Sustainability Assessment of Water Ecosystems based on Modified Water Poverty Index (WPI) with Birds' Biodiversity Parameters. Case study: Juan Angola Creek- Cartagena, Colombia

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Aquatic ecosystems are essential for the development of all forms of life. Water is the most valuable natural resource. The impact caused by contamination, urbanism, and population growth in the water bodies affects the ecosystems sustainability, raising the contamination levels in the water coast systems, and affecting the biodiversity of the ecosystems. One of the most important water bodies in Cartagena-Colombia is Juan Angola Creek. This study presents the sustainability assessment of water ecosystems based on the modified Water Poverty Index (WPI) to determine access, impact of anthropogenic activities, availability, and related parameters of bird biodiversity in the creek. The information to assess the index was taken from government reports for the components: resource, access, use, and capacity. Physicochemical, environmental, and bird parameters were taken in two samples distributed in a transect from the mouth of the creek to Torices' bridge in the rainy and dry seasons of 2021 (m1), and 2022 (m2), respectively. The results indicated that water poverty was low in WPI and modified Water Poverty Index (WPI-mB), which indicates favourable environmental conditions for access to water sources and sustainable development measures. The bird parameters implementation marked a difference in the WPI-mB values because this involves the species that inhabit the water body affected by environmental changes. For future research, it is recommended to monitor other taxonomic groups in the biodiversity index to expand the information on ecosystem overexposure.

1. Introduction

Environmental pollution is one of the biggest problems facing humanity today (Beck et al., 2020). Therefore, it is necessary to ensure a sustainable water supply to the growing population (Bafarasat, 2021). Surface waters are found in lakes, seas, wetlands, streams, oceans, and rivers. They are the most exploited water source in the world due to the intensification of agriculture and industrial activities, waste disposal, and sewage disposal (Akoto et al., 2021). Resource scarcity water has generated the development of strategies that seek to help its conservation (Chin et al., 2021). Colombia is one of the most biodiverse countries in the world. It has many water bodies in different regions, including the Caribbean region, where Cartagena is located. Cartagena has important water bodies and one of them is the Juan Angola Creek located in the northern part connecting La Virgen wetland with the Cabrero Lagoon. However, the Juan Angola Creek, its mangroves, the bed through which its waters flow, and the inhabitants who live on its banks suffer serious problems caused by the uncontrolled deposit of waste, the noise generated by vehicles, the aircraft leaving the Rafael Nuñez Airport, illegal occupation, rainwater runoff, water served through informal settlement on the creek banks, and the presence of a gas station these are causes of dangers to the ecosystem preservation. Currently, there is inequality in the distribution of water resources throughout the world, a situation that is aggravated by climate change. This scarcity is known as water poverty and can be related to the lack of resources.

The water poverty index (WPI) was developed to measure the degree of affectation to water from a holistic perspective, considering the physical, social, environmental, and economic spheres. WPI can be applied at the local, district, and national levels (Sullivan et al., 2003). WPI shows an overview of the state of water resources, where factors specific to the territory under study are evaluated, managing to guide the development of public and government policies that take measures against the results of monitoring (Thakur et al., 2017). However, water poverty is not only due to the lack of the resource but also to the management that occurs from the multidimensionality of the environment (Ladi et al., 2021), therefore, the WPI combines five components or dimensions, among which are: resources (R), access (A), capacity (C), use (U), and environment (E) (El-Gafy, 2018). Each of the components has several subcomponents that vary depending on accessibility and the site where they are evaluated (Kallio et al., 2018).

In this research, the WPI was modified with biodiversity parameters using bioindicator species for the ecosystem's evaluation considering the resources and the environmental affectation. Through alpha diversity (such as wealth), birds are model bioindicators because it responds to environmental changes in the ecosystems (Garizábal-Carmona and Mancera-Rodríguez, 2021). Ecosystems are threatened by the decline in bird diversity as they influence ecosystem functions and indicate the destruction of their habitats (Soifer et al., 2021). Currently, to estimate the wealth and birds' abundance of different classifications, systematic censuses are carried out in different seasons, and statistical analyzes of alpha and beta diversity, using the Shannon-Wiener diversity indices, and the Sorensen dissimilarity index (Li et al., 2021), density index, and community proportion of birds (Zhang et al., 2021). Therefore, bird parameters were used to analyze Juan Angola Creek as a new dimension in the WPI.

2. Materials and methods

2.1 Study area

The study area for this research relates to the City of Cartagena-Colombia considering one of its most important water bodies: the Juan Angola creek, located in the northern part of the city (10º25'28.57" N and 75º30'55.66" W). Two samplings were conducted for the measurement of physicochemical parameters and bird biocount (four points), the first in the semi-rainy season of 2021 (m1) and the second in the dry season of 2022 (m2), nevertheless this research unit has been carrying birds counting during four (2019-2022) consecutive years, in both the rainy and dry season; in 2020 a seven-day sampling was conducted using a Rapid Assessment Method (Zogaris and Killimanis, 2016). For bird counts, the point and fixed radius methodology was applied at each sampling station, with a diameter of 100 m and 10 minutes of counting (Melles et al., 2003). Taxonomic classification and functional groups were adjusted according to Clements et al. (Clements et al., 2021).

2.2 Development of the mathematical model

Selection of sub-components of the WPI categories

Considering that the water poverty index (WPI) includes five essentials categories (resource, access, capacity, use, and environment) that define WPI (Lopez-Alvarez et al., 2020). Some appropriate subcomponents were selected for the measurement of the system after reviewing several articles with applicability to water bodies and communities with characteristics like the study area. For the Resource (R) component, the subcomponent is Months per year with water [%] (R1) (Goel et al., 2020). Access (A) includes the percentage of the Population with access to drinking water [%] (A1), the percentage of the population with access to sanitation [%] (A2) (El-Gafy, 2018), and the Reliability of pipe water supply [L/year] (A3) (Thakur et al., 2017). Capacity (C) involves the Under-five mortality rate [inhabitants/year] (C1) (Wurtz et al., 2019), citizens above the poverty line [inhabitants/ year] (C2) (Shadeed et al., 2019), the percentage of the population having completed primary school [inhabitants/year] (C3) (Ladi et al., 2021), the average unit price of water [USD] (C4) (Shadeed et al., 2019), GDP index (C5), Economically active population [%] (C6) (Khadka and Pathak, 2021), Gini coefficient (C7) (Lopez-Alvarez et al., 2020). Use (U) consists for purposes of this research only of Domestic water use [L/inhabitants*year] (U1) (Gong et al., 2017). Environment (E) in this research includes the water quality index (WQI) (E1) (Makubura et al., 2022) and the percentage of area with natural vegetation [ha] (E2) (Thakur et al., 2017). Water quality index (WQI) Model Development: WQI was developed using weights for each of the parameters (Makubura et al., 2022) evaluated as follows:

$$WQI = \frac{\sum Q_i W_i}{\sum W_i} \qquad (1)$$

Where Q_i is the quality classification of the parameters, W_i is the unit weight of the selected water quality parameters and WQI value between 0 – 25 is a water quality excellent (Makubura et al., 2022).

Proposed modification

Considering that the environmental parameter usually focuses on water supply and management (Ladi et al., 2021). In this research, a biodiversity component associated with birds, called Biodiversity of the environment (B) was proposed, since birds are a means to measure the environment biodiversity, they are susceptible species to changes in ecosystems and particular habitats, easy to identify, and monitor (Simamora et al., 2021). Biodiversity of the environment (B) is made up of 4 subcomponents: abundance (B1), wealth (B2) (calculated with the total specie number, and according to different classifications), the Margalef index (B3), the Shannon-Weiner index (B4). Margalef index (D_{Mg}): assesses species wealth and is sensitive to sample size (Tikadar et al., 2021).

$$D_{Mg} = \frac{S-1}{lnN} \tag{2}$$

It where S is the total specie number and N is the total individuals number. Shannon-Weiner Index (H') is used to evaluate the variability, wealth, consistency, and uniformity of the species, the values are estimated between 1.5 and 3.5 or even exceed 4, increasing the value increases the diversity of species (Alnashiri, 2021):

$$H' = -\sum_{i=1}^{S}(p_i \times \log_2 p_i) \tag{3}$$

Where $p_i = n_i/N$, n_i is the number of individuals and N is the total numbers of individuals.

Standardizing the data and subcomponents weight

The population, economic, and social data of this research were taken from official sources and government reports depending the population near the Juan Angola creek in the years 2021 and 2022 (Cartagena Cómo Vamos, 2022), while physiochemical parameters and birds data were taken from the authors' measurements. Standardization was performed using the min-max approach (Khadka and Pathak, 2021), dividing the values for each subcomponent by the total population, area, or the mean of each report. In addition, to align the percentage data, they are subtracted from 100 or the opposite procedure (Ladi et al., 2021). In this research, the same weights are used for the all components and subcomponents (Jemmali, 2017), due to the importance that the selected ones represent for the study area.

Calculation of the Water Poverty Index (WPI)

For the calculation of WPI, Sullivan et al. (2003) described it as:

$$WPI = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} \tag{4}$$

Where X_i is the components i and w_i is the weight of that component i, the WPI result fluctuates between 0 and 100, the latter being the best possible score (Sullivan et al., 2003). The same formulation was used for the WPI-mB including the new category.

3. Results and Discussion

The results in Table 1 show an initial measurement of the values for each WPI component and the WPI modified with bird parameters (WPI-mB). Since different sub-indexes were used for every component, all the values were brought to one dimensionless scale were each indicator was assigned a score between 0 and 100. The variables presented without percentage were normalized applying a minimum-maximum approach (Goel et al., 2020). Errors were considered for bird and water quality parameters before calculating WPI and WPI-mB. The errors were between 1 and 4%.

Table 1: Water Poverty Index (WPI) subcomponents and values for the study area

Year	Resource (R)	Access (A)			Capacity (C)							Use (U)	Environment (E)		Biodiversity of the environment (B)			
	R1	A1	A2	A3	C1	C2	C3	C4	C5	C6	C7	U1	E1	E2	B1	B2	B3	B4
2021	83.3	94	86	70	80.5	50	43	47.7	86.1	57.2	50	65	35	60	31.8	70	75.8	62.6
2022	91.7	98	86	62	75	40	51	44	86.9	59.5	50	65	70	60	43.3	25	55.1	56.1

Starting with the Resources (R) component, since only one subcomponent (R1) was taken into account and that the water supply in the city of Cartagena is almost permanent, except when maintenance work is carried out, the value obtained was high, however, in the influence areas of the Juan Angola creek there are no official records that specify the water sources or the supply regularity to the inhabitants. In Table 1, for the subcomponents of Access category (A), data was taken at the city level, which influences the regular values of

the component; a determining factor is the reliability of the water potability consumed by the population, aqueduct coverage and sewerage services, except for coastal invasion areas that increased in 2022, which is reflected in the lower value for A3 in that year. The capacity (C) category involves aspects of health, education, and economy (Ladi et al., 2021), where the subcomponents that related the lowest values were those that involve poverty, which is consistent with the specific inhabitants' situation of the neighborhoods on the banks the Juan Angola creek, where the percentages of the population finishing primary school are low, as are the levels of poverty. The use (U) component only had a subcomponent quantified at the city level, indicating that the population majority use more water at the household level than the estimated average per capita amount. Environment (E) component shows that E1 is half the quantification for 2022, registering very poor water quality for the year 2021, which is justified by the return to normal activities after the Covid-19 pandemic, presenting the overexposure of the water body with the dumping from the informal settlement on the sides of the Juan Angola Crek, the increase in flights from the airport and the greater presence of local garbage dumps. Relating Access (A) and Environment (E) components the population has availability of water, but having poor quality becomes a latent threat that threatens accessibility (Thakur et al., 2017). The new component Biodiversity of the environment (B) presented different results in B1 and B2 subcomponents, whereby in the year 2021 the birds' abundance was lower although the species diversity was higher, quite the opposite of the year 2022 due to there are more migratory species from North hemisphere in the dry period (December to March), the above justified by the variety of birds that arrive at the water body of an accessory, the incidental or constant type depending on the time of year, how in this case two different weather periods are contrasted, while B3 and B4 related the types of species with the total, for 2022, the relationship decreased by a small range compared to 2021 because the Juan Angola creek presented an environmental recovery, the birds did not have easy food, a situation that forced some to migrate to other water bodies.

Table 2 shows the quantification of the WPI components and the WPI modified (WPI-mB), where for Resources (R) and Access (A) it is necessary for government entities to present more specific data for the communities and thus obtain a value that shows the water availability annually to the entire population in the front sector of the Juan Angola creek. It is necessary to improve the reliability of piped water supply. Capacity (C), an urgent measure must be taken to reduce the poverty levels, social inequality, and access to education in the neighborhoods near Juan Angola creek, since they are the main destabilizers of the component; The Use (U) although it was reported the same for both years, it is necessary to minimize the water consumption for domestic use. The environmental component (E) evidenced the recovery of the body of water in 2022, but more cleaning campaigns, and environmental education must be carried out in this area. The biodiversity of the environment (B) component showed the variability (decrease) in biodiversity levels for the year 2022, considering the presence/absence of birds as an important item of the creek state.

Table 2: Water Poverty Index (WPI) components and values for the study area

Year	Resource (R)	Access (A)	Capacity (C)	Use (U)	Environment (E)	Water Poverty Index (WPI)	Biodiversity of the environment (B)	WPI modified with birds' parameters (WPI-mB)
2021	83.3	83.3	59.2	65	47.5	67.7	60.1	66.41
2022	91.7	82	58.1	65	65	72.3	44.9	67.77

Figure 1 compare the application of the WPI and WPI-mB to estimate the influence of the Biodiversity of the environment (B) component, in this case, the difference relating to Table 2, the WPI values are more distant than those calculated with WPI-mB. In addition, the significant contribution of the Environment (E) component to the WPI calculation in both cases is due to the specificity data for the water body in the area under study. From Table 2, the WPI values presented a greater variation than those calculated with the WPI-mB, mainly because WPI considers that the Juan Angola creek presents less water poverty in the year 2022, however, when incorporating the biodiversity parameters in WPI-mB the water poverty increases between 1.3 and 4.6 percentage points indicating the creek deterioration, although the index had a higher score, biodiversity (B) in the year 2022 decreased due to the increase in the creek contamination and little food for the birds. B component in WPI-mB provides a complete perspective that involves other species inhabiting the water body and suffer in a measurable, evident, and marked way the changes in its environment, acting as bioindicator species based on the other components of the water poverty index, a situation that demonstrates the importance of incorporating the proposed component (B) in this research. The values obtained for water poverty were low (65-75) in WPI and WPI-mB, which indicates favourable environmental conditions for access to water sources, and sustainable development measures should be applied to some specific areas that lack the resource (Thakur et al., 2017). Although water poverty is low, components such as Environment (E) and Biodiversity of the

environment (B) are in low ranges. In addition, Capacity (C) subcomponents indicate a high rate of inequality in the city, and between influence areas of the Juan Angola creek, a situation that should generate serious concern among the education, human development, and promotion of equity secretariats.
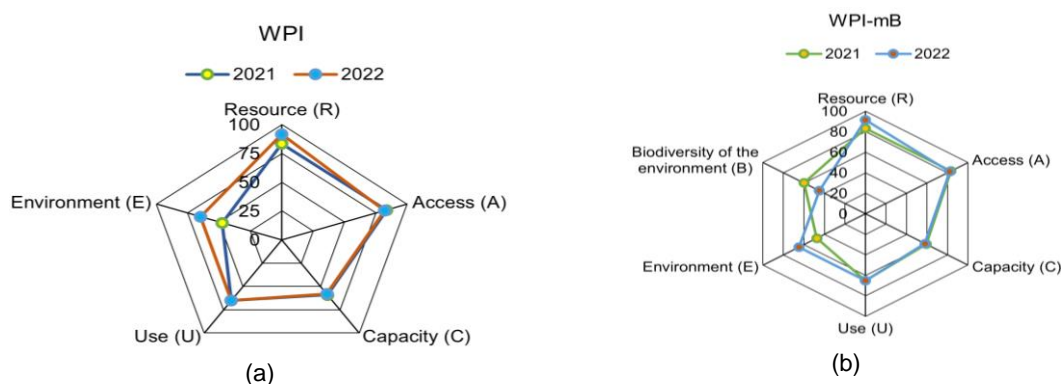

Figure 1: (a) WPI components values, (b) WPI-mB components values

4. Conclusions

Cartagena is a Colombian city rich in water, the Juan Angola creek is one of its most important and polluted water bodies due to the high anthropogenic affectation to which it is exposed. The general components of the WPI showed good levels for the case of Resources (R), and Access (C) from a city perspective, while in Capacity (C) there were drastic variations in the subcomponents that show high levels of social and economic inequality, in the Use (U) the amounts of water used in homes should be improved according to the national average, the Environment (E) component for including the direct calculation of the water quality index with specific parameters of the Juan Angola creek indicated the bad state of the body of water for 2021, however, there was a recovery for 2022, while the Biodiversity of the environment (B) deteriorated by 2022. In this research, birds were chosen because they are high-order consumers, easy to observe, and very sensitive to changes in food supply, shelter, nest building, and the maintenance of their younglings. In a mangrove forest ecosystem, there are birds that occupy very specialized niches, which are completely dependent on the ecosystem quality. Changes in environmental conditions could swiftly affect these bird communities' compositions. In general, WPI and WPI-mB were found within low levels of water poverty. However, it is possible that by placing some data from specific subcomponents to the areas of influence, the results are less favourable. Therefore, the importance of incorporating the biodiversity component (B) lies in showing how the population of birds that inhabit the water body varies, becoming a bioindicator of the affectations suffered in the creek and that groups how the other components are related for their influence on the conditions of water poverty. Therefore, for future research, it is proposed to include other bioindicator species in the component B calculation.

Acknowledgments

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