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Prioritization and Analysis of Watershed: A Study Applied to Municipal Solid Waste

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Abstract: This paper shows a watershed prioritization analysis applied to municipal solid waste. The study area was the macrowatershed "Cañón del Sumidero", in the state of Chiapas, Mexico. Geographic information systems, multi-criteria evaluation techniques, as well as several geomorphometric, land use, vegetation and waste management variables were used. The results indicate that, of the set of watersheds analyzed (4 subwatersheds and 80 microwatersheds), only 14 (2 subwatersheds and 12 microwatersheds) have high priority, since they are severely affected by the mismanagement of solid waste. This is also due to the major presence of urban settlements, which are places with different dynamics in terms of population growth, migration, as well as access to infrastructure and services, such as collection and final disposal of waste. Additionally, the incidence of certain biophysical and geomorphometric variables, such as steep slopes, high rainfall and high drainage density, among others, exacerbate the waste-related problems. The remaining watersheds (2 subwatersheds and 68 microwatersheds) showed moderate or low prioritization values because of the low amount of solid waste produced there. Finally, this work concludes that the regionalization of municipalities and the management of solid waste through decentralized operating agencies can help solve solid waste management problems since this approach would permit to delegate non-primary activities from watershed operating agencies to other specialized waste agencies.

Keywords: geographic information systems; municipal solid waste; prioritization; spatial analysis; watershed approach

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1. Introduction

Watersheds are natural surface units that delimit the landscape through divisions and channel rainwater to rivers, streams and eventually to an exit point, such as reservoirs, the ocean or infiltration. They include watersheds of a lower order (subwatersheds and microwatersheds) and morphologically differentiate their various parts [1,2].

Watershed studies have great relevance today, since concepts such as watershed approach, watershed management or healthy watersheds permit to build an integrating axis of the territory, where different (social, economic, biophysical or cultural) elements of the environment interact harmoniously. The participation of different actors such as the government, private companies and society is also sought [3–5].

As regards territorial planning, watershed studies seek to integrate use of soil, water, flora and fauna in order to establish conservation areas and to promote the sustainable use of resources (see [6–8]). Regarding natural risk, these studies focus on coordinating efforts to establish priority attention zones in case of contingencies, such as landslides or floods (see [9–12]). Finally, as regards environmental impacts, the studies are aimed at solving problems of contamination of surface, groundwater and soils, derived from multiple activities carried out within the watersheds (see [13–17]).

One of the currently most relevant topics is municipal solid waste (MSW). This issue is addressed through diagnostic studies in various parts of the world (see [18–21]). Studies are also often carried out to quantify waste (see [22,23]), as well as to optimize collection routes and locate treatment or final disposal infrastructure (see [24–27]). Unfortunately, there are few MSW works carried out with a watershed approach, with the participation of watershed operators and municipal bodies that jointly structure waste management policies. This is due to the fact that MSW management schemes are commonly rigid, each municipality or locality being responsible for storing, collecting and disposing of its wastes, regardless of its location within a hydrographic watershed. In fact, according to Silpa et al. [28], in most countries, MSW management is a local responsibility by default or through decentralization policies. Therefore, the direct participation of central governments or watershed operators in waste management services, as well as regulatory oversight, is rare.

Despite the above, it is essential to develop MSW projects within watersheds, mainly due to the interactions between the waste and the biophysical components of the environment, which can cause great damage to the watersheds. One of the most used tools in watershed studies is prioritization, which has gained importance in the management of natural resources [29]. This tool is also used as a pre-decision step and is useful for identifying the most vulnerable parts of a watershed [30]. Prioritization has not yet been used for MSW management. According to Olguín and Pineda [31], the prioritization of watersheds refers to the classification of hydrographic units according to the order in which they must be attended, based on a goal or objective set by decision makers.

The literature on the use of this tool is quite extensive. Geomorphometric parameters are commonly used to obtain preliminary results regarding the characteristics of the territory [32]. In the studies by Badar et al. [33], Javed et al. [34], Puno and Puno [35], Rahmati et al. [36] and Singh and Singh [37] other parameters, such as land use, vegetation and socioeconomic factors have also been used, which permit to understand the relationship between the territory of the watersheds and the activities that affect them.

This paper shows a watershed prioritization analysis applied to MSW management. Geographic information systems (GIS) and multicriteria evaluation (MCE) methods are used. Initially, a prioritization index is constructed based on an analysis of morphometric, land use and vegetation parameters, as well as MSW management technical parameters. Subsequently, using the created prioritization index, an analysis is carried out at the level of subwatersheds and microwatersheds that belong to a larger watershed in the state of Chiapas, Mexico. The results obtained will serve for decision making in the prioritization of areas to implement conservation programs and projects in the study area. They will also serve as base research to develop future work.

2. Materials and Methods

2.1. Description of the Study Area

The Cuenca del Cañón del Sumidero (CCS) is a watershed located in the state of Chiapas, in the southeastern part of Mexico, between the coordinates 15°56′55′′ and 16°57′26′′ north latitude and 92°30′44′′ and 93°44′35′′ west longitude (Figure 1). The CCS has a territorial extension of 6700 km^2, covering 24 municipalities, 2847 localities (2816 rural localities and 31 urban localities), 4 subwatersheds and 80 microwatersheds of interest [38,39]. It is important to mention that the localities have a high spatial dispersion, particularly in the largest subwatersheds.

The CCS is of great biological importance. According to spatial data from CONABIO [40], the study area has 1842.66 km^2 of priority terrestrial sites, categorized as medium, high or extreme priority. There are also 1662.26 km^2 of protected natural areas, such as national parks, biosphere reserves or forest protection zones. Sightings of several species of amphibians, birds and mammals have been made in these areas of natural importance, particularly in the north, northeast and southwest of the CCS, over areas that have high forest cover. To the north of the CCS is a protected natural area of great scenic beauty, known as the Cañón del Sumidero National Park, where there is a habitat for 1736 species, of which 28 are threatened, 43 are subject to special protection, 6 are in danger of extinction and 34 are endemic [41].

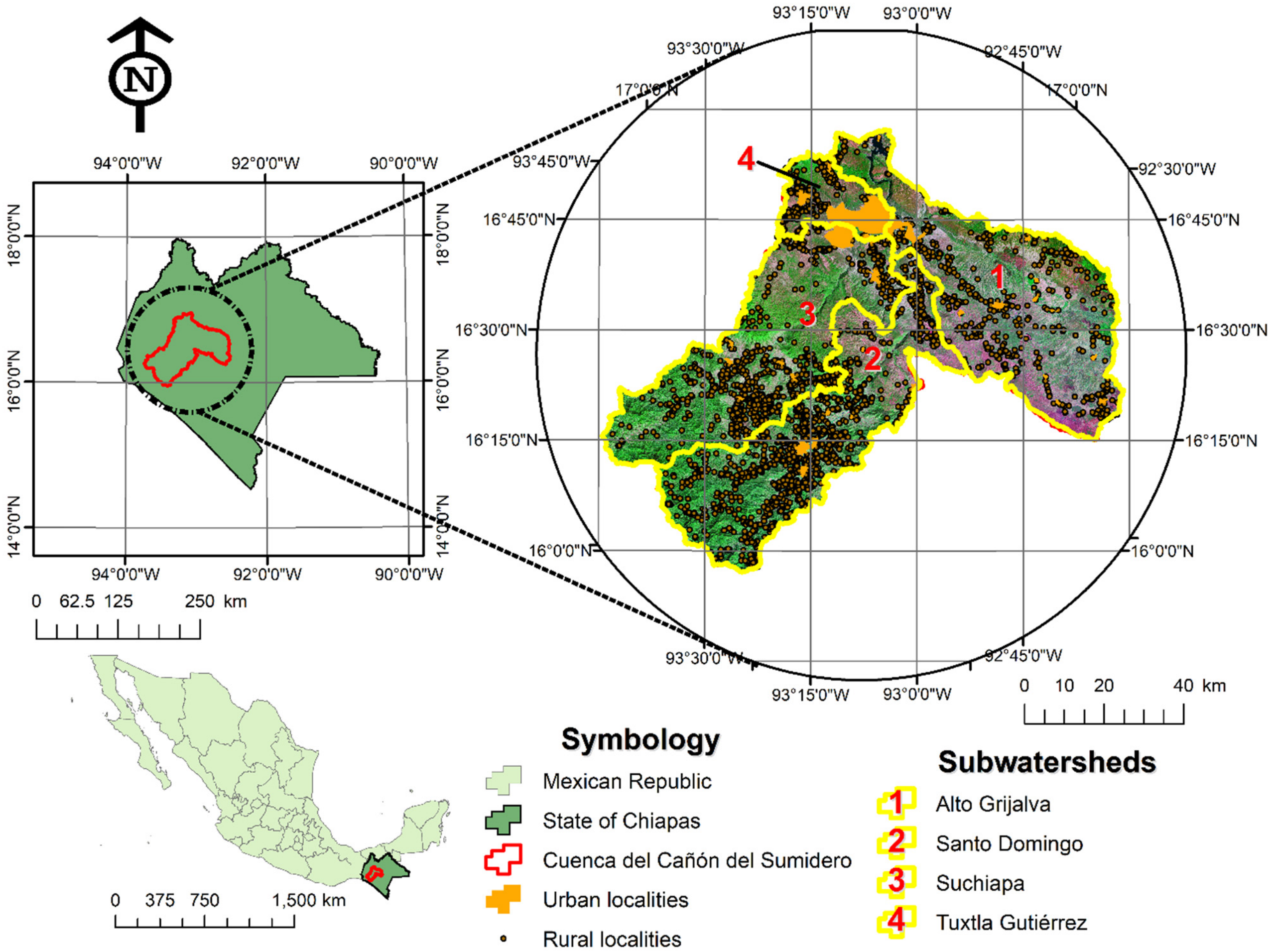

Figure 1. Study area.

CCS is also important because it promotes the development of society and the economy. The "Manuel Moreno Torres" hydroelectric dam (Chicoasén), which produces energy for Mexico, is located there. In addition, agricultural, tourist and industrial development poles have been installed in its surroundings. Unfortunately, the CCS also has severe environmental problems. In the studies by Castañón and Abrajan [42] and Ecobiosfera [43], problems of contamination of main and secondary rivers due to wastewater discharge are addressed. Regarding MSW, Araiza et al. [44] and López [45] detail impacts in various municipalities and localities of the CCS, especially due to the dragging of waste in the rainy season.

2.2. Description of the Prioritization Index

Three types of parameters and nine variables were used to construct the watershed prioritization index. These parameters and variables are important because they participate in MSW production, movement or dispersion processes.

The geomorphometric parameter included 3 variables. The first one is the slope (Slp), which is an important variable in hydrological studies because it is related to water runoff and erosive processes in the soil [36]. In waste management, Slp has a direct influence on the evacuation or movement of leachates and on the dispersion of solid materials [46]. On steep slopes, leachate and solid materials tend to move beyond where they were generated, while they tend to remain stationary on light slopes. The second variable of the geomorphometric parameter is the density of drains (Dd), which is a quotient between the total length of the water courses (perennial, intermittent and ephemeral) of a watershed and its own area [47]. Dd is also related to the dragging of waste deposited in ravines, especially in watersheds with large urban settlements that are crossed by several watercourses. The compactness index (Ci) is the third variable of the geomorphometric parameter. According to Gravelius [48], Ci compares the length of the perimeter of the analyzed watershed with the circumference of a circle of the same size as the watershed. Ci is related to MSW by the degree of dispersion and carryover of wastes that can occur along elongated watersheds, compared to flattened watersheds.

The biophysical, land use and cover parameter included 3 variables. Land use and cover (LULC) is the first variable of interest. LULC refers to the degree of occupation of the land surface by some type of vegetation, but also by assignments derived from human activity [49]. LULC is related to MSW due to changes in land use that can occur in watersheds, especially the growth of human settlements, which produce greater amounts of waste. The other two variables that make up the analyzed parameter are biophysical. Precipitation (Pr) is commonly related to increased levels of surface water pollution [13]. Pr also influences the dragging of improperly deposited waste and may lead to a higher rate of leachate production within the final disposal sites. Finally, lithology (Lt) refers to the type of rock and processes related to them. Lt affects both permeability and erodibility and in addition, it plays an important role in the groundwater contamination process by liquid discharges such as MSW leachates.

The waste topic parameter used 3 variables that describe the most important stages of MSW management, such as production, collection and final disposal. The first variable is the generation of waste (Wg), which refers to the rates of waste production within the human settlements of the study area. According to Araiza et al. [44], population settlements with high population density, due to their intrinsic nature, are the ones that produce the greatest amount of waste, but sometimes they are also the ones that have the greatest problems associated with waste management. The second variable is the level of waste collection coverage (Wc), which refers to the number of localities or inhabitants served in relation to all of them [50]. Less efficient waste collection causes improper disposal, for example, in vacant lots or water bodies. Finally, the waste dumping method (WDm) refers to the technology used to eliminate solid waste in the municipalities of the study area. Commonly there are 3 modalities of final waste disposal. The first modality, the sanitary landfill, has control structures for landfill leachate, gases and others, preventing serious environmental impacts. The second modality is the controlled site, which has partial infrastructure to control emissions, for example, controlled site access or frequent waste coverage. The third modality is the open-air dump, which is so called because it does not comply with the regulations and therefore causes severe environmental and social damage.

2.3. Construction of the Prioritization Index

In order to build the prioritization index, the MCE technique called the Analytic Hierarchy Process (AHP) was used in the GIS environment. This technique was developed by Saaty [51]. Its mathematical function is shown in Equation (1), where $P(C_i)$ is the prioritization value in the analyzed watershed, $v(c_{ik})$ is the value function, w_l is the weight associated with the l-th criterion (l = 1, 2 . . . , p) and $w_{k(l)}$ is the weight assigned to the k-th sub-criterion associated with the l-th criterion.

$$P(C_i) = \sum_{k=1}^{n} w_l w_{k(l)} v(c_{ik}) \quad (1)$$

The hierarchical scheme of this MCE technique consists of 3 levels: goal, decision criteria (usually accompanied by sub-criteria) and alternative solutions (analyzed watersheds) (Figure 2). The first level symbolizes the main objective to be achieved, i.e., it represents the prioritization of watersheds related to the MSW problem in the study area. The second level corresponds to the components to perform the prioritization, i.e., the morphometric, coverage and land use parameters, as well as MSW technical parameters. Finally, in the third level, all the variables that evaluate or characterize the prioritization components are grouped.

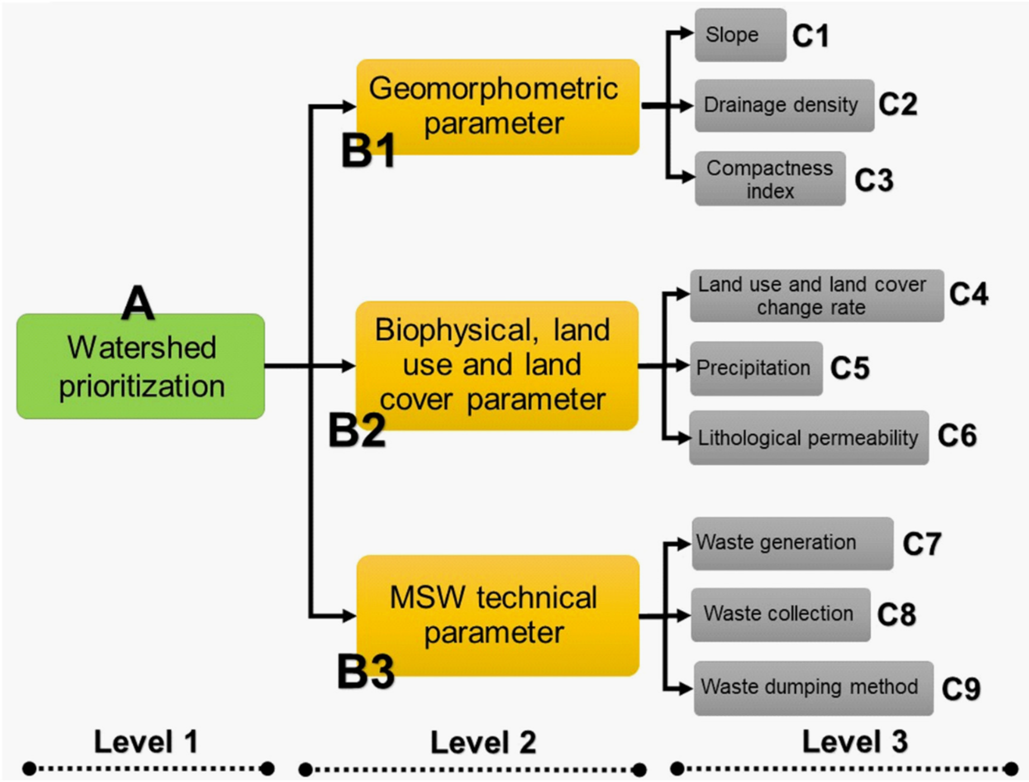

Figure 2. Hierarchical structure of the prioritization index.

The elements of each hierarchical level were weighted using the pairwise comparison of Saaty [51], which begins with the determination of the importance values of each element analyzed. Table 1 shows the reference scale of the importance values used, where each number indicates the relative importance of an element. This process is iterative since each author of this manuscript contributed with their experience and knowledge to adjust these values through expert panel sessions.

Table 1. Saaty's pairwise comparison scale.

Numerical Value	Verbal Judgment
1	Equally important
2	Slightly more important
3	Moderately more important
4	Moderately to strongly more important
5	Strongly more important
6	Strongly to very strongly more important
7	Very strongly more important
8	Very strongly to extremely more important
9	Extremely more important

According to Malczewski and Rinner [52], the pairwise comparison is commonly organized in matrices $C = \left[C_{kp}\right]_{nxn}$, where C_{kp} is the score for the k-th and p-th element to evaluate. It should be noted that C is reciprocal, which means that $C_{kp} = C_{kp}{}^{-1}$ and all the entries in the main diagonal are 1. Given that property of the matrix, only $n(n-1)/2$ paired comparisons are necessary for an $n \times n$ matrix. Once the comparison matrices of each hierarchical level are finalized, a vector of weights $w = [w_1, w_2, \ldots, w_n]$ is obtained, and the final weights are determined as a unique solution to $Cw = \lambda_{max}w$. The Equations (2) and (3) are used within the "C" matrices to normalize to each element C^*_{kp} and approximate the weights w_k.

$$C^*_{kp} = \frac{C_{kp}}{\sum_{k=1}^{n} C_{kp}}\ ,\ for\ all\ k = 1,\ 2, \ldots,\ n. \tag{2}$$

$$w_k = \frac{\sum_{k=1}^{n} C^*_{kp}}{n}\ ,\ for\ all\ k = 1,\ 2, \ldots,\ n. \tag{3}$$

Note that prior to using the final weights within Equation (1), it is necessary to analyze the logical consistency of the "C" matrices. This is done through the Consistency Ratio (CR) and the Consistency Index (CI), which are calculated using the Equations (4) and (5). In these equations, λ_{max} is the maximum eigenvalue obtained from the matrices "C", RI_n is a random index obtained from tables, and n is the order of the matrix used.

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \tag{4}$$

$$CR = \frac{CI}{RI_n} \tag{5}$$

According to Saaty [51], values of CR < 0.1 indicate a reasonable level of consistency in the comparison matrices. Values of $CR \geq 0.1$ indicate inconsistent judgments, therefore, the "C" matrices must be adjusted by means of corrections in the importance values of each element. Table 2 shows the final weights obtained.

Table 2. Weights of each element within the hierarchical scheme of the prioritization index.

Level 1	Level 2 [1]	Weight	Level 3 [2]	Weight
A	B1	0.17	C1 C2 C3	0.45 0.48 0.07
	B2	0.09	C4 C5 C6	0.79 0.13 0.08
	B3	0.74	C7 C8 C9	0.68 0.20 0.12

[1] CR of the parameters = 0.024. [2] CR of B1 variables = 0.003; CR of B2 variables = 0.041; CR of B3 variables = 0.037.

In order to normalize the value functions $v(c_{ik})$ of each variable used within the watershed prioritization index, a simple assessment was used with values ranging from 1 to 5, where the smallest number corresponds to the most unfavorable condition, while the largest value corresponds to the most favorable condition. The values adopted for each variable are shown in Table 3.

Table 3. Normalized values of each variable used.

Variable		Levels/Classes	Nv [1]
C1	Slope	<1°	1
		1–10°	2
		10–20°	3
		20–45°	4
		>45°	5
C2	Drainage density	<0.3 km/km^2	1
		0.3–1 km/km^2	2
		1–2 km/km^2	3
		2–4 km/km^2	4
		> 4 km/km^2	5
C3	Compactness index	Kc = 1.00–1.25	1
		Kc = 1.25–1.50	3
		Kc = 1.50–1.75	5
C4	Land use and land cover change rate	0.00–1.00%	1
		1.00–2.00%	2
		2.00–3.00%	3
		3.00–4.00%	4
		4.00–5.00%	5
C5	Precipitation	800–1000 mm/year	1
		1000–1100 mm/year	2
		1100–1200 mm/year	3
		1200–1300 mm/year	4
		>1300 mm/year	5
C6	Lithological permeability	Low level	1
		Medium level	3
		High level	5
C7 [2]	Waste generation	< 50 Tons/day	1
		50–100 Tons/day	2
		100–200 Tons/day	3
		200–500 Tons/day	4
		>500 Tons/day	5
C8	Waste collection	High waste collection coverage: >80%	1
		Medium waste collection coverage: >60%	3
		Low waste collection coverage: <25%	5
C9	Waste dumping method	Sanitary Landfill	1
		Controlled site	3
		Open dump	5

[1] Nv = Normalized value. [2] The values of the levels or classes of C7 decrease 10 times in the analysis at the microwatershed level.

2.4. Techniques and Data Used to Build the Variables

It is important to mention that the construction of the variables in the GIS environment was carried out through databases, digital cartography, satellite images and geoprocesses such as Buffer or Intersect. CEIEG [53], INEGI [54], INEGI [55] and UNAM [56] provided small-scale digital cartography (1: 250,000), as well as digital elevation models and processed satellite images. Araiza et al. [57], CONAGUA [58] and INEGI [59] provided tabular databases. The techniques used for the construction of variables are shown in Figure 3.

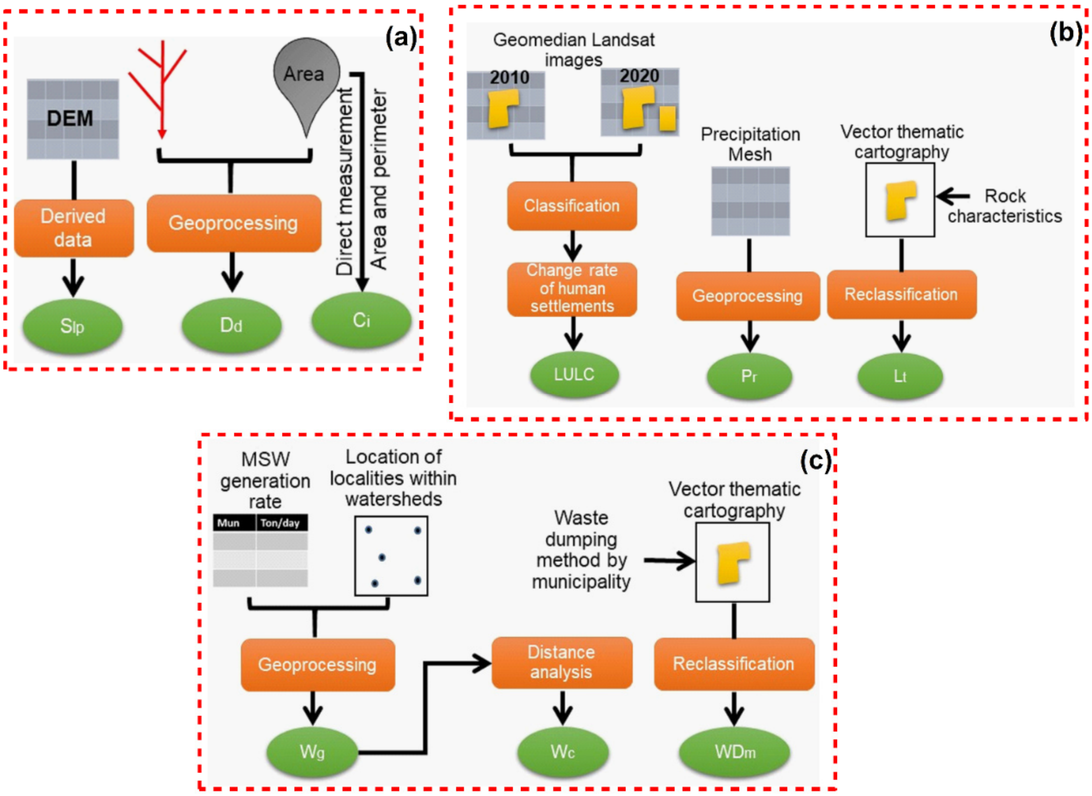

Figure 3. Variable construction procedure: (**a**) geomorphometric parameters; (**b**) biophysical, land use and cover parameters; (**c**) MSW technical parameters.

3. Results and Discussion

3.1. Comments about Parameter and Variable Weights

As previously indicated, three types of parameters were used in the construction of the prioritization index. The MSW management parameter was assigned the highest weight through expert panel sessions (Table 2). This was due to the fact that the variables related to this parameter commonly trigger severe damage to humans and the environment within the watersheds. Such affectations are described in detail in Araiza [46] and Butt et al. [60]. They are even often referred to as risks associated with MSW management.

On the other hand, the other parameters and their variables only function as amplifiers or damage regulators, so their weights are lower than the MSW management parameter. Note that the weighting is also related to the objective or focus of the prioritization. For example, CONAGUA [38] conducted prioritization studies to promote sustainable development activities and improve the social and economic context of the CCS. However, in this work the prioritization is directed in another direction, since initially it is intended to detect damaged watersheds, so that in later stages, conservation programs and projects can be implemented in the study area, but in terms of MSW management.

3.2. General Analysis of the CCS Watershed

The study area is made up of four rivers of great importance that give their names to several of the subwatersheds analyzed (Grijalva, Santo Domingo, Suchiapa and Sabinal). There is also a hydrographic network of just over 3700 km of secondary and tertiary channels, which make up the 80 microwatersheds of interest. The Tuxtla Gutiérrez subwatershed (SW1), whose main river is the Sabinal, is the smallest of the four subwatersheds, with an area of only 391.70 km^2. In addition, it is made up of four microwatersheds of interest. The Alto Grijalva (SW2), Suchiapa (SW3) and Santo Domingo (SW4) subwatersheds have similar territorial extensions (2236.63 km^2, 2050.79 km^2 and 2020.89 km^2, respectively). Together, these subwatersheds occupy 94.15% of the study area and include 76 of the analyzed microwatersheds.

In terms of the prioritization analysis, Figure 4 and Table 4 show a summary of the values obtained by subwatersheds and microwatersheds. Note that SW1, despite being the smallest, is the one with the highest prioritization values (Figure 4a). This occurs because the microwatersheds forming it are mostly urban, i.e., they are places that have different dynamics in terms of population, migration and access to infrastructure, among others. In addition, the incidence of certain biophysical and geomorphometric variables exacerbate the situation regarding MSW management.

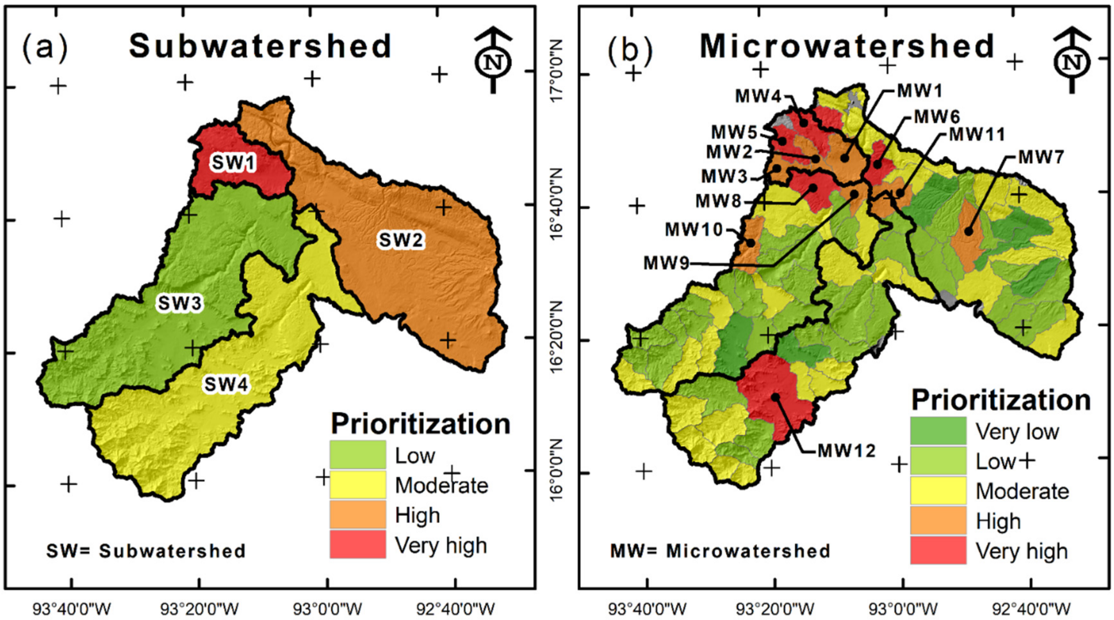

Figure 4. Prioritization of the study area: (**a**) subwatershed level; (**b**) microwatershed level.

SW3 and SW4 have a prioritization value that ranges from moderate to low, which is in accordance with the value of most of their microwatersheds. SW2, on the other hand, has a high prioritization value, although its microwatersheds mostly do not. Note that there are microwatersheds with high prioritization values, which is due to the fact that they are also highly urbanized. In total, 12 microwatersheds with high prioritization values were identified (Figure 4b). The remaining 68 microwatersheds have moderate or low prioritization values, so in terms of MSW management, it is presumed that they do not have severe difficulties.

3.3. Detailed Analysis in Subwatersheds and Microwatersheds

Due to the location of the CCS within the physiographic context of Chiapas, Mexico, where there are plains and mountains, it is possible to find elevations that range between 230 and 2700 m above sea level over relatively short distances. This causes varied terrain geoforms with slopes between 2° and greater than 45°, as well as significant fluvial dissection (average Dd of 1.88 km/km^2) and, therefore, the presence of watersheds with elongated shapes (Ci > 1.5).

The most important waste-related aspects occur within the microwatersheds and their population settlements. Regarding the variable Slp, both inside and outside urban and rural localities, there are flat areas and areas with steep slopes (Figure 5a). This causes the movement and dispersion of low volumetric weight waste, such as paper, bags and plastic bottles, which reach great distances and then accumulate on the banks of rivers and ravines in the study area. These wastes are commonly exposed to view in the rainy season.

Table 4. Values of variables found in the analyzed subwatersheds and microwatersheds.

Watersheds	Dd (km/km^2)	Slp (Degrees)	Ci [1]	LU/LC Change Rate (%)	Pr (mm/Year)	Lt [2]	Wg (Tons/Day)	Wc [2]	WDm [2]
SW1	1.25	7.13	1.66	1.63	1015.93	Mostly medium level	799.05	Mostly high level	Mostly in open dumpsite
SW2	1.72	9.04	1.81	4.00	1203.51	Mostly high level	156.52	Mostly low level	Mostly in open dumpsite
SW3	1.88	10.71	2.04	3.56	1066.40	Mostly low level	78.25	Mostly low level	Mostly in controlled site
SW4	2.14	11.50	2.31	2.93	1200.80	Mostly low level	93.18	Mostly low level	Mostly in open dumpsite
MW1	1.54	7.82	1.41	0.78	1026.62	Mostly medium level	679.51	Mostly high level	Mostly in sanitary landfill
MW2	1.47	6.81	1.89	2.07	973.04	Mostly medium level	93.10	Mostly high level	Mostly in sanitary landfill
MW3	1.30	5.03	1.80	8.60	979.93	Mostly medium level	10.45	Mostly medium level	Mostly in open dumpsite
MW4	0.96	8.67	1.70	3.79	1092.17	Mostly high level	25.13	Mostly medium level	Mostly in open dumpsite
MW5	1.21	5.42	1.68	3.34	1012.15	Mostly medium level	31.92	Mostly low level	Mostly in open dumpsite
MW6	1.80	10.25	1.51	3.21	1075.16	Mostly medium level	64.68	Mostly high level	Mostly in open dumpsite
MW7	1.94	7.28	1.55	3.37	1056.98	Mostly medium level	11.59	Mostly medium level	Mostly in open dumpsite
MW8	1.77	6.80	1.48	5.23	977.75	Mostly medium level	55.90	Mostly high level	Mostly in sanitary landfill
MW9	1.48	4.74	1.49	4.05	1063.07	Mostly high level	15.64	Mostly low level	Mostly in sanitary landfill
MW10	1.03	11.61	1.65	2.43	1228.62	Mostly high level	5.70	Mostly low level	Mostly in open dumpsite
MW11	1.66	5.63	1.47	3.06	1003.09	Mostly medium level	24.87	Mostly high level	Mostly in open dumpsite
MW12	2.33	9.32	1.41	2.12	1141.99	Mostly low level	36.77	Mostly medium level	Mostly in open dumpsite

[1] Dimensionless variable. [2] Categorical variable.

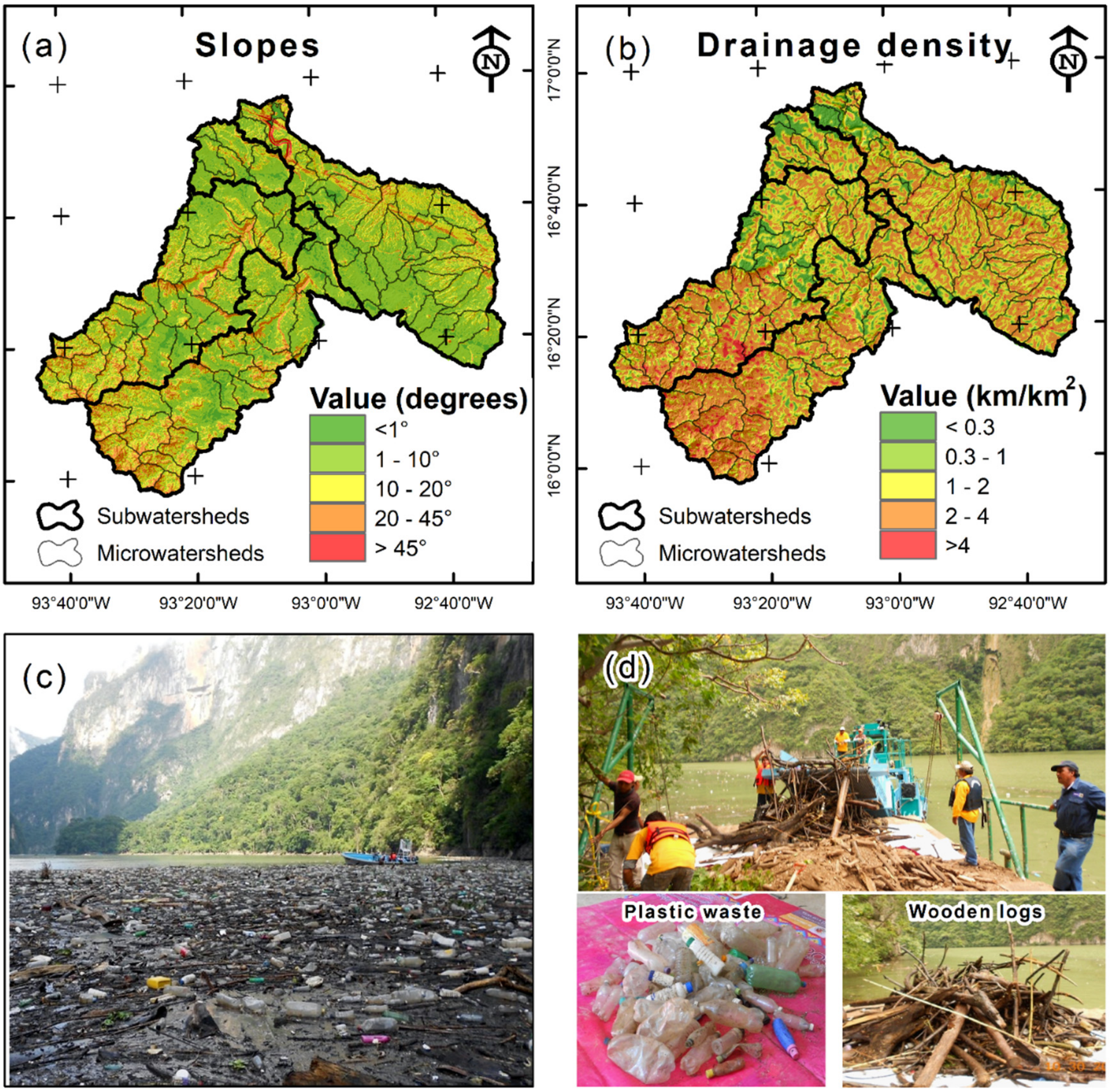

Figure 5. Influence of the variables of the geomorphometric parameter: (**a**) slopes; (**b**) drainage density; (**c**) unpleasant sight due to the presence of waste; (**d**) main sub-products found in the rivers of the study area.

It is important to mention that what is described above is usually very noticeable within the 12 microwatersheds identified with high priority, particularly MW1, MW6 and MW12. For example, López [45] identified nine places with a high presence of MSW, along the banks of several important rivers of the study area. Unfortunately, these wastes cannot be collected very frequently, due to the lack of infrastructure, economic resources and policies implemented by the different municipalities that form the subwatersheds and microwatersheds.

Regarding the variable Dd, commonly the south-southwest zone of the CCS has the highest values, which are influenced by the physiography of that zone (Figure 5b). At the level of microwatersheds, the cases of MW7 and MW12 stand out, which present high global values (1.94 and 2.3 km/km^2 respectively), although few are the channels that cross their municipal seat. In the opposite case, the microwatershed MW1, MW2, MW5, MW6 and MW8 presents low global values (1.54, 1.47, 1.21, 1.80 and 1.77 km/km^2 respectively), but its most important population settlement is crossed by a large number of river channels, which provide MSW that eventually flow into important rivers (Table 5).

Table 5. River channels within important population settlements.

Microwatersheds	Municipal Seat	km of Channels within the Municipal Seat
MW1	Tuxtla Gutiérrez	115.91
MW2	Tuxtla Gutiérrez	29.90
MW5	Berriozábal	13.08
MW6	Chiapa de Corzo	36.61
MW8	Tuxtla Gutiérrez	59.44

Note that the proximity of the population settlements, with respect to the river channels, not only causes waste dispersion but also the affectation of these water bodies. Some researchers have reported the poor quality of the rivers in the CCS. For example, Ecobiosfera [43] sampled different places along the "Grijalva" river, finding very low dissolved oxygen values (less than 6 mg/L) and high biochemical oxygen demand values (greater than 50 mg/L). Jiménez et al. [61] and Castañón and Abraján [42], also reported a poor quality of aquatic ecosystems to sustain life, particularly of the "Sabinal" river, which crosses several of the analyzed microwatersheds (MW1 to MW5).

It is important to clarify that the poor quality of the rivers of the CCS is not necessarily due to the inadequate deposit of MSW, but rather to the discharged wastewater, which provides a large amount of nutrients and organic matter in the process of decomposition. MSW can also contribute organic matter, but essentially contribute inorganic components of low volumetric weight, which cause unpleasant landscapes (Figure 5c). In the work of López [45], the composition of the solid waste found in the current of the "Grijalva" river was analyzed, finding that the fraction of low volumetric weight (mainly plastic containers) represents 2.69% by weight (Figure 5d). The remaining percentage (97.31%) corresponds to organic material, such as wooden logs or thick branches, which normally do not float (tend to partially sink).

Regarding the Ci variable, the CCS and practically all the microwatersheds have values above 1.5, which means that there are elongated watersheds with a high degree of waste dispersion, causing several of the problems described in the previous paragraphs.

Another aspect that caused high prioritization values in the CCS has been the noticeable change in land use over the decades, mainly influenced by the construction works of the "Manuel Moreno Torres" hydroelectric dam (Chicoasén). According to CONAGUA [38], in the period 1980–1990, there was a decrease in the primary forest area of the study area (from 210,635 ha to 96,300 ha) and an increase in the area of disturbed forests (from 121,607 to 248,627 ha). In the period 1990–2000, the disturbances were not severe and small positive changes could even be observed in the development of coffee and fruit areas.

In more recent years (2010–2020 period), the analyzed subwatersheds, such as SW2 and SW3, have presented high LULC change rates, especially due to the appearance of residential uses, although these changes have not been greater than 5%. At microwatershed level, only MW3 and MW8 showed values higher than that rate. According to Araiza [46], several of the patches or fragments of primary forest will disappear in the near future because of the creation of new human settlements, but also due to inappropriate MSW management strategies. Examples of these changes can be seen in the city of "Tuxtla Gutiérrez" (MW1, MW2, MW8 and MW9) or Berriozábal (MW3 and MW5), in which the settlements have gained land from other land uses such as agriculture or forestry. In this same context, lands that today function as open dumpsites in the municipalities of Berriozábal (MW2), Chiapa de Corzo (MW11) or Villaflores (MW12), previously had a different land use.

In terms of MSW generation (Wg), the CCS has presented gradual increases over the years (4.67% in the 2015–2020 period), mainly due to population growth and the internal migration of people between the different municipalities of Chiapas, Mexico. In 2020, CCS production was approximately 1127 tons/day, of which 70.9% came from SW1, while the lowest percentage came from SW3 (6.94%). The microwatersheds, MW1, MW2 and MW6, generate a greater amount of MSW (679.51, 93.10 and 64.68 tons/day, respectively), precisely because they include the most populated settlements. A more detailed analysis of waste generation by municipality forming the CCS can be seen in Araiza et al. [57].

It is important to comment again that local organizations (municipalities), and not watershed organizations, provide urban cleaning services, including collection and final disposal of wastes, and so these stages of MSW management are mostly carried out with poor municipal infrastructure. For example, regarding Wc, only the most important and densely populated municipalities, which include MW1, MW2, MW5, MW6, MW8 and MW12, have specialized trucks that increase collection coverage (between 70 and 90%), including far away localities. The rest of the municipalities use unconventional equipment, such as dump trucks or pick-up trucks. This causes low collection coverage in distant population settlements (<20%), particularly those located beyond 15 km from the municipal seat. Regarding WDm, only MW1, MW2, MW8 and MW12 are found within municipalities with access to final waste disposal sites, which comply with Mexican regulations, particularly NOM-083-SEMARNAT-2003 [62]. The rest of the municipalities and their microwatersheds use open dumping sites, which lack the infrastructure to control liquid and gaseous emissions.

Finally, other biophysical variables that also affect the dispersion or movement of MSW are Lt and Pr. For example, regarding Lt (Figure 6a), two of the four subwatersheds (mostly SW1 and SW2) are located on igneous rocks, such as the andesites and granites, which have low permeability. For this reason, the waste dumping sites located in these areas do not have severe environmental problems. On the contrary, SW3 and SW4 have high permeability rocky strata, mainly sandstones, conglomerates, limestones and groups with lutites and limolites. MW1, MW2 and MW8 are found in these areas, which means that groundwater tables close to the surface are highly polluted.

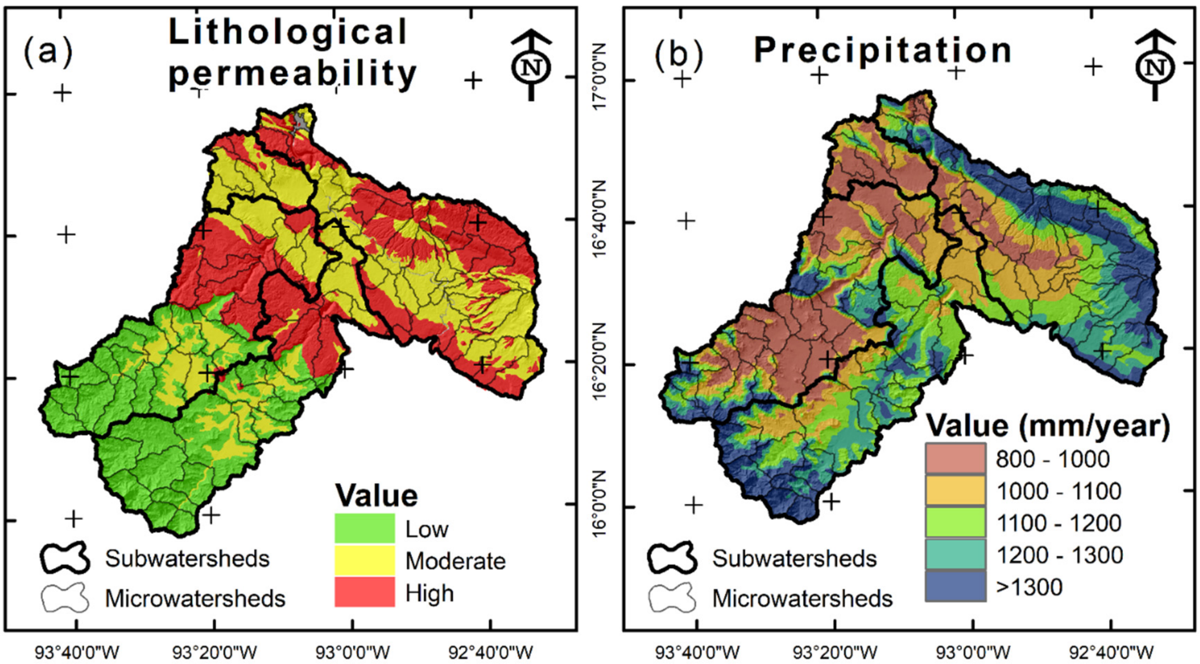

Figure 6. Influence of the variables of the biophysical parameter and LULC: (**a**) lithological permeability; (**b**) precipitation.

Regarding Pr, the CCS mainly present a climate type A1 (w), which means warm subhumid with rains in summer. The most intense rains normally fall from May to October and for this reason, the most important production of leachate within the waste dumping sites also occurs in those months. SW2 and SW4 have the highest annual precipitation (1203.51 and 1200 mm, respectively), while at microwatershed level, MW10 and MW12 stand out (Figure 6b). Note that Pr can cause unpleasant sights because of the presence of wastes (Figure 5c). According to López [45], the amount of MSW that reaches various rivers in the study area can be subdivided into two seasons clearly defined by rainfall. In the first season, or dry season, between 9 and 12 tons of waste can reach the rivers, while in the second season, or rainy season, the amount of MSW tends to increase significantly, ranging from 30 to 100 tons.

3.4. Sensitivity Analysis

The use of weights different from those employed in this work will not necessarily generate more realistic prioritization scenarios in terms of MSW management, but rather different prioritization objectives or approaches. As an example, a sensitivity analysis is shown in Figure 7. Figure 7a shows two additional scenarios besides the one analyzed in this work (Scenarios 2 and 3), but with modified weights for the prioritization index parameters. Figure 7b presents the values and prioritization levels obtained from such scenarios. Note how SW1 and SW2 show low levels of prioritization in scenarios 2 and 3, while the opposite is true in the case of SW3 and SW4. This is due to the modification of the weights, since the MSW management parameter is no longer important. It is also not a good option to assign equivalent weights to all the parameters, since the important variables of waste management can be masked, which also leads to objectives or prioritization approaches different from the one originally proposed in this work.

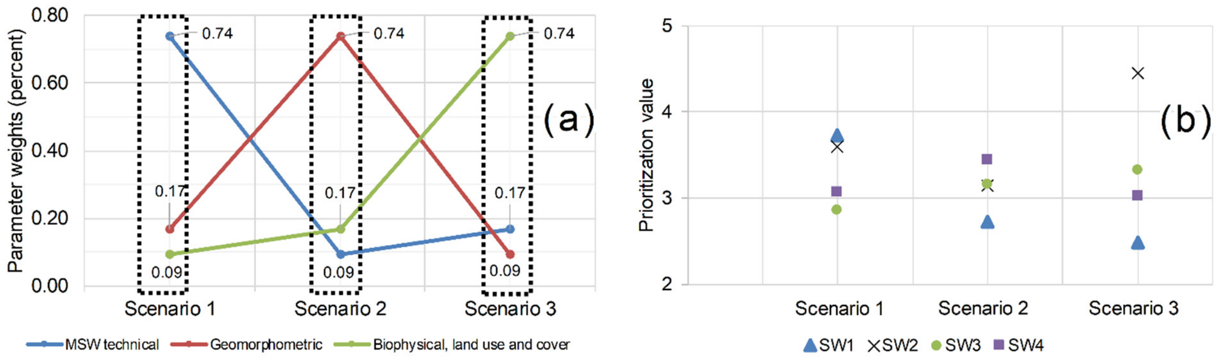

Figure 7. Sensitivity analysis: (**a**) modified weights for the prioritization index parameters; (**b**) values and prioritization levels in scenarios.

3.5. Policies within the CCS

The current regulatory framework in Mexico, mainly through the National Water Law, establishes that the Integral Management of Water Resources is the appropriate way to administer the water resource, considering the watershed as the main management unit [63]. In this context, the CCS has different management entities, such as a watershed commission, an intermunicipal board, as well as various committees within the subwatersheds of interest. Other federal agencies in Mexico address specific matters.

Unfortunately, intervention efforts regarding the management of MSW have been nil for three main reasons. The first reason is the incomplete development of regulations to manage MSW because of the constant changes in the policies of municipal governments, which are in office for three years. The second reason is the limited competences and attributions established in the environmental regulations, which do not allow direct coordination between the different watershed local actors (government, private companies and society). The third reason is the inverted orientation of the applied policies, since many of them are focused on restoring damage rather than preventing it.

In this context, the regionalization of municipalities and the management of MSW through decentralized operating agencies can be a good solution. However, first of all, some of the problems stated in the previous paragraphs must be solved. In the works of CONAGUA [64], ONYSC [65] and Rodríguez and Tuirán [66], the benefits of these types of alternatives are shown, ranging from technical to political to economic solutions, which may provide adequate public services in both urban and rural localities. In fact, in European countries such as Poland, cooperation in the field of MSW management is more common than in public transport, wastewater management or physical planning [67].

4. Conclusions

In this work, a watershed prioritization analysis was applied to MSW, with implementation of GIS and MCE techniques, as well as the use of various morphometric variables, LULC and MSW management. Note that despite the detection of only two subwatersheds and twelve microwatersheds with the highest priority in terms of MSW, all the watersheds (four subwatersheds and eighty microwatersheds) must be addressed together to reduce severe environmental impacts, such as the dispersion of waste over water bodies, or its accumulation on riverbanks and ravines in the study area.

On the other hand, the regionalization of municipalities and the management of MSW through decentralized operating agencies may be a good option to solve the null intervention of the management entities within the CCS. These mechanisms can offer technical, political and economic solutions. They also offer the possibility of delegating non-essential activities from watershed operating agencies to other specialized agencies in the field of waste management.

Finally, the workflows, variables, techniques and approaches used in this paper can be useful for all those interested in these topics. They can also be replicated elsewhere and improved.

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