before they are conveyed downstream [40]. Understanding the possible impacts in the upstream and downstream areas could help develop a framework that could function in multiple spatial scales [41] and, therefore, may be utilized in subsequent research.

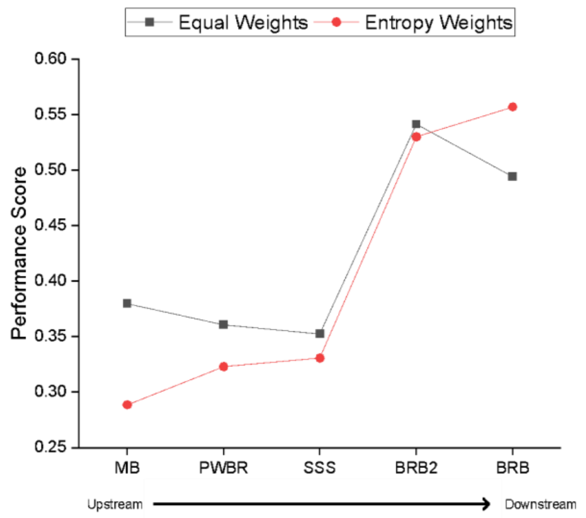

Fig. 6. Performance score comparison between the two weight scenarios

3.5 Implications on LID selection and watershed management

Understanding site conditions can help in the selection of LID application in the site. Eckart, et al [42] has dictated that there are two categories of LID techniques: infiltration-based techniques and retention-based techniques. Results from their review have shown that all LID controls have impacts on the hydrology of site, reducing runoff and improving infiltration particularly those under infiltration-based techniques. Swales, biofilters, and rain gardens have been given attention in multiple other studies as they have significant pollutant reduction rates, particularly in heavy metals and sediments [43], which have high concentrations in the site. In the urbanized Palo watershed, the application of retention-based rainwater harvesting systems on built roofs may also have significant contributions to the reduction of runoff, a topic that was initially explored by Co, et al [44] in the province of Leyte, while providing additional benefits on rainwater reuse. The usage of combined LID practices that cater to the characteristics of a specific site also improves the respective performances of the LIDs [45]. However, the selection of the optimal LID control for placement in the site may require additional analysis on site characteristics, environmental conditions, and the construction of pilot scale studies to assess their effectiveness.

The complexity of urban stormwater management currently transcends just the prevention of flooding and controlling runoff rates, as other concerns from high concentration of runoff pollutants, channel erosion, changing temperatures, groundwater recharge, accumulation of suspended sediment loads, and sewerage overflows, to name a few, have heavily impacted urban environments [41]. The concept of incorporating environmental dynamics into urban planning is currently being introduced in watershed management although this has not been addressed by tropical regions, where the impact of climate change is most felt. While the application of MCDA techniques on tropical spatial scales is still scarce, several studies have attempted this methodology through the identification of erosion-induced land [46] and mapping groundwater potential zones [47]. The research on the combined use of MCDA and LID could help improve the current policy on sustainable urban planning, floodplain management, and environmental concerns.

4. CONCLUSIONS

This study was able to prioritize the sub-catchments in a tropical watershed using TOPSIS and two weight scenarios. The assessment of the site's current topographic and hydrologic data shows the variation of environmental conditions across the stream's vicinity, with the ‘worst’ scenario alternating between each sub-catchment. The topographic analysis in the region has shown that Palo has a slopy terrain and has undergone significant development exacerbating the changes in the area’s hydrology, as presented in the high runoff and low infiltration values. While most heavy metal concentrations in the area were within acceptable conditions, collected data implies the need to start the treatment of diffuse pollution. The lack of sediment control measures has caused a large build-up of RDS in each catchment, which also contributes to the diffuse pollution in the stream. MCDA results have favored the downstream areas for prioritization from the preliminary data collected, even though the optimal placement of LID controls is at the top of the catchment to prevent the accumulation of pollutants downstream. Considerations for this issue should be researched in future research. Additionally, various factors should still be considered in constructing LID controls, including available space, cost, and other water quality parameters. At the same time, relevant socio-economic considerations could also be included in future analyses.

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