




Creation of an environmental sustainability index for water resources applied to watersheds

Darllan Collins da Cunha e Silva¹  · Renan Angrizani Oliveira¹ ·
Vanessa Cezar Simonetti¹ · Bruno Pereira Toniolo¹ · Jomil Costa Abreu Sales¹ ·
Roberto Wagner Lourenço¹

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Abstract

One of the problems regarding water resources is the management and interactions with the environment in terms of ensuring conservation. An efficient way to assess problems arising from the interaction of water resources with management and the environment is to apply water quality indicators. In view of this, a water sustainability index for a watershed was developed. The watershed under study predominantly uses soil and water for agricultural purposes. The indicator was called water resources sustainability index (WRSI). The values range from 0 (worst condition) to 1 (best condition) based on an integration of water quality parameters, environmental sanitary conditions, and vegetation indexes analyzed by geoprocessing techniques and weighted by analytic hierarchy process. The results show that the lowest WRSI values are obtained in regions with predominantly agricultural activities and extremely poor basic sanitary conditions. Approximately 24% of the study area had WRSI values around 0.6, indicating a regular status; values above 0.9 would be desirable. Precarious conditions mean poor basic sanitary conditions and agricultural activities that, in addition to the high load of organic fertilizers, also produce a high load of sediments, causing degradation of the water environment. It is also noteworthy that urban areas, in comparison with rural areas, presented on average higher WRSI values, which is related to the population's access to better basic sanitation conditions and to low exposure to possible water contamination.

Keywords Geoprocessing · Environmental indicators · Water quality · Pollution · Water resources

✉ Darllan Collins da Cunha e Silva
darllan.collins@unesp.br

¹ Department of Environmental Science, São Paulo State University (UNESP), Av. Três de Março 511, Sorocaba, São Paulo 18087-180, Brazil

1 Introduction

Studies on sustainability began in the 1970s by observing environmental impacts on natural resources caused by human activities. Such studies resulted in several debates at a global level. In these debates, the concept of sustainability has been widely discussed in several dimensions that involve the human being, its behaviors, and its needs (Costanza et al., 2009; Franceschini et al., 2016; Pinto et al., 2017; Silva et al., 2016; Singh et al., 2009).

The assessment of sustainability of a location requires the grouping of different information that may reflect the degree of sustainability of an area. The development of analysis methodologies that can support this assessment contributes significantly to the generation of quick responses to understand this recurring problem. Thus, the development of environmental sustainability indexes allows assessing and monitoring the environment, enabling the definition of goals and actions for the improvement of environmental systems, which can take different approaches to assessing sustainability at different scales, including indicators/indexes, product-related assessment, and integrated assessment tools (Chen et al., 2008; Elliott et al., 2016; Franceschini et al., 2016; Graymore et al., 2009; López-Ridaura et al., 2002; Ness et al., 2007; Sales et al., 2018; Silva et al., 2017b).

In addition, such indicators are important mechanisms to communicate summary information or provide solid bases regarding the environment to those responsible for its management, contributing to a sustainable relationship between social, economic, and environmental factors (Graymore et al., 2009; Møller, 2015; Sales et al., 2018; Silva et al., 2017b). In addition, it should allow assessing a current situation and its temporal trend of behavior, which can be compared on a temporal and spatial scale (Meng et al., 2018; Su et al., 2011). Therefore, such approaches can be considered important support mechanisms for decision-making involving environmental issues.

The formulation of a methodology based on indexes and indicators focused on the characterization of water systems and based on decision support theory can contribute to the improvement of management of these resources (Prasanna et al., 2012; Simonetti, Frascareli, et al., 2019). In this sense, it is necessary to foster environmental indicators that provide updated information and that serve as management tools and support to decision-making within the scope of sustainability of water systems (Graymore et al., 2009; Santos et al., 2020).

Therefore, this interest in generating sustainability indexes applied to water systems has been strongly influenced by the United Nations Commission for Sustainable Development (UNCSD), as well as by the Organization for Economic Cooperation and Development (OECD), associated with the global context of degradation of water resources (Carbajal-Hernández et al., 2013; Singh et al., 2009).

However, decision-making based on multiple information on water sustainability assessment requires a comprehensive assessment using multiple-criteria decision analysis (MCDA) methods, which present a wide variety of methodologies, such as Electre and Macbeth (Chen, 2020; Cinelli et al., 2021; Marques et al., 2015; Molinos-Senante et al., 2016). Among MCDA methods, the analytic hierarchy process (AHP) proposed by Saaty (2004) stands out for its simplicity, popularity, and effectiveness. It is considered a robust method to assist in decision-making (Afolayan et al., 2021; Aykut, 2021; Fang & Partovi, 2021; Masroor et al., 2021; Moumeni et al., 2021). Compared to other MCDM methods, AHP generates a classification of all alternatives instead of the most

favorable alternative and therefore provides more information to decision makers rather than simply reporting the “best” alternative (Xi & Poh, 2015).

In this sense, several studies have used AHP to create indicators of water sustainability or water resources with different approaches, addressing the issue of water scarcity and availability, as well as the management and planning of water resources applied to both watersheds and urban areas (Calizaya et al., 2010; Du, 2020; Wang, 2008; Xi & Poh, 2015; Young et al., 2009). The integration of geographic information systems (GIS) and AHP has been quite effective in the spatial assessment of water sustainability and water resources (Chowdary et al., 2013; Ahmad & Verma, 2018; Patra et al., 2018; Karakuş, 2019; Hagagg and Sadek, 2020).

Although many of these applications developed in a GIS environment provide necessary information for decision-making using AHP, including the mapping of sustainability and management of water resources, there is a lack of studies that prioritize areas in watersheds for management, mainly, in countries where environmental data are scarce, such as Brazil.

In view of the above, this work aims to develop an index with values ranging from 0 (worst condition) to 1 (best condition) called water resources sustainability index (WRSI) based on an integration of water quality parameters, environmental sanitary conditions, and vegetation indexes that may reflect the degree of water quality and its ability to remain sustainable in face of potentially degrading processes of water quality and supply caused by human activities.

2 Methodology

2.1 Study area

We analyzed the Una River Watershed, located in the municipality of Ibiúna, State of São Paulo, Brazil, between 23°39'23" S and 47°13'21" W (Fig. 1). The Una River, which gives its name to the watershed, together with the Sorocabuçu River and the Sorocamirim form the Sorocaba River, giving rise to the main reservoirs of the Sorocaba Region, called Itupararanga Dam, which is used as a source of water for human consumption and services a population of approximately 1,000,000 inhabitants. It irrigates hundreds of agricultural properties and is used for electricity generation (Silva et al., 2017a).

The Una River basin has a population of approximately 19,000 inhabitants, with a human development index of 0.760 (Sales et al., 2018). The territorial area of the basin is approximately 100 km² inserted in an Environmental Protection Area (EPA) called EPA Itupararanga, with a predominant Cwb climate, according to the Köppen classification, with rainy summers and dry winters. The vegetation is dense montane ombrophilic (Silva et al., 2017a), with predominant soils of the Ferrasol type and small portions of Gleysols and Acrisols (Simonetti, Frascareli, et al., 2019).

2.2 Water resources sustainability index (WRSI)

To generate the map of the environmental sustainability of water resources in the Una River basin, the water resources sustainability index (WRSI) was prepared. This index seeks to identify the sustainability of the local environmental system through the analysis of physical–chemical parameters and potentially degrading processes of water quality and supply.

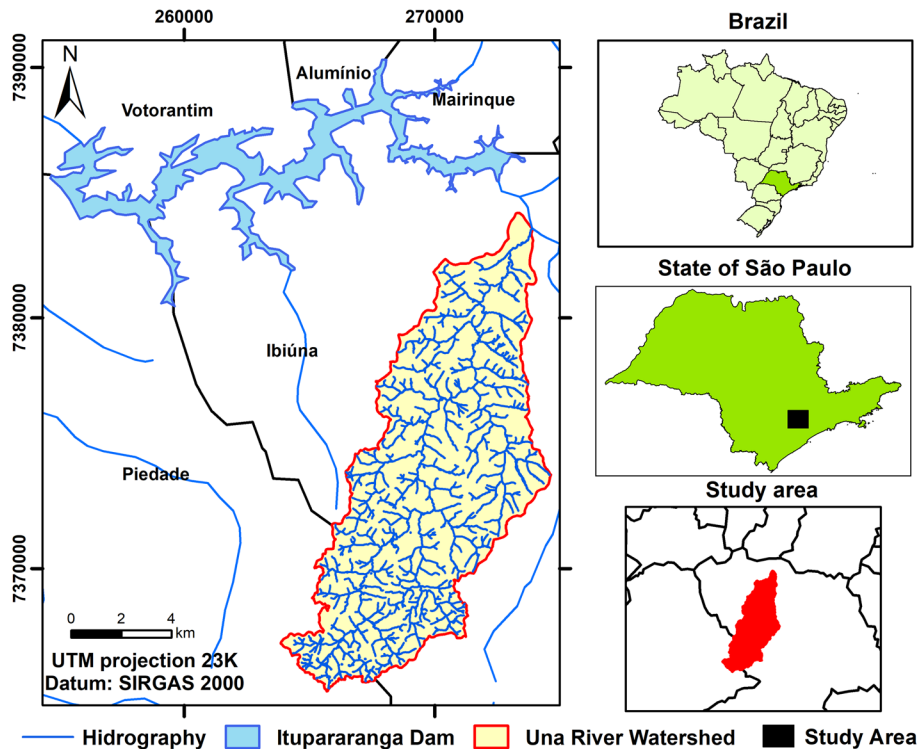


Fig. 1 Location of the Una River Watershed

In this context, the WRSI is a synthesis of the sustainability of water resources since it records the environmental changes and aggressions that have occurred in the watershed.

The WRSI comprises the integration of the following indicators: physicochemical water index (PWI), wet vegetation index (WVI), and potential water degradation index (PWDI). The physicochemical variables of the water that make up the PWI provide a static view, a momentary scene of the watershed, while the WVI and PWDI indexes allow identifying potentially degrading processes of water sustainability, as the water quality and supply depends on the state of the riparian forests and the preservation of native vegetation, in addition to the destination of sewage and the collection of water for human consumption in the watershed. In this sense, these three WRSI indexes are sufficient to provide a quick response to the decision maker on the state of the water resources of a given watershed.

The analytic hierarchy process (AHP) was used to assign weights to each WRSI component indicator due to the low uncertainty and reliability in the identification of the prominent factor and for being effective in the decision-making process, in addition to being able to transform qualitative attributes into quantitative measures, which increases its applicability in various spheres of science (Aykut, 2021; Fang & Partovi, 2021; Masroor et al., 2021; Moumeni et al., 2021). Thus, it is a robust way to mathematically convert decision makers' judgments into numerical results (Afolayan et al., 2021). Once these weights are established, they can be replicated in other case studies, thus maintaining the integrity of the index and enabling comparison between watersheds.

2.2.1 Physicochemical water index (PWI)

The values of the physicochemical water index (PWI) were measured in watercourses within areas that met the following criteria: soil loss above 50 t/ha.year without riparian forest cover (up to 30 m from watercourse margins) and areas of agricultural activities with temporary crops or urban areas with a polluting load. To determine these areas, vectorized land use and soil loss maps were used as proposed by Silva et al. (2017a). Twenty-one collections were carried out, distributed by sub-watersheds along the study area (Fig. 2).

The parameters electrical conductivity (EC), dissolved oxygen (DO), and nitrate in situ were determined using the Hanna HI 9829 Multiparameter Probe (NO_3^-). The hydrogen potential (pH) of the water was measured using an Instrutherm PH-1900 digital potentiometer, while turbidity (Tu) was obtained using a Quimis Q 279P turbidity meter.

In laboratory, biological oxygen demand (BOD) concentrations were determined from water samples collected in sterile amber bottles from each sampled point. First, DO was measured at room temperature (20°C) using a Digimed DM-4P oximeter. Subsequently, the DO was measured after incubation in an oven for five days at 20 °C. The biological oxygen demand after five days (BOD_5) at 20 °C was determined by the difference between the final and initial DO values.

Total solid (TS) residues were determined in 100 mL water samples stored in previously weighed beakers and transported to a heated oven (100 °C) for water evaporation and then weighed again. Depending on the measured mass and the initial volume used, the concentration of total solid residues per volume of sample was calculated.

The values of phosphate (PO_4^{3-}) were obtained using the Hach DR 3900 spectrophotometer from a blank preparation and from samples of phosphate (PO_4^{3-}). To prepare the samples of phosphate (PO_4^{3-}), the Persulfate Method 4500 NC was used (USEPA 1997).

After the analysis of water quality parameters was completed, the values (0 to 1) were assigned according to the methodology proposed by Silva et al. (2017b). The PWI was generated from the weighting of each sampled value according to Eq. 1 (Silva et al., 2017b).

$$\text{PWI} = \sum_{i=1}^8 \left(\text{Var}(i) \times p(i) / \sum p(i) \right) \quad (1)$$

where $\text{Var}(i)$ is the value of parameters EC, DO, NO_3^- , pH, Tu, BOD, TS, and PO_4^{3-} qualified with 0 to 1 for a given sample point; $p(i)$ is the weight value of the parameters EC (0.06), DO (0.36), NO_3^- (0.10), pH (0.17), Tu (0.06), BOD (0.10), TS (0.06), and PO_4^{3-} (0.10).

After calculating the PWI for each sampling point, the PWI value was calculated per sub-watershed. For this, in sub-watersheds that presented two PWI values, Eq. (2) was used, which weighs PWI values by area of vegetated and deforested riparian forest.

$$\text{PWI}_{\text{sub}} = (\text{PWI}_{\text{Def}} \times A_{\text{Def}} + \text{PWI}_{\text{Exh}} \times A_{\text{green}}) / (A_{\text{Def}} + A_{\text{green}}) \quad (2)$$

where PWI_{sub} is the PWI value per sub-watershed; PWI_{Def} is the PWI value calculated for the sampling point that presents a deforested area with the presence of agriculture and temporary crops or urban area with high soil loss (> 50 t/ha.year);

PWI_{Exh} is the PWI value calculated for the sampling point located in the exhortory of sub-watersheds; A_{Def} is the area (in hectares) of riparian forest without vegetation cover with the presence of agriculture and a temporary crop or urban area, and in a place with high soil loss (> 50 t/ha.year) up to 30 m from the margins of watercourses;

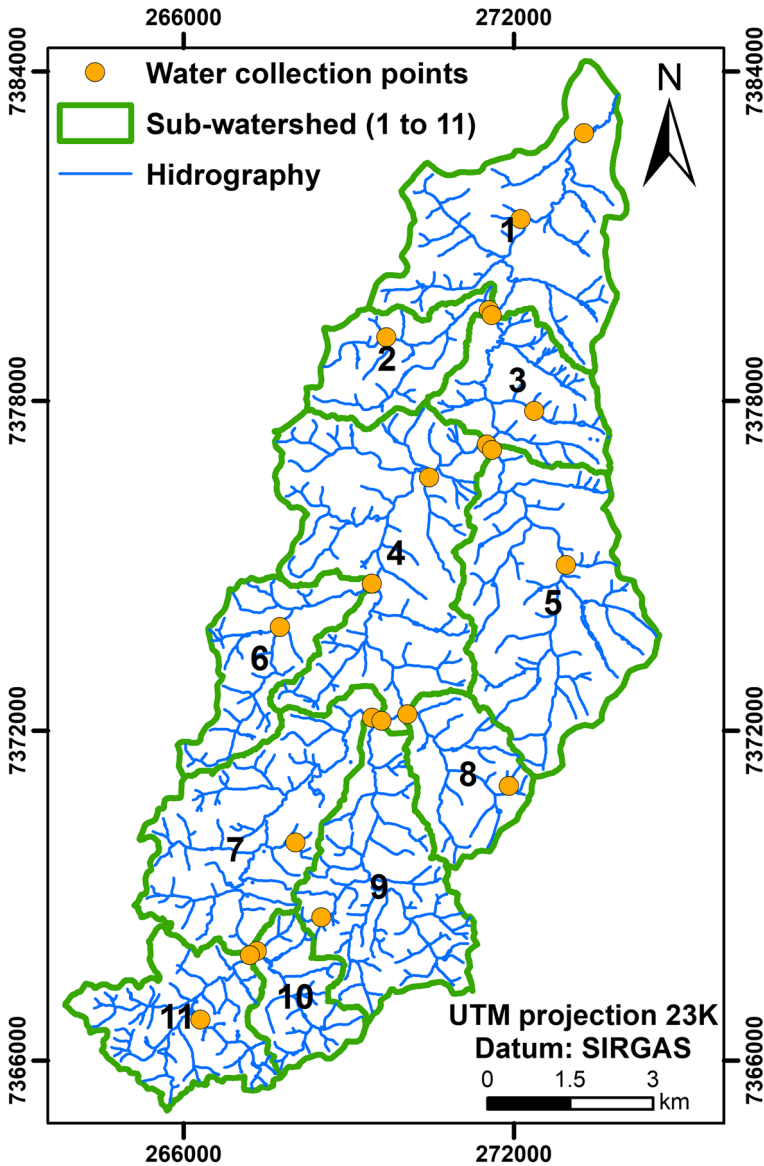


Fig. 2 Location of water collection points

A_{green} is the area (in hectares) of riparian forest with vegetation cover up to 30 m from the margins of watercourses. The final values of PWI were geocoded in ArcGIS 10.1 and spatialized by sub-watershed. The classes assigned to the PWI_{sub} are compatible with the ranges established by the National Sanitation Foundation (NSF), adapted to centesimal numbers (Effendi et al., 2015) ranging from 0 to 1, where 1 represents the sub-watershed with better water quality and riparian forest with vegetation cover, while 0 represents the sub-watershed with low water quality and riparian forest areas occupied by human

activities that degrade water quality, and values of PWI_{sub} above 0.90 can be considered excellent water quality, while values of PWI_{sub} between 0.5 and 0.7 are classified as regular, following the recommendations for water quality by the NSF.

2.2.2 Wet vegetation index (WVI)

The wet vegetation index (WVI) was obtained per sub-watershed to verify the potential for water availability from the presence of water in the forest cover using the normalized difference water index (NDWI). The NDWI can detect the presence of water in plants and evaluate the water stress of a vegetation. For this reason, it can be used to assess the water availability of a local hydrography (Gao, 1996; Gu et al., 2007). It is obtained by Eq. (3).

$$NDWI = (NIR - SWIR)/(NIR + SWIR) \tag{3}$$

where

NIR corresponds to the near-infrared band;

SWIR corresponds to the middle-infrared band.

The images from bands 5 and 6 of the Landsat-8 satellite, TM sensor, with orbit/point 220/76 of July 23, 2019, were used. This date corresponds to the drought period. Then, the forest cover was broken down into wet (positive values) and dry (negative values) (Gao, 1996). Then, the WVI was generated considering the ratio between areas with wet forest cover in relation to the total area covered by forests per sub-watershed multiplied by the adapted drainage density (Dd_{ad}) proposed by Silva et al. (2016) and according to Eq. (4).

$$WVI = A_{sup}/(A_{veg} \times Dd_{ad}) \tag{4}$$

where WVI is the ratio between areas of NDWI values greater than zero present in the forest area class of each sub-watershed; A_{sup} is the area occupied in forest areas of each sub-watershed for NDWI values greater than zero; A_{veg} is the total area of forest area in each sub-watershed; Dd_{ad} is the drainage density indicator adapted from the sub-watershed that varies from 0 to 1, which is calculated according to Eq. (5);

$$Dd_{ad} = \begin{cases} 0 & \text{for } Dd \leq 0.5 \text{ km/km}^2 \\ 1/3 \times Dd - 1/6 & \text{for } 0.5 \text{ km/km}^2 < Dd < 3.5 \text{ km/km}^2 \\ 1 & \text{for } Dd \geq 3.5 \text{ km/km}^2 \end{cases} \tag{5}$$

where Dd is the drainage density of the sub-watershed (km/km^2). Therefore, sub-watersheds that have forest cover with positive values for NDWI and high drainage density ($\geq 3.5 \text{ km/km}^2$) indicate sub-watersheds with healthy and humid vegetation cover with WVI values equal to 1, while sub-watersheds with forest cover with negative values for NDWI (droughts) and low drainage density ($\leq 0.5 \text{ km/km}^2$) indicate stressed vegetation cover, which requires environmental monitoring and measures to ensure the preservation of vegetation cover, indicating WVI values equal to 0, as exposed in Eq. (5).

2.2.3 Potential water degradation index (PWDI)

The potential water degradation index (PWDI) was obtained seeking to emphasize water quality considering the degradation of riparian forests surrounding rivers, the type of sanitary sewage, and the method of water supply in sub-watersheds inside the study area. It was

generated by integrating the following indicators: water protection index (WPI), sanitary sewage index (SSI), and water supply index (WSUI).

The water protection index (WPI) was generated to assess the importance of riparian forests for the protection of water resources. Riparian forests act as regulators of flows of water, sediments, and nutrients within a watershed by performing ecological functions that are extremely important for the conservation of water resources (USDA 2003; Anbumozhi et al., 2005). The WPI was defined based on the protection band of riverbanks (Law no. 12.651/2012). It considers the percentage of area protected by riparian forests on riverbanks, and its values range from 0 (worst protection) to 1 (best protection), according to Table 1. Accordingly, values with WPI greater than 0.8 show areas with preserved riparian forests, covering at least 90% of the watercourse margins defined by Law no. 12,651/2012, indicating healthy environments for the Atlantic Forest biome (Metzger, 2000), as shown in Table 1.

The sanitary sewage index (SSI) was constructed using information from permanent private households without bathrooms or toilets, and households with bathrooms or toilets connected to a rudimentary pit, ditch, river, lake, sea, among others, per census tract within the study area (IBGE 2012). The calculation of the SSI was performed per sub-watershed using Eq. (6), which weighs the SSI value of each census tract per area in each sub-watershed. It ranges from 0 (worst condition) to 1 (best condition). Therefore, SSI_{sub} values greater than 0.9 indicate that 90% of households have a domestic sewage collection network, which reduces the incidence of diseases and unhealthy conditions in these communities (Alves et al., 2021), thus indicating better quality of life conditions (Silva et al., 2019). Furthermore, it is important to point out that SSI_{sub} varies according to the percentage of households in precarious sanitary sewage disposal conditions, as explained in Eq. (6).

$$SSI_{sub} = \sum_{i=1}^n A_i \times (1 - Nph_{san}/Nph_{total})/A_{sub} \quad (6)$$

where SSI_{sub} is the SSI value per sub-watershed; A_i is the area of each census tract within the limits of the sub-watershed; Nph_{san} is the number of private households in each census tract without a bathroom or toilet and households with a bathroom or toilet connected to a rudimentary pit, ditch, river, lake, sea, among others; Nph_{total} is the total number of private households in each census tract; A_{sub} is the area of each sub-watershed studied.

As the SSI, the water supply index (WSUI) was also obtained using information from census tracts (IBGE 2012). In this case, information from permanent private households supplied with water from wells and springs and other forms of collection other than the general distribution network or cisterns was considered. This information is important, as

Table 1 Score of WPI

Riparian forests (%)	Score
$WPI \leq 60$	0
$60 < WPI \leq 70$	0.2
$70 < WPI \leq 80$	0.4
$80 < WPI \leq 90$	0.6
$90 < WPI \leq 95$	0.8
$WPI \geq 95$	1

it indicates how much water is extracted directly from water resources, potentially increasing the risk of water scarcity and deficit. Obtained per census tract, the final WSUI was calculated per sub-watershed using Eq. (7). So, $WSUI_{sub}$ values greater than 0.9 indicate that 90% of these households have a water supply network that regularly supplies water to the residents, enabling better water management by public managers, reducing the risk of water scarcity (Ahmad & Verma, 2018) and indicating the sub-watersheds that have the best conditions in terms of public water supply (Silva et al., 2019). It is important to note that the $WSUI_{sub}$ varies according to the percentage of households in precarious water supply conditions, as explained in Eq. (7).

$$WSUI_{sub} = \sum_{i=1}^n A_i \times (1 - Nph_{water}/Nph_{total})/A_{sub} \tag{7}$$

where

$WSUI_{sub}$ is the WSUI value per sub-watershed;

A_i is the area of each census tract within the limits of the sub-watershed;

Nph_{water} is the number of private households in each census tract that draw water from wells and springs and other forms of extraction that are neither part of the general distribution network nor capture rainwater stored in cisterns;

Nph_{total} is the total number of private households in each census tract;

A_{sub} is the area of each sub-watershed studied.

Finally, using the simple arithmetic mean between WPI, SSI, and WSUI, the potential water degradation index (PWDI) was obtained for each sub-watershed in the study area, according to Eq. (8).

$$PWDI = (WPI + SSI + WSUI)/3 \tag{8}$$

2.3 Creating the water resources sustainability index (WRSI)

To obtain the water sustainability index (WRSI), the analytic hierarchy process (AHP) method, as proposed by Saaty (2004), was applied. The AHP was used to establish weights within a value structure compared pairwise between the physicochemical water index (PWI), the wet vegetation index (WVI), and the potential water degradation index (PWDI). This allows even the least important indexes to contribute to the construction of the global indicator, thus being part of the decision-making process.

This process of comparison with indicators was improved with the support of specialists in watershed management, involving a multidisciplinary team composed of biologists, agronomists, geographers, forestry, and environmental engineers, to weights the pair-wise structure, allowing the replication, maintaining the integrity of the index and enabling the comparison, consequently, facilitating the management of territories that include different watersheds. To verify the consistency of the values were used the consistency ratio (CR) and the consistency index (CI). WRSI values were calculated per sub-watershed according to Eq. (9).

$$WRSI = \sum_{i=1}^3 ID(i) \times p(i) \tag{9}$$

where $ID(i)$ is the values of the PWI, WVI, and PWDI indicators per sub-watershed; $p(i)$ is the weight value determined by AHP for each index.

Then, the WRSI was classified into five classes of water sustainability as follows: excellent (1.0 to 0.91), good (0.90 to 0.71), regular (0.70 to 0.51), poor (0.50 to 0.26), or very poor (0.25 to 0.0). The classes assigned to the WRSI are compatible with the ranges established by the National Sanitation Foundation (NSF), adapted to centesimal numbers, as used in studies involving other locations, such as those developed by Effendi et al. (2015) in Banten Province, Indonesia, and Ferreira et al. (2015), in the Brazilian semiarid region. The adaptation of these WRSI classes is based on the variables used in the PWI indicator, which deals with the physical–chemical conditions of the water, which are deteriorated due to land use without adequate soil management practices captured by the WVI indicator, since the watershed has large arable areas (Silva et al., 2020), as well as the discharge of domestic effluents, represented in this study by the PDWI indicator that exposes the precarious sanitary and water supply conditions found in most Brazilian regions (Alves et al., 2021; Moura et al., 2020; Narzetti & Marques, 2020), and in the region of this study, as reported by Simonetti, Frascareli, et al. (2019) and Silva et al. (2019).

The composition of the WRSI variables is something new for the reality of Brazil, which has a scarcity in the supply of data (Sousa et al., 2021). Therefore, the set of these WRSI variables for watershed analysis is an important management tool that allows the assessment of different impacting conditions found in watersheds that exert relevant influences on their functional performance.

3 Results

Table 2 shows sampled values related to water quality parameters in the Una River Watershed, as well as the limits established by the Brazilian legislation for human consumption supply from rivers, after conventional treatment and considering protection of aquatic communities (CETESB, 2015).

The values obtained for phosphate (PO_4^{3-}) were transformed into total phosphorus (TP) by dividing phosphate (PO_4^{3-}) by 3.066. It is noteworthy that total solids (TS) do not present a standard concentration provided for in the CONAMA Resolution no. 357/05. The parameters PWI, pH, DO, and TP showed values above those allowed by the CONAMA Resolution no. 357/05, especially phosphorus in 81% of the points, a fact that may be related to the presence of agricultural activities that use fertilizers, since there is a predominance of agricultural vegetable crops. In addition, some of these points favor the carrying of phosphorus-rich sediments from agricultural areas within the watershed.

As for pH, there is a predominance of acid values above those allowed for the southern part of the watershed. These points also presented values above the limits allowed for both DO and TP, indicating that the presence of anthropic activities (agriculture) affects water quality in the watershed.

The DO presented values along the watershed lower than those allowed by the legislation, especially in agricultural areas with a high soil loss. This shows that sediment transport affects water courses, that is, the organic matter present in the soil is being carried away, thus consuming oxygen in its degradation. The other parameters were within the values determined by the legislation for this body of water.

Figure 3 shows the PWI map for the Una River Watershed per sub-watershed.

Table 2 Values of parameters sampled in field related to water quality. *Source:* SÃO PAULO (1978)⁽¹⁾; CONAMA (2005)⁽²⁾; CETESB (2015)⁽³⁾

Brazilian legislation and limits	6 a 9 ⁽²⁾	< 100µS/cm ⁽³⁾	> 5 mg/L ⁽²⁾	< 5 mg/L ⁽²⁾	Tu	TS	NO ₃ ⁻	< 0.1 mg/L ⁽²⁾
Collection points	pH	EC	DO	BOD	Tu	TS	NO ₃ ⁻	TP
1	6.61	106*	4.64*	2.01	3.77	104	0.70	0.20*
2	6.84	93	6.67	2.49	5.45	83	0.39	0.15*
3	6.76	108.1*	4.30*	0.71	4.28	83	0.00	0.20*
4	7.18	84	7.29	2.87	2.98	71	0.20	0.13*
5	6.71	114*	3.00*	1.16	5.85	110	0.25	0.21*
6	8.31	100*	3.95*	0.68	4.02	58	1.30	0.05
7	8.78	46	4.32*	0.45	6.32	34	1.10	0.11*
8	8.83	48	4.95*	0.56	8.22	24	0.69	0.08
9	8.15	37	3.52*	0.53	5.83	33	0.71	0.07
10	7.94	47	2.58*	1.11	18.90	70	1.10	0.18*
11	6.05	41	5.80	0.11	7.07	74	0.81	0.11*
12	4.65*	72	2.43*	1.94	10.00	105	0.50	0.28*
13	6.53	55	5.76	0.77	3.41	75	0.21	0.17*
14	6.26	30	5.38	0.54	4.50	59	0.67	0.11*
15	5.63*	42	5.40	0.92	6.59	65	0.27	0.39*
16	5.49*	43	5.07	0.80	5.69	66	0.64	0.09
17	4.78*	52	2.46*	2.18	9.92	77	0.10	0.39*
18	5.70*	27	5.10	0.03	3.41	53	0.60	0.12*
19	5.05*	30	4.49*	1.22	5.50	83.2	0.18	0.13*
20	5.41*	37	4.88*	1.52	4.71	55	0.29	0.13*
21	5.53*	104*	4.71*	1.42	8.74	67	0.46	0.13*

(*) It did not meet water quality limits

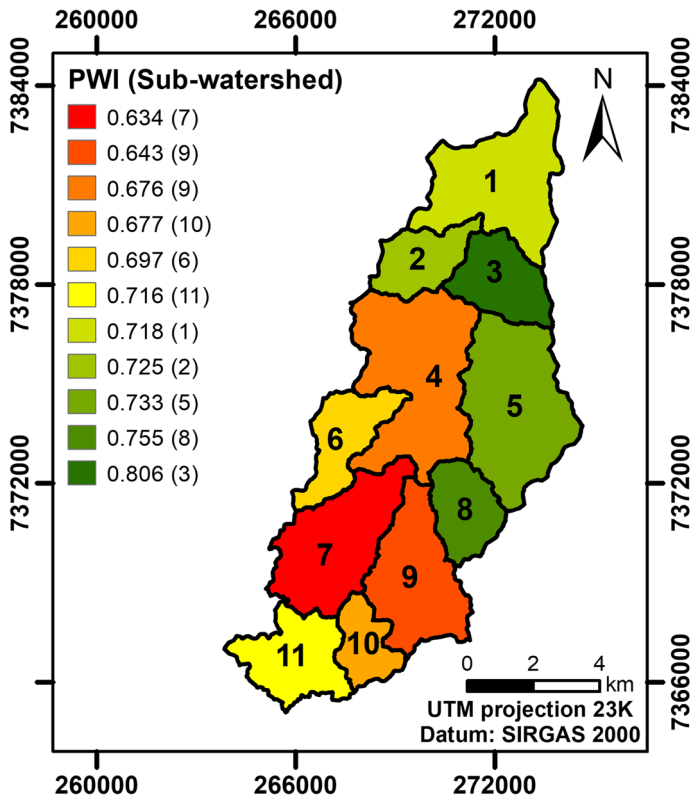


Fig. 3 Map of distribution of PWI values

The values found for PWI varied considerably. The lowest values are in the southern region of the watershed. They are influenced by the poor DO values and the regular values of phosphate and pH. It is noteworthy that EC also affected the low values of PWI, but to a lesser degree due to its low weight in the calculation of PWI and due to the few results above those allowed by the Brazilian legislation.

Figure 4A shows the NDWI map for forest area, and Fig. 4B shows the WVI map per sub-watershed.

NDWI values (Fig. 4A) varied considerably. The lowest values were found especially in the vicinity of urban areas to the north and in areas with intense agricultural activity close to the central region, including the occurrence of negative values, which indicate a high water stress suffered by the vegetation.

The map in Fig. 4B shows WVI values distributed per sub-watershed. It is possible to observe that the highest concentration of vegetation under water stress is in urban and agricultural areas, where the vegetation must compete with anthropic activities for water. In the northern region of the watershed, the WVI values were high since all values were above 0.9. This indicates that the vegetation of this area does not suffer from water scarcity. Thus, it is the most preserved area in the watershed.

Figure 5 shows SSI, WPI, and WSUI maps distributed per sub-watershed.

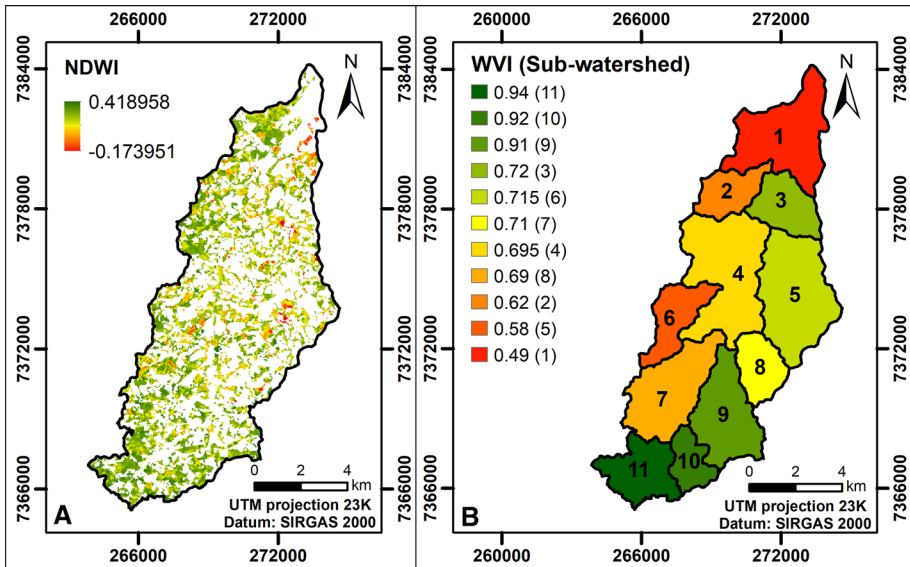


Fig. 4 NDWI map for forest areas and WVI map per sub-watershed

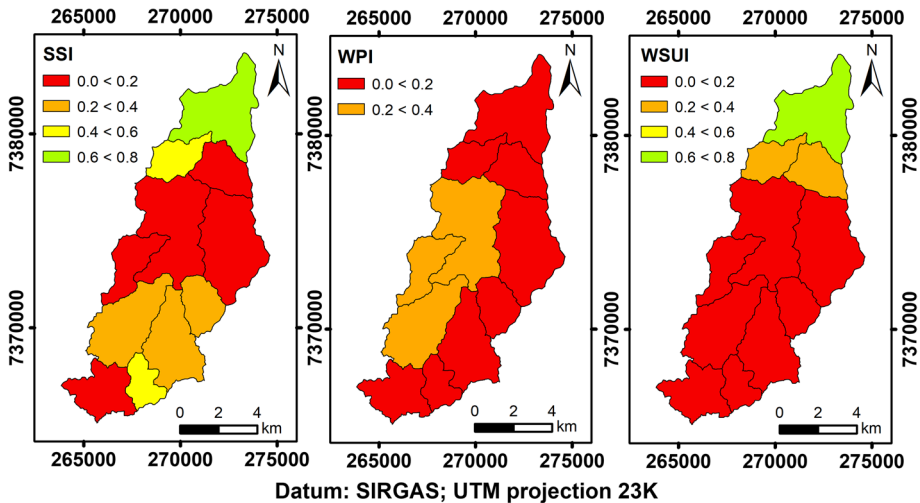


Fig. 5 Maps of SSI, WPI, and WSUI

According to the WPI map (Fig. 5), it is possible to observe that the integrity values of riparian forests are low for this watershed, even in its southern region, that is, the most preserved one. This is because the Law no. 12,651/2012, which provides for the protection of native vegetation, has given amnesty to the deforestation that occurred before its publication, making it less restrictive than the minimum value range for riparian forests adopted in this study and due to anthropic pressure mainly from agriculture.

The SSI map shows low values in the central and southern watershed and indicates that the population of these areas affects water resources due to the release of domestic sewage. Conversely, in the northern region, where most of the municipality's urban area is concentrated, the figures indicate a less marked impact on water resources in relation to the discharge of domestic sewage. This is explained by the fact that the population residing in the central and southern region of the watershed mostly discharges domestic sewage into rudimentary pits, while the population residing in the northern region of the watershed discharges most of its domestic sewage in the municipal collection network, since residents of that area are in an urban region supplied by the collection network.

Regarding WSUI values, both the southern and central regions showed low values, while the northern region presented the highest values in comparison with the rest of the watershed, since almost all households in this region are connected to the municipality's water distribution network.

Figure 6 shows the PWDI map for the Una River Watershed. It is possible to observe that PWDI values are below 0.5, that is, below 50% of the maximum allowed value for this index, which is partly explained by the low values of riparian forest conservation, while the south and central regions had very low values due to the lack of management in the distribution of water for human consumption and the release of domestic sewage. The central region is where the greatest concentration of agricultural activities in this watershed is and, possibly, there is a greater waste of water due to irrigation of agricultural crops.

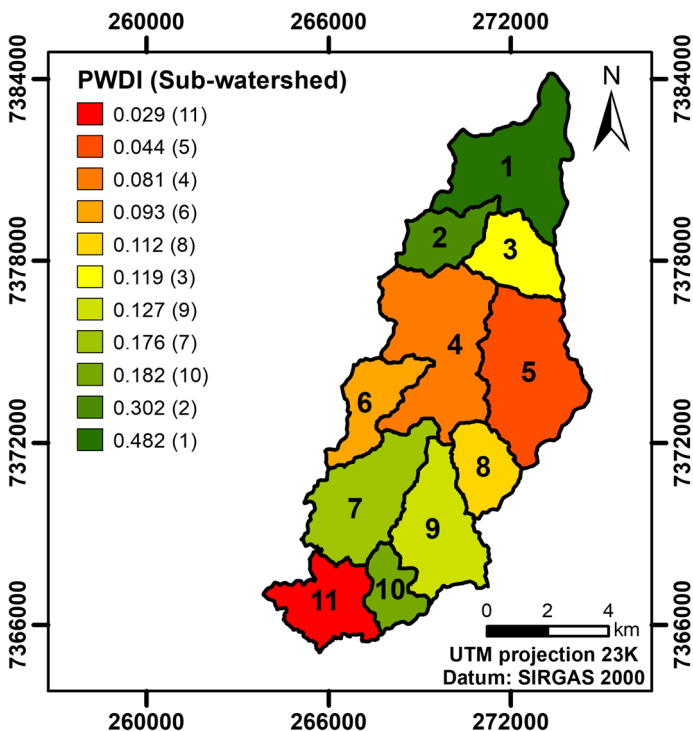


Fig. 6 PWDI map

Table 3 Matrix of paired comparisons of WRSI component variables

Variables (WRSI)	PWI	PWDI	WVI
PWI	1	3	9
PWDI	1/3	1	7
WVI	1/9	1/7	1

Table 4 Normalized weights of WRSI component variables

Variables (WRSI)	Normalized weight (p)
PWI	0.65
PWDI	0.29
WVI	0.06

The AHP method was applied to quantify the weight of each WRSI indicator. For this purpose, a paired comparison matrix was established between the three WRSI component variables through pairwise comparisons based on the judgment of the importance intensity of each variable, as shown in Table 3.

Table 4 shows the normalized weights for each WRSI index, determined by AHP for each index.

The consistency index (CI) value, calculated to assess the consistency of weights attributed to WRSI component variables by the AHP method, was 0.04, that is, below 0.1. Therefore, there is consistency in the values obtained. To further reinforce the assessment of data consistency, the consistency ratio (CR) was calculated, and the value obtained was 0.07, that is, below 0.1. According to Saaty (2004) and Franek and Kresta (2014), the suggested value of the CR should be no higher than 0.1. Therefore, this value indicates that the normalized weights calculated for WRSI are consistent.

Studies focused on environmental monitoring that used peer comparison, such as the one carried out by Do et al. (2013), used the AHP to assess the frequency of sampling the water quality of the Jingmei and Xindian Rivers in Taipei (Taiwan). To this end, the authors used historical monitoring data (2006 to 2010) containing water quality parameters, such as biological oxygen demand, suspended solids (SS), dissolved oxygen, total phosphorus, and ammoniacal nitrogen. Chowdary et al. (2013) used the AHP in Geographic Information Systems (GIS) as an aid in multicriteria decision-making for prioritizing micro-watersheds in India using information of potential erosion index and sediment delivery ratio, which is indicative of transport capacity. The authors found an agreement rate of 78%, revealing that watershed prioritization based on only thematic layers can be reliable.

In this study, the variable with the highest weight was the PWI, with a value of 0.65, while the variable WVI had the lowest weight (0.06), as can be seen in Table 4.

According to Franek and Kresta (2014), who compared different scales of judgment and measures of consistency in the AHP, it is up to the decision maker to choose the most appropriate scale for its problem. Thus, in order to minimize bias, the present study invited a group of experts and used their expertise, since judgment scales have a significant impact on the priorities of criteria, but not necessarily on the classification of criteria. A similar approach was found in the studies carried out by Singh et al. (2018), who assessed water

quality adequacy rates for irrigation purposes in India. The authors used the experience of a group of five members of the research area related to the theme of the study to compose the comparison matrix, similar as the method adopted in the present study, which resulted in weights corresponding to the 12 water parameters that drive irrigation in India, and which served as a subsidy for the elaboration of the irrigation water quality index.

Figure 7A shows the WRSI map, and Fig. 7B shows the classified sub-watersheds.

The WRSI values distributed per sub-watershed show that the lowest values are concentrated in the south of the basin. The sub-watersheds numbers 4 and 7 (Fig. 7A) presented the lowest value, close to 0.50. They are in the rural area of the municipality of Ibiúna, with the presence of agricultural activities and poor conditions of basic sanitation, which caused the low value, classified as "poor." All other sub-watersheds were classified as "regular" according to the proposed classification.

The WRSI values distributed by sub-watershed show that the best values are concentrated in the north of the watershed, while in the central portion toward the south of the watershed the values are lower, with emphasis on the sub-watersheds 4 and 7 (Fig. 7A), which presented the lowest value (close to 0.50). Figure 7B shows that all sub-watersheds have a regular classification, with the exception of sub-watersheds 4 and 7, which presented a poor classification. In general, the sub-watersheds that presented the worst values are in the rural areas of the municipality and, in large part, are areas with predominance of agriculture. Yet, the sub-watersheds with the lowest classifications have poor conditions of basic sanitation.

In this sense, several studies support the results found in this study, as they reported a decrease in the water quality of the Itupararanga reservoir, in which the Una River is one of the main components. Studies by Simonetti, Silva, et al. (2019) found the supply of nutrients in the Una River and other rivers that form the Itupararanga reservoir, such as nitrogen and phosphorus, coming from diffuse sources, of which agricultural areas are the main

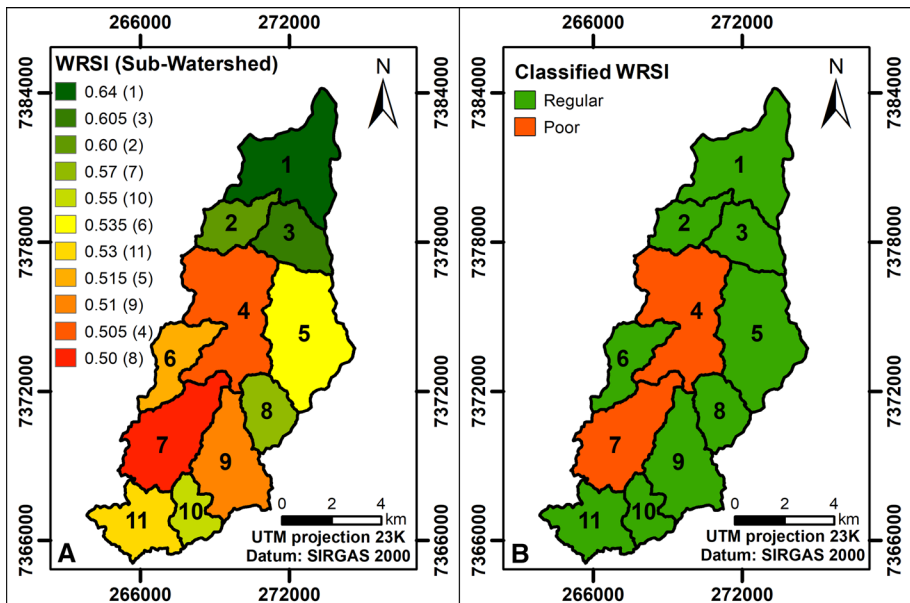


Fig. 7 Map of distribution of WRSI values

contributors. The authors quantified large agricultural extensions that, according to the findings of Silva et al. (2020), are areas that do not have conservationist practices, resulting in significant soil losses that may contain fertilizers. The authors accounted for the loss of annual chemical elements in the watershed, such as potassium (K) at 62.639 kg, 2.514 kg of phosphorus (P), 71.293 kg of magnesium (Mg), with calcium (Ca) being the element with the greatest loss (552.210) kg. However, the losses were observed in the entire extension of the watershed, with emphasis on the central-west of the watershed, which presented the highest annual losses. It is worth noting that the worst WRSI values obtained in the present study are corroborated by the studies by Silva et al. (2020), since the sub-watersheds present in this region, such as sub-watershed 4, obtained one of the worst WRSI values.

Temporal studies also point to a decrease in the water quality of the Itupararanga reservoir, such as those carried out by Frascareli et al. (2015), who evaluated the spatial and temporal heterogeneity of limnological variables in the Itupararanga reservoir, formed by the Una, Sorocabuçu, and Sorocamirim Rivers. Beghelli et al. (2016) evaluated the evolution of the trophic state of the reservoir over 15 years and reported the influence of the organic load that reaches the reservoir without treatment. Melo et al. (2019) also found problems associated with the supply of nutrients and high values of trophic state, in addition to metals such as iron (Fe) and manganese (Mn), released from the sediments to the water column, while aluminum and iron (Fe) were related to agricultural and urban areas through multivariate techniques and the use of self-organizing maps (SOMs).

Therefore, the low values obtained in this study are justified by the poor basic sanitary conditions in the study area and by agricultural activities that use fertilizers and are not guided or supervised by any public agency. The urban area, compared to the rural area, presented the best WRSI values, justified by the population's access to the best basic sanitary conditions and the low exposure to possible water contamination.

In view of the results, it is recommended that urban planning be carried out to expand basic sanitation for the entire watershed aiming to improve water resources and the population's access to good quality water, especially in the sub-watersheds characterized as "poor," as they are in conditions that may compromise the quality of life of the population.

According to the values found for each sub-watershed, it was possible, through a weighted average per area, to obtain the general WRSI value for the Una River Watershed, which was equal to 0.54, that is, the WRSI value found for that watershed can be classified as regular.

The database generated is an important instrument for the management of water resources and complies with the provisions of the Law no. 9433/97, which provides for Brazil's national water resources policy, since one of the water resource management instruments provided for is the Information System on Water Resources. Therefore, the generation of indicators supplies this information system and can facilitate the communication of the quality of water resources in a region, in addition to being an instrument comparable between watersheds.

4 Conclusion

Conclude that social inequalities, translating into access to quality basic sanitation, are more present in the rural area of the study area, in the central and southern part of the watershed, while the urban area of the municipality has 100% of its sewage treated. According to the 2010 Demographic Census, there are households not connected to the

public sewage collection network, which reflected in the values obtained for the PWDI. Thus, we conclude that the PWDI is sensitive enough to assess the water management situation and assist decision makers in managing the watershed.

A very positive aspect of PWI is that more indexes can be added to its composition considering the particularity of each region studied and the cases where these indicators are available for access by public and private managers who wish to work on it.

The limitation of this research is the fact that it used PWDI data corresponding to the last demographic census (carried out in 2010). Censuses are carried out every ten years and, due to the pandemic, it was not carried out in 2020. Even so, they are important data because they offer an overview of the environmental sanitation of municipalities, serving as the basis for several studies carried out in Brazil.

For future research, it is suggested to conduct a temporal analysis of the PWDI using data from the PWDI, WVI, and PWI indicators for the same year of publication of the demographic census, making it possible to establish a future projection that may identify which sub-watersheds are more propitious to a scenario of greater degradation in the quality of water resources. This helps to outline more effective urban planning strategies and, consequently, reflect positively on the quality of life of the population residing in this watershed. In addition, it is suggested to use other multiple-criteria decision analysis (MCDA) methods to compare the results and assess which method is best suited for analyzing the sustainability of water resources.

Using the information collected in this study, we conclude that the water resources sustainability index (WRSI) is an important tool that arises from the aggregation of three indicators (PWDI, WVI, and PWI), which allows to numerically interpret the reality of the water status in the Una River Watershed from a sustainable and simple perspective focusing on residents and water quality parameters in that area. Therefore, it is a quick, simple, and valid alternative for assessing water resources sustainability, in addition to being able to serve as a decision-making instrument for public managers and those interested in this issue.

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