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Development of a Watershed Sustainability Index for the Santiago River Basin, Mexico

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Abstract: Sustainability indices are a way of quantifying the progress that a certain region has achieved in terms of sustainability that can be transmitted to society and decision makers. The watershed approach has become relevant for managing water resources and ensuring their sustainability. This study combined the above two approaches by applying an adapted watershed sustainability index (WSI) to evaluate the sustainable development of the Santiago–Guadalajara River basin (SGRB), which passes through Guadalajara, the second-most populous city in Mexico. The river is the most polluted waterway in the country. The WSI of each sub-basin places the SGRB at a sustainability level between low in the upper and lower basin region and intermediate in the central basin region. Regions with a low sustainability level are characterized by environmental degradation due to changes in land use, while in the region with intermediate sustainability, the factor that most affect the evaluation is water availability. An overall sustainability score of WSI = 0.36 was obtained for the study area, which is lower than that of any other basins evaluated in the same manner around the world. These results send a clear message to decision makers of the three government levels, in charge of the environmental sustainability of the basin, of the need to take action to facilitate its recovery.

Keywords: watershed sustainability index; Santiago–Guadalajara River basin; human impacts on basins; natural resources preservation; mitigation policies

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1. Introduction

In Mexico, the increasing contamination of its rivers has made it necessary to develop policies focused on their sanitation and remediation. Guadalajara City was settled by the Spaniards in 1542, and it has grown from an initial population of 300 to 5 million in 2017, making it the second-largest metropolitan area in the country. The main fluvial stream that borders the city is the Río Grande de Santiago (i.e., Santiago River), which originates in Lake Chapala and flows 562 km to the Pacific Ocean. It has a catchment area of about 76,400 km^2 and an average flow of 320 m^3/s. A section of the river known as the Santiago–Guadalajara River basin (SGRB) is characterized by intensive industrial development extending from Ocotlán City near Lake Chapala to Guadalajara [1]. Over the last 50 years, the increasing population and rapid development of agriculture and industry have made the SGRB become one of the most polluted waterways in the country. The insufficient treatment of wastewater discharge, limited management of solid urban waste, and intensive use of agrochemicals have contributed to the environmental degradation of the SGRB. Erosion and sedimentation are becoming a serious problem because of the geomorphological characteristics of the SGRB resulting from poor agricultural practices, deforestation, and changes in land use due to rapid urbanization, where the application of environmental planning and management principles is generally absent [2,3].

Sustainable development has gained importance in recent decades, and for this reason, it has been gaining ground in the formulation of public policies, by not only stimulating economic growth but also promoting the equitable distribution of wealth, prioritizing environmental problems, and empowering people instead of marginalizing them [4], in its classic definition; however, the institutional dimension was added later, which focuses on peace and security [5,6]. In addition to these dimensions, Pawłowski [7] suggested including four more dimensions, namely moral, legal, technical, and political. Later, in 2015, world leaders, through the United Nations, adopted a set of global goals to eradicate poverty, protect the planet and ensure prosperity for all, establishing seventeen goals that are part of the sustainable development agenda. Of the seventeen objectives, the sixth focuses on guaranteeing the availability of water and its sustainable management, and sanitation for all.

Watersheds are vital to the existing inhabitants and wildlife within the respective region. The watersheds represent a hydrological unit due to the geography of the place and its runoff; the basins are a natural water drainage system, and this applies both to water within its natural cycle and to all water that has had human interaction: industrial, urban, and agricultural discharges, to name a few. The importance of watershed sustainability has become more relevant due to the growing awareness that the sustainability of watershed functions is an essential requirement for a sustainable future and human security [8].

Achieving watershed sustainability is not as simple as technical problems. It has become part of a complex interplay of ecology, socioeconomic, and policy processes. It must also ensure a long-term watershed management program while minimizing ecosystem degradation and maintaining the multiple roles of hydrology, environment, life, and policy indicators [8].

An increasingly common approach to making policy decisions regarding sustainable development is to aggregate sets of indices into an overall index [9] which returns a single value between zero and one that is easy to interpret. Sustainability indicators can help policymakers objectively understand the state and change over time of complex systems such as river basins and cities [10]. They help quantify the extent to which sustainability is being achieved, track progress toward sustainability, and provide information and guidance for development projects [11]. The indicators measure the progress of water resource management from the perspective of sustainability by observing the results of actions implemented in a basin [12]. Quantitative indicators and an objective means of verification are critical to assessing the degree of application and development, the results of intervention strategies and use of natural resources, and the extent to which sustainable development is realized [13,14].

This study focused on the environmental problems facing the SGRB and the efforts that the government and society have undertaken to improve its environmental conditions. The watershed sustainability index (WSI) developed by Chaves and Alipaz [15] was adopted to describe the socioenvironmental conditions of the SGRB. The results of this study can be used to inform stakeholders of the state of the SGRB and the need for actions to facilitate its recovery and sustainability.

2. Study Area

2.1. Geographic Location

The SGRB is in the Central West Hydrological Meso Region within the R12 Lerma-Santiago Hydrological Region. It belongs to administrative region VIII of the National Water Commission (CONAGUA), which is also called Lerma–Santiago–Pacifico [1]. Figure 1 shows the SGRB location and its hydrographic features. The highest concentration of population in the SGRB is in the Metropolitan Area of Guadalajara, which has more than

5.2 million inhabitants in the municipalities of Guadalajara, Zapopan, El Salto, San Pedro Tlaquepaque, Tlajomulco de Zúñiga, Tonalá, Ixtlahuacán de los Membrillos, Zapotlanejo, Acatlán de Juárez, and Juanacatlán (Figure 2) [16]. The small urban nucleus of Ocotlán, which has a population of close to 200,000 inhabitants, is also in the SGRB [17]. These inhabitants represent 62.0% of the entire population of the State of Jalisco. The SGRB has 3132 rural localities and 82 urban localities registered for a total of 3214 [1]. The SGRB has a total surface of 9829.63 km^2 with an elevation range of 2557 m and an average elevation of 1679 m above sea level. The highest elevations are at Tequila Volcano and Cerro Viejo at 2930 and 2960 m above sea level, respectively. The lowest elevations are at the bottom of the canyon of the Río Grande de Santiago. Slopes of 1°–3° cover 22.9% of the surface area, followed by slopes of 5°–10° covering 20.6% and slopes of 3°–5° covering 17.5%. Thus, 61% of the entire basin is covered by slightly to moderately inclined slopes. The dominant stream density is medium to high (2–8 km/km^2), which occupies 75% of the surface area [1]. Figure 2 shows the hypsometric map of the SGRB with sub-basins and municipal delimitation.

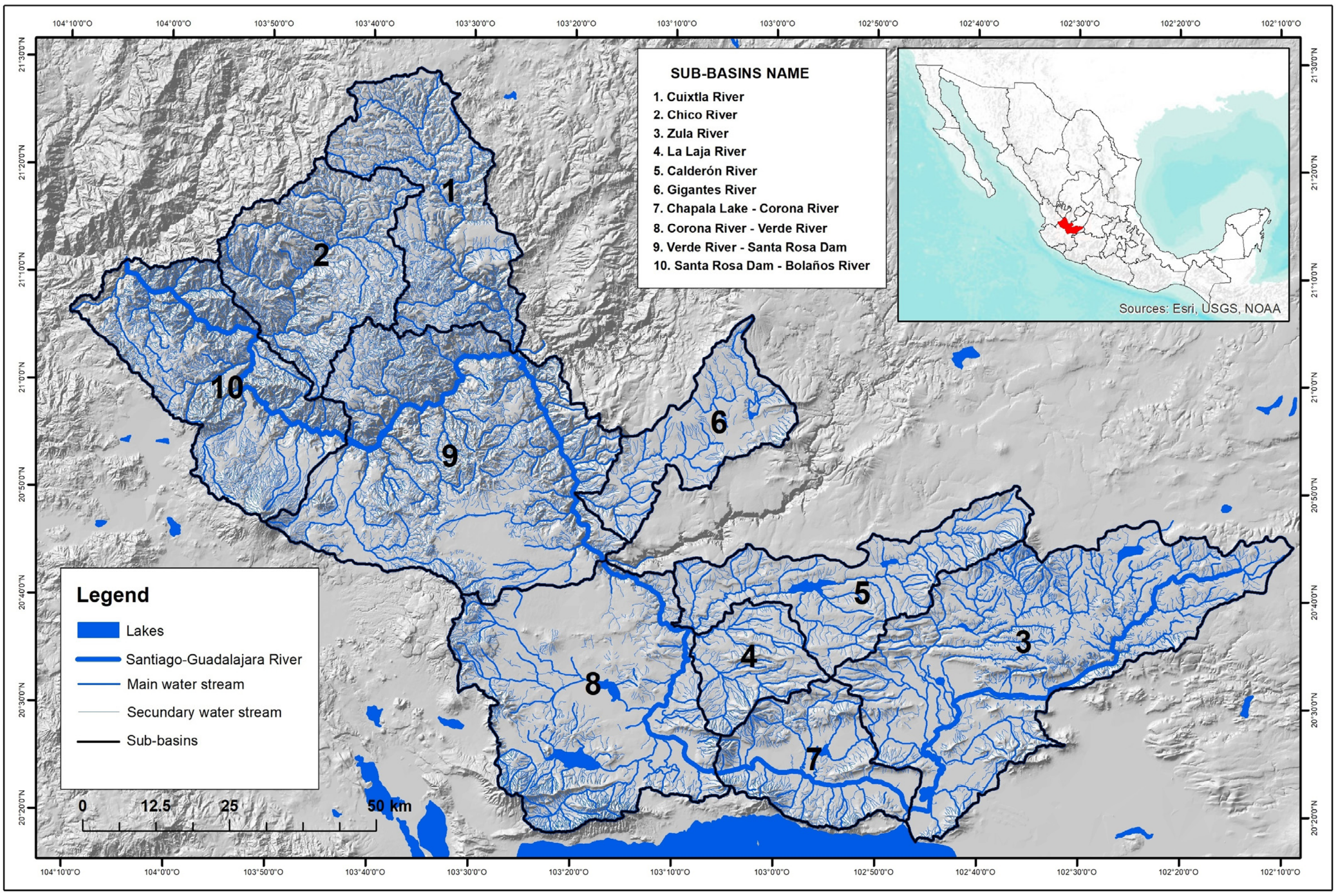

Figure 1. Location and hydrographic map of the sub-basins in the study area.

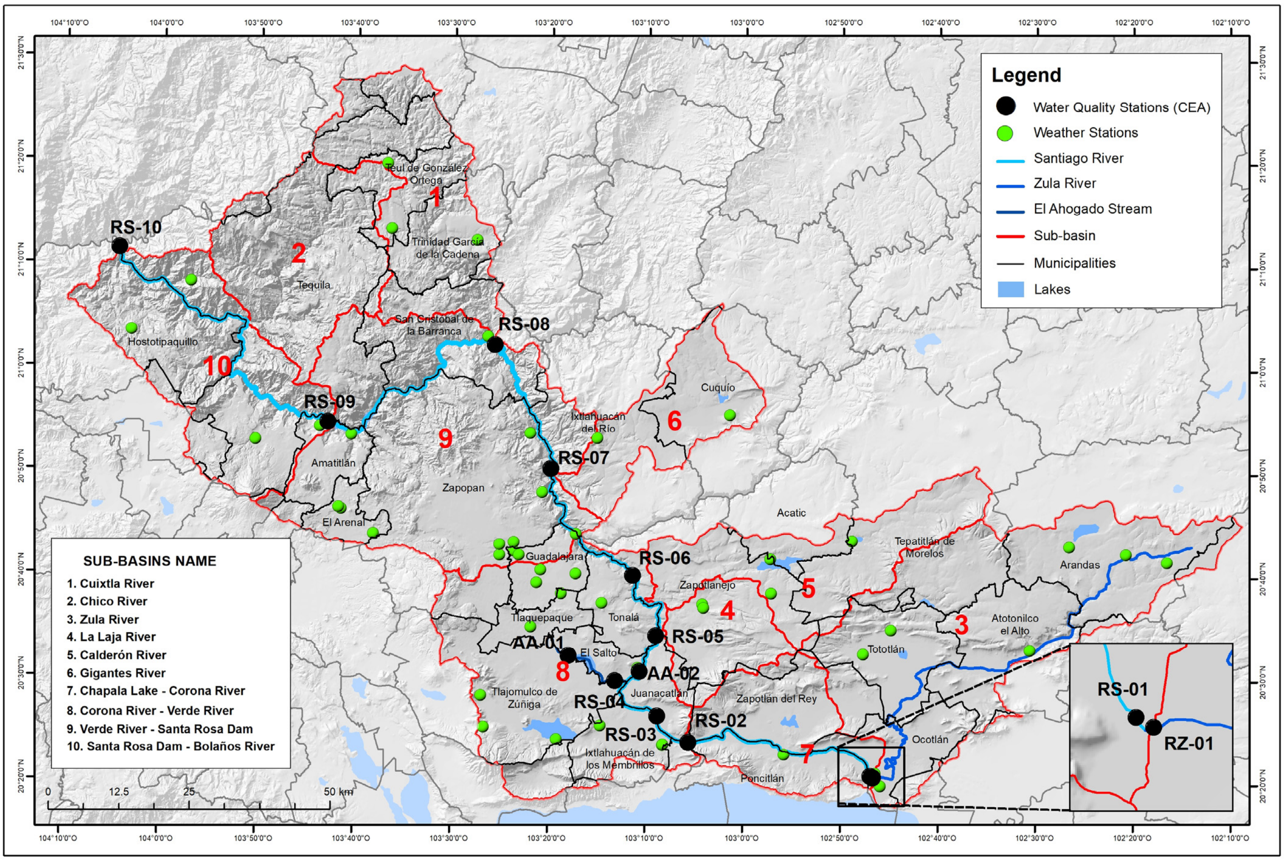

Figure 2. Geographic location of the Santiago–Guadalajara River basin, sub-basins and municipalities, and weather and quality stations of CEA Jalisco (i.e., study area).

2.2. Land Use

Figure 3 shows the land use and vegetation in the SGRB. The predominant land use is for agriculture, at 45.05%. Rainfed agriculture takes up 36.49% of the total area, followed far behind by irrigation agriculture at 8.37% and, finally, by humidity agriculture at 0.19% [1,18]. The largest area of rainfed agriculture is in the east of the SGRB, from the limits of the Guadalajara to Arandas municipalities (Figure 2). The area surrounding Tequila is also very important. Most of the irrigated agriculture is in the southeastern part of the SGRB north of Lake Chapala [1,18]. Forests (primary and secondary) cover the second-most area (20.09%) and include oak (13.71%), oak–pine (4.76%), and pine–oak (1.62%) forests [1,18]. The forests are predominantly in the northern part of the SGRB. In particular, the pine–oak forests are at the northern boundary. The oak forests have a wider distribution but are also predominantly in the north, with small and isolated patches in the southeast. The oak–pine forests surround the pine–oak forests in the north and center of the basin [1]. Deciduous forest covers the third-most area (14.86%), but most of this is secondary forest (9.96%). Deciduous forest is the most widely distributed among the types of land use and stretches from a very thin west–east strip in the north to the center and south, where it is mostly surrounded by agriculture [1,18]. Pastures (10.6%) cover the fourth-most area and are predominantly induced (10.5%), with the rest natural (0.1%), and they are covered by shrubby secondary vegetation. Grasslands are distributed as patches throughout the SGRB. The largest patches are in the north and are surrounded by forests and jungles (which are under serious threat of deforestation), and the smallest are in the agricultural zone [1,18]. Because of the small areas occupied by hydrophilic halophytic vegetation (i.e., other types of vegetation) (0.01%), no apparent vegetation (0.02%), and water bodies (0.91%), these land-use types were not included in further analysis [1,18]. Urban areas covered the fifth-most area (7.62%). Despite the small surface area, this land use had the greatest impact. The Metropolitan Area of Guadalajara lies at the center of the SGRB [1,18]. Other urban settlements include the cities of Arandas, Atotonilco el Alto, Totolán, Ocotlán, Poncitlán, Zapotlanejo, El Arenal, Amatitán, and Tequila.

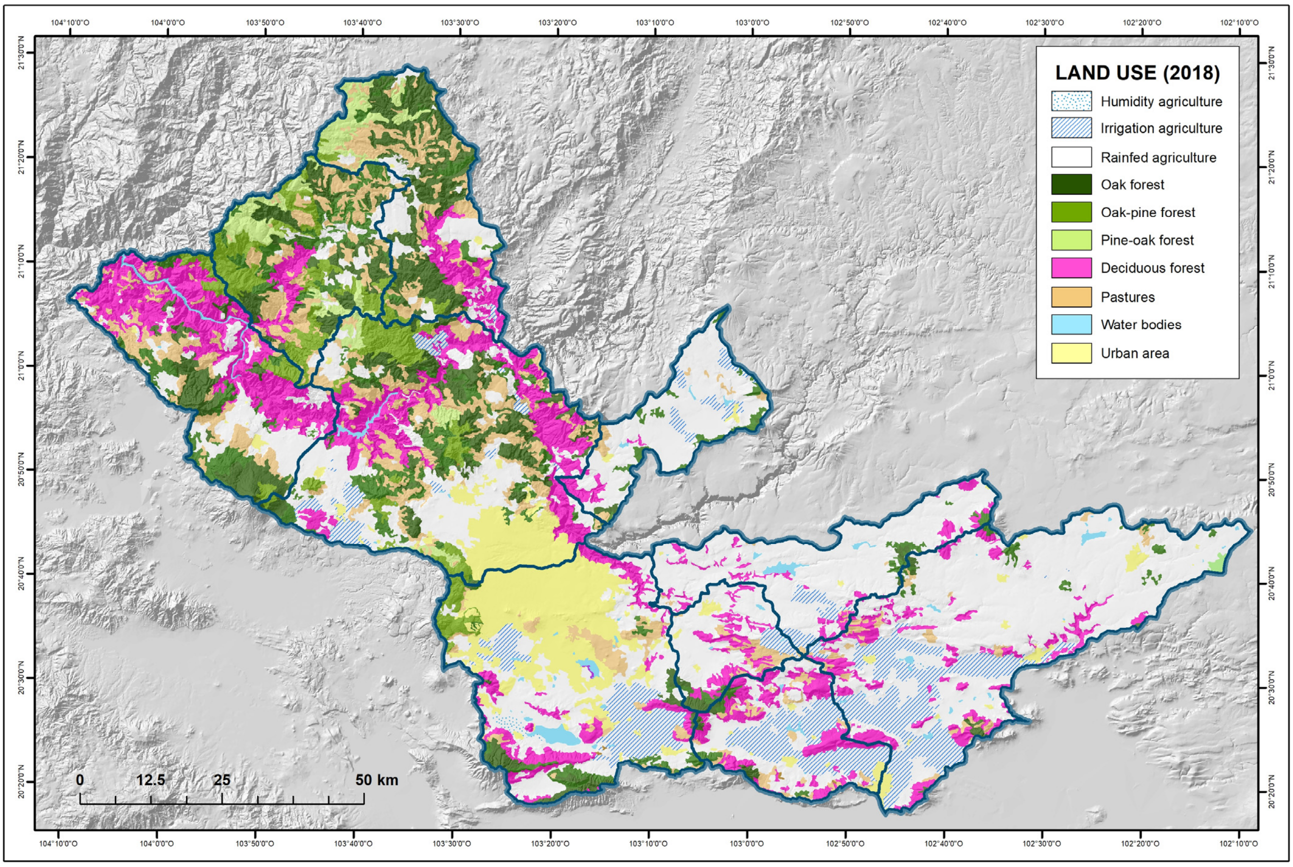

Figure 3. Land use and vegetation in the study area.

2.3. Main Industrial Activities

In 2021, the National Statistical Directory of Economic Units (DENUE) of the National Institute of Statistics and Geography (INEGI) reported that the SGRB has 27,858 companies, which is equivalent to 13.1% of all business activity in the State of Jalisco [19]. Of these companies, 85.8% are within the Guadalajara Metropolitan Area [20]. DENUE classifies economic activities according to their type of sector (i.e., primary, secondary, and tertiary). For this study, the following economic activities were considered. There were 107 companies dedicated to agriculture, animal breeding and exploitation, forestry, fishing, and hunting (0.38% of the total). There were 21 mining companies (0.07%). There were 189 utility companies (0.67%). There were 1560 construction companies (5.59%). There were 24,058 manufacturing companies (86.3%). There were 1923 companies (6.9%) dedicated to transport, mail, and storage. Of these companies, 2.6% were considered large (i.e., >250 workers), 23.3% were medium, and 74% were small (i.e., <50 workers). Most of the manufacturing companies were related to the food industry (22.9% of the total number of companies): animal feed, grinding grain and seed, and slaughter and processing of livestock and poultry. The textile industry represented 5.2% of all companies, and the plastics/rubber industry represented 3%. The chemical industry represented only 2.1% of the companies, but most were large, and they produced resins, synthetic rubbers, fertilizers, pesticides, paints, and adhesives. Figure 4 shows the degree of concentration of the main industrial activities in the SGRB. The cities of Arandas and Atotonilco El Alto stand out in the sub-basin of the Zula River up to Ocotlán. The Lake Chapala–Río Corona sub-basin contains an industrial corridor that goes from Poncitlán to the industrial corridor of El

Salto and Juanacatlán. The La Laja River sub-basin has the city of Zapotlanejo. Most of the Corona–Verde River sub-basin is covered by the Guadalajara Metropolitan Area. The cities of Arenal, Amatitán, and Tequila in the Río Verde-Presa Santa Rosa sub-basin towards the west of the SGRB have been developing thanks to the impetus of the tequila industry, which has been promoting agricultural activities in this area.

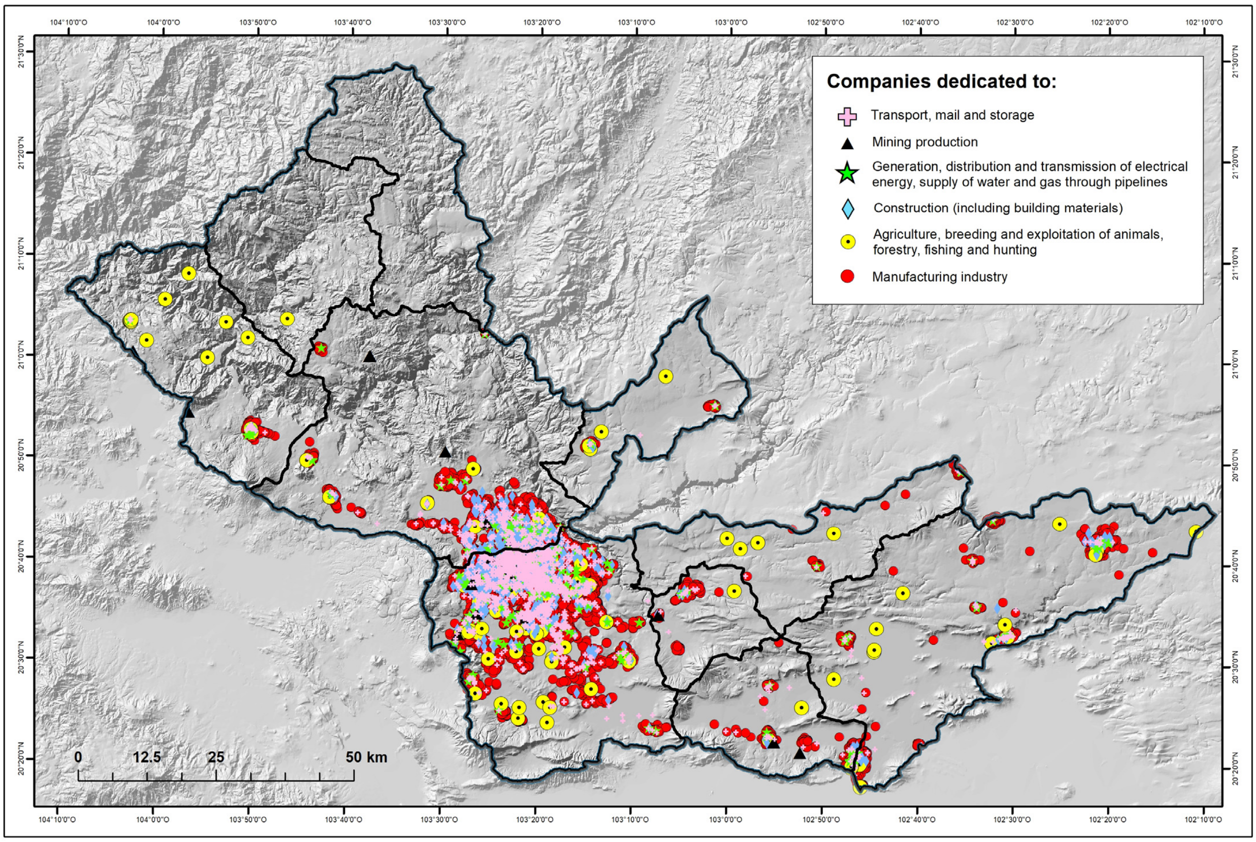

Figure 4. Locations of main industrial sectors in the study area.

2.4. Problem Description

As with any large river, the population within the SGRB depends heavily on its resources. The river serves as a source of drinking water, to irrigate and grow crops, to generate hydroelectric power, and as a way to discharge stormwater and wastewater. People who live outside the SGRB also use the river because it plays an important socioeconomic and environmental role for the entire State of Jalisco. The SGRB is one of the most important industrial corridors of the country, and the agricultural, livestock, and farming activities contribute significantly to maintaining the state as a leading food producer. However, wastewater discharge, agricultural runoff, infiltration of contaminants to the subsoil, leachate from municipal landfills, pollutant emissions from industry, vehicles, and brickmakers, and ongoing deforestation and degradation have accelerated the surface water contamination of the SGRB and its tributaries [1]. The lack of adequate environmental planning and management and poor surveillance of the existing environmental regulatory framework has led to significant problems with water and soil pollution [14,21]. The greatest degree of environmental degradation has been observed in the Ocotlán–El Salto–Juanacatlán corridor, which affects the health of inhabitants [22]. This has generated strong socioenvironmental conflicts and has provoked the collective action of organizations at the local, national, and international levels to address the above problems. The SGRB is one of the most important ecosystems in the region and a major water supply source for Guadalajara, and it is becoming more vulnerable to water contamination, overexploitation of surface water and groundwater, and the global effects of climate change. The increase in environmental temperatures and the depletion of the rainfall regime in the SGRB are becoming more obvious each year. Deforestation, excessive pollution, overexploitation of water resources, and overpopulation have been implicated as the main factors [3,14,23].

2.5. Environmental Monitoring Efforts

The CONAGUA has approximately 50 weather stations in the SGRB and even more in its vicinity. The State Water Commission (CEA) has a water quality laboratory that regularly monitors 13 of its own stations in the SGRB. These stations include one at the confluence of the Zula River with the Santiago River, two stations in the El Ahogado stream watershed, and one station in the Verde River watershed (Figure 2). CONAGUA monitors 43 water quality parameters [17], and CEA monitors 44 water quality parameters. In both cases, the main parameters are physicochemical and microbiological. The water quality monitoring network for the SGRB has not yet been expanded. Some attempts have been made to develop a water quality index that represents the river conditions as a single value, but the reliability needs significant improvement [24]. Rizo-Decelis and Andreo [16] are the only previous researchers to present a formal study on river water quality. They used the data from the CEA water quality laboratory in their analysis [25]. Tables 1 and 2 present the main parameters being monitored by CEA.

Table 1. Mean values of physicochemical and microbiological parameters measured in the water column of 13 sampling stations of CEA Jalisco for the Santiago watershed in the period of 2009–2019 [25].

Parameter	Units	WQ Data Points	Mean	Standard Deviation	Min	Max	Federal Law of Rights *
Dissolved oxygen	mg/L	1190	3.20	2.45	-	12.72	5
Fecal coliforms	MPN/100 mL	1234	2,312,635.50	9,505,245.49	3.00	1.10×10^8	1000
Biochemical oxygen demand	mg/L		26.82	42.98	1.26	300.00	
Potential of hydrogen	pH	1249	7.66	0.43	6.32	9.60	6.5–8.5
Water temperature	°C	1253	23.22	3.54	11.00	32.60	CN + 1.5
Total phosphorus	mg/L	1249	2.65	2.02	0.12	11.93	0.05
Nitrate nitrogen	mg/L	1237	1.03	1.54	0.05	10.97	-
Turbidity	NTU	1217	43.15	60.67	1.00	450.00	-
Total solids	mg/L	1242	639.89	260.01	4.00	1472.00	-
Sulfate	mg/L	1230	88.31	43.23	1.19	251.38	-
Sulfides	mg/L	1208	4.09	5.94	0.06	40.00	0.002

* Limits according to Water Quality Guidelines of the Federal Rights Law. Water body type C: protection of aquatic life in freshwaters, including wetlands [26].

Table 2. Mean values of heavy metals measured in the water column of the 13 sampling stations of CEA Jalisco for the Santiago watershed in the period of 2009–2019 [25].

Parameter	Units	WQ Data Points	Mean	Standard Deviation	Min	Max	Federal Law of Rights *
Aluminum	mg/L	1231	1.56	2.52	0.01	17.10	0.05
Arsenic	mg/L	1252	0.00	0.00	0.00	0.02	0.2
Barium	mg/L	1220	0.05	0.06	0.00	0.26	0.01
Cadmium	mg/L	1250	0.00	0.01	0.00	0.10	0.004
Copper	mg/L	1247	0.05	0.01	0.05	0.22	0.05
Iron	mg/L	1243	1.25	2.02	0.01	14.83	1
Mercury	mg/L	1247	0.00	0.00	0.00	0.00	0.0005
Nickel	mg/L	1246	0.10	0.01	0.10	0.24	0.6
Manganese	mg/L	1251	0.22	0.16	0.02	1.34	-
Lead	mg/L	1246	0.00	0.00	0.00	0.03	0.03
Zinc	mg/L	1247	0.07	0.09	0.01	0.95	0.02

* Limits according to the Water Quality Guidelines of the Federal Rights Law. Water body type C: protection of aquatic life in freshwaters, including wetlands [26].

3. Methods

3.1. Environmental and Sustainable Development Indices

In 2003, the Organization for Economic Co-operation and Development (OECD) published the reference paper "OECD Environmental Indicators" [27]. It adopts a conceptual framework based on the pressure–state–response model, which classifies indices as environmental pressures (both direct and indirect), environmental conditions, and societal responses. It also distinguishes several environmental issues that reflect major environmental concerns and challenges in OECD countries. In 2009, the United Nations (UN) published a guide on environmental and sustainable development indicators for Latin American and Caribbean countries [28]. In this study, the above two documents were used as a basis to propose suitable indicators for measuring the environmental and socioeconomic state of the SGRB [10,28,29].

3.2. Watershed Sustainability Index

The watershed sustainability index (WSI) was developed by Chaves and Alipaz [15], and it estimates the sustainability of a specific watershed by considering cause–effect relationships and the response to implemented policies. As given in Table 3, the WSI integrates four indices: hydrology (H), environment (E), life (L), and policies (P). Each index is further characterized by three parameters: the pressure, state, and response. The pressure refers to human impacts exerted on the basin over the environment and the natural resources such as flora, fauna, soil, air, and water. The state represents the situation that currently preserves the environment and the natural resources of the basin. The response is a measure of society's reaction to facing impacts on the environment and natural resources through the implementation of policies or projects to mitigate damages. The pressure–state–response model incorporates cause–effect relationships, so it provides a more general understanding than that provided by an index that only examines a single parameter, such as the state. Figure 5 presents the aggregation stages of the WSI. If each index is given an equal weight, the simplest linear form of the WSI is given by [15].

$$\mathrm{WSI} = \frac{\mathrm{H} + \mathrm{E} + \mathrm{L} + \mathrm{P}}{4} \tag{1}$$

Table 3. Indices and parameters of the watershed sustainability index (WSI) [15].

Indices	Pressure	State	Response
Hydrology (H)	Variation in the basin's per capita water availability in the analysis period	Basin per capita water availability (long-term average)	Improvement in water-use efficiency in the analysis period
	Variation in the basin BOD5 in the analysis period	Basin BOD_5 (long-term average)	Improvement in sewage treatment/disposal in the analysis period
Environment (E)	EPI of the basin (rural and urban) in the analysis period	Percent of the basin area with natural vegetation	Evolution in basin conservation (percent of protected areas, BMPs) in the analysis period
Life (L)	Variation in the basin per capita income in the analysis period	Basin HDI (weighted by county population)	Evolution in the basin HDI in the analysis period
Policy (P)	Variation in the basin HDI-education in the analysis period	Basin institutional capacity in integrated water resources management (IWRM)	Evolution in the basin's integrated water resources management (IWRM) expenditure in the analysis period

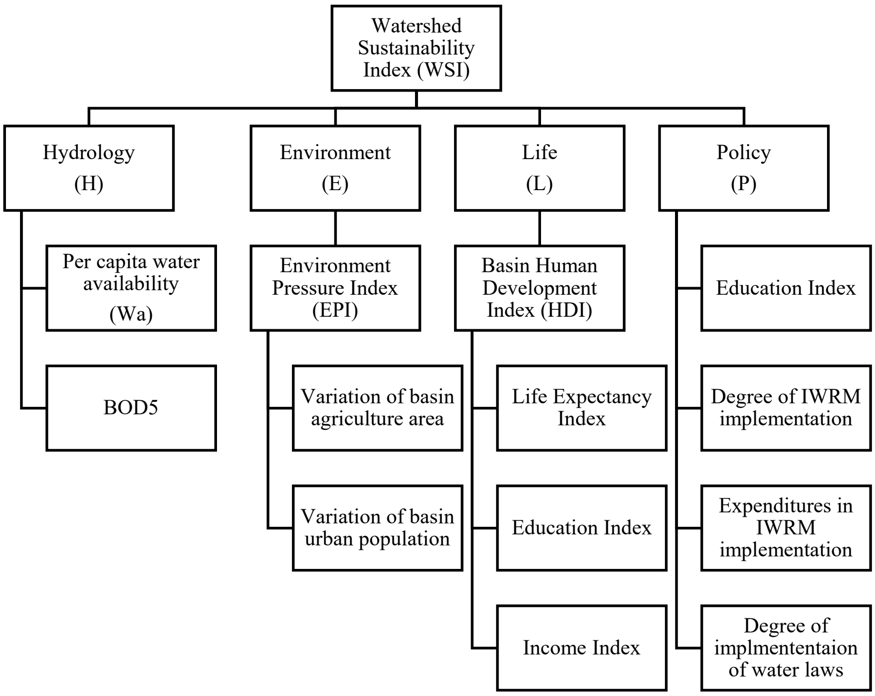

Figure 5. Stages of aggregation for the WSI [15].

3.3. Literature Review of the WSI

Since Chaves and Alipaz [15] published their work, several authors have adopted and modified their approach to estimate the WSI for specific river basins. In the present study, a careful analysis of the state of the art was carried out by comparing the strategies adopted by different authors to generate WSI values for different river basins. Table 4 indicates that most of the authors followed the basic principles of the original WSI [15], but some added other indices or modified the original [30]. Figure 6 shows the locations of the river basins to which WSI was applied.

Table 4. Comparison of WSI values for different river basins in the literature.

Author	Year	Studied Basin	WSI
Chaves and Alipaz [15]	2006	Verdadeiro River basin, Brazil	0.65
Calizaya [31]	2008	Lake Poopo watershed, Bolivia	0.46, 0.36, 0.59 *
Cortés [32]	2012	Elqui River basin, North-Central Chile	0.61
Preciado-Jiménez [33]	2013	Lerma–Chapala watershed, Mexico	0.61
Catano [9]	2014	Reventazón River basin, Costa Rica	0.74
Chandniha [34]	2014	Chhattisgarh basin, India	0.55
Firdaus [8]	2014	Batang Merao watershed, Indonesia	0.59
Vanle [30]	2015	Nhue–Day River basin, Vietnam	0.50
Senent-Aparicio [35]	2016	Cuenca del Segura, Spain	0.64
Mititelu-Ionuş [36]	2017	Motru River, Romania	0.36, 0.51 **
Elfithri [37]	2018	Langat River basin, Malaysia	0.68
Ahuchaogu [38]	2019	Ikpa River basin, Nigeria	0.60

* WSI calculated without storage, in dry season, and with storage. ** WSI calculated for 5- and 10-year periods.

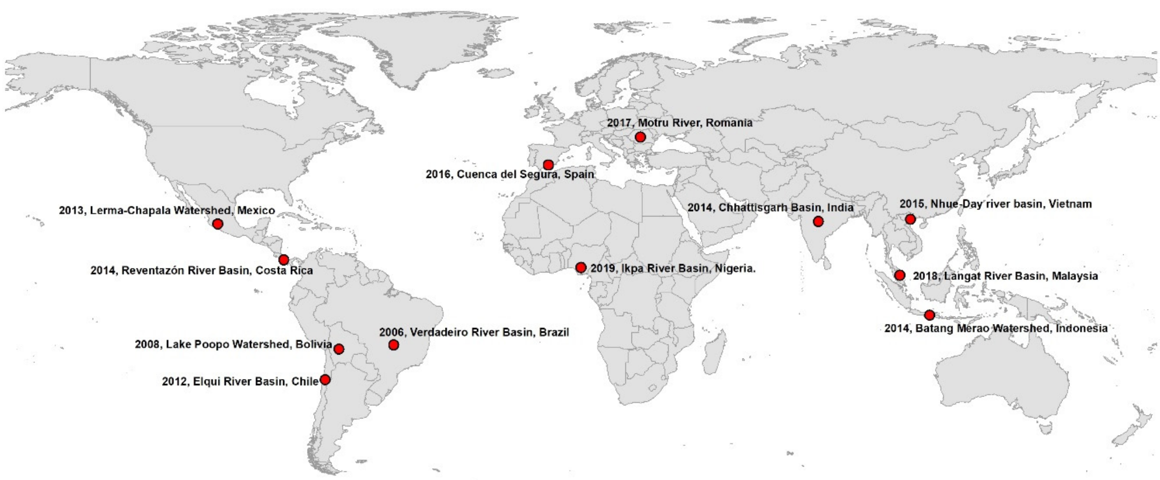

Figure 6. Applications of WSI to river basins around the world [8,9,15,30–38].

3.4. Implementation of the WSI to the SGRB

The component indices of the WSI are explained as follows: hydrology, environment, life, and policy. The hydrology index is further divided into quantity and quality sub-indices. As noted above, each index is represented by the pressure, state, and response parameters. All parameters are referred to on a five-point scale according to the normalized limits indicated in Table 5, and colors match with scores where red is the worst scenario and baby blue is the best scenario. With this criterion, the range of each index goes from 0 to 1. For the present work, the evaluation of each index and each parameter was carried out for each of the ten sub-basins that comprise the SGRB (Figure 1), given that basin management at the local and regional level is more effective in basins of up to 2500 km^2 as mentioned in Schueler [39].

Table 5. Five-point scale for grading component indices and parameters.

Very Low	Component $\leq$ 0.2
Low	0.2 < Component $\leq$ 0.4
Intermediate	0.4 < Component $\leq$ 0.6
High	0.6 < Component $\leq$ 0.8
Very High	Component > 0.8

3.4.1. Hydrology Quantity

For the hydrology (quantity) index, the pressure parameter evaluates the variation in per capita water availability (Wa) in the study period. The state parameter evaluates the long-term average Wa in the basin. The response parameter evaluates the change in water usage efficiency in the period. The pressure parameter is evaluated on a five-point scale according to the percentage variation of Wa with respect to the reference year to the end of the study period: (1) $\Delta 1 \leq -20\%$, (2) $-20\% < \Delta 1 < -10\%$, (3) $-10\% < \Delta 1 < 0\%$, (4) $0\% < \Delta 1 < 10\%$, and (5) $\Delta 1 > +10\%$. The state parameter is the value of Wa in the reference year and is evaluated on a five-point scale as a function of the stress produced when Wa falls below a minimum of 1700 m^3/year [40] and subsequent multiples: (1) Wa < 1700, (2) 1700 < Wa < 3400, (3) 3400 < Wa < 5100, (4) 5100 < Wa < 6800, and (5) Wa > 6800 m^3/year. Finally, the response parameter is evaluated qualitatively on a five-point scale: (1) very low, (2) low, (3) intermediate, (4) high, and (5) very high. For all parameters, a score of 5 is good, while a score of 1 is bad.

The Wa data were obtained from the Official Gazette of the Federation (DOF) [41–55]. The Wa obtained from DOF considers some environmental water requirements to preserve the ecosystems. The Wa was calculated by considering the per capita water availability of the sub-basins (surface water) and the per capita water availability of the aquifers (groundwater). Because the parameters were referred to the sub-basins, the per capita water availability in the aquifers was distributed by weighting their areas of influence within each sub-basin (Figure 7). The study period was set to 2016–2020 in intervals of 5 years.

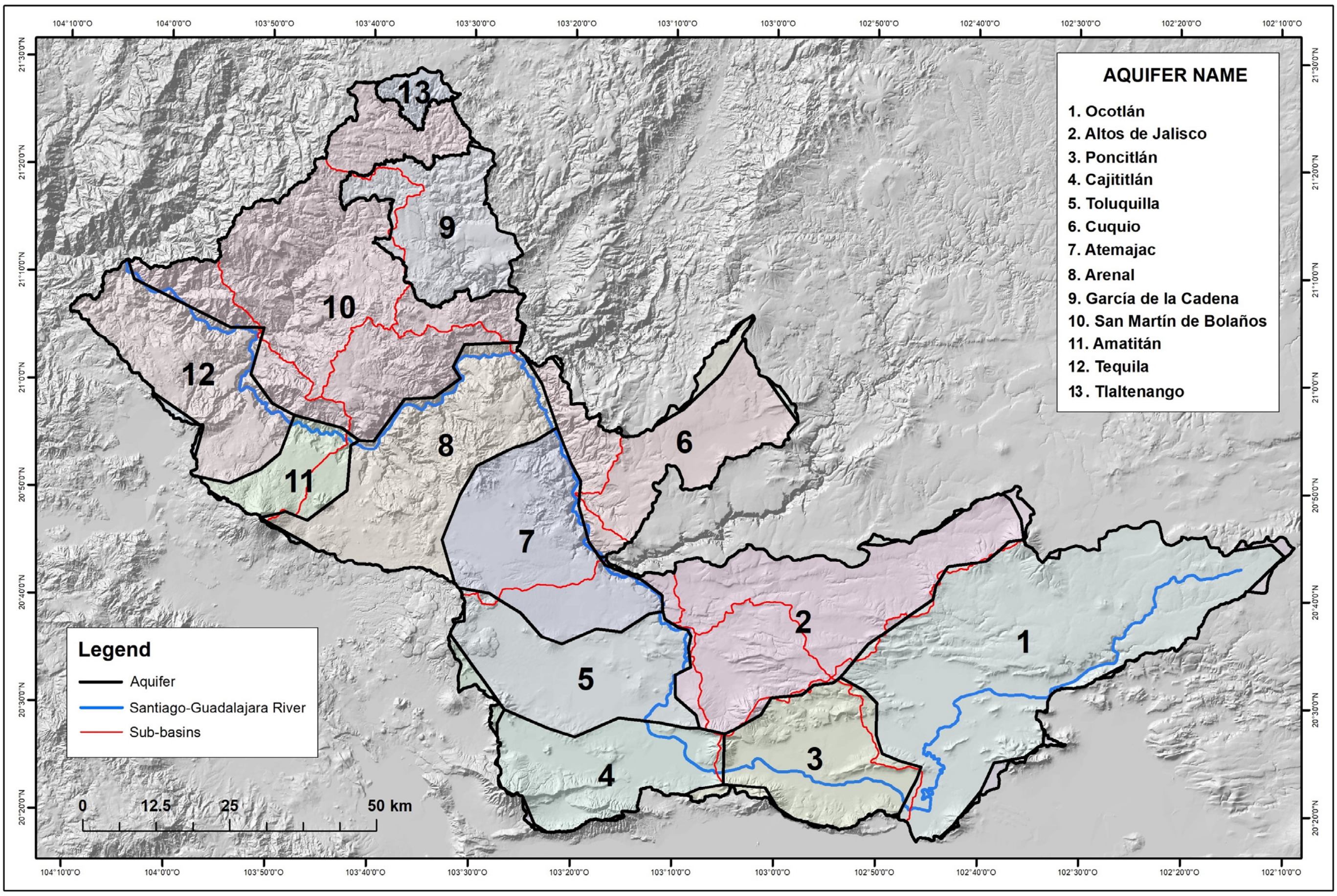

Figure 7. Aquifers within the Santiago River basin.

To estimate the population of each sub-basin, population centers were analyzed under the assumption that the total municipal population lives in the sum of the areas of the population center. Furthermore, the populations were assumed to be uniformly distributed in these areas (i.e., the population centers of the municipality had the same population density). Under these assumptions, the areas of urban sprawl were used to obtain the population percentages that each municipality contributes to each sub-basin. Once the populations for each administrative sub-basin were obtained, the percentages of population contribution from each municipality to each sub-basin were calculated for each year. The population data were obtained from data collected by INEGI every 5 years. INEGI has published population census data from 2000 to 2020.

The response parameter was evaluated according to the UNEP questionnaire described in Section 3.5. This parameter used the Management Instruments section, which was shared with the response parameter of the hydrology quality sub-index.

3.4.2. Hydrology Quality

For this sub-index, the water quality is represented by the biochemical oxygen demand for a period of 5 days (BOD_5). It provides important information on how favorable a body of water is to life. It is also a commonly measured parameter and thus is widely available. The pressure parameter is evaluated on a five-point scale according to the variation in BOD_5 in the study period: (1) $\Delta 2 > 20\%$, (2) $20\% > \Delta 2 > 10\%$, (3) $10\% > \Delta 2 > 0\%$, (4) $0\% > \Delta 2 > -10\%$, and (5) $\Delta 2 < -10\%$. The state parameter is evaluated on a five-point scale according to the long-term average BOD_5: (1) $BOD_5 > 10$, (2) $10 > BOD_5 > 5$, (3) $5 > BOD_5 > 3$, (4) $3 > BOD_5 > 1$, and (5) $BOD_5 < 1$. Finally, the response parameter is evaluated qualitatively according to the evolution in the treatment/disposal of wastewater in the study period: (1) very low, (2) low, (3) intermediate, (4) high, and (5) very high; this qualitative parameter was obtained via the section of Management Instruments from the questionary explained on Section 3.5.

The pressure and state parameters of the hydrology quality sub-index were evaluated according to BOD_5 data measured by CEA Jalisco from 2009 to 2019. The data were taken from 13 sampling points along the Santiago River (Figure 2), which were used to represent different sub-basins according to their geographical locations. These samples are collected monthly.

3.4.3. Environment

The environment index considers the variation in agricultural areas, population, and protected regions within the basin. The pressure parameter is represented by the environmental pressure index (EPI), which is the average between the variations of the agricultural area and population of the basin and is an indicator of the basin's overall environmental integrity.

The pressure parameter is evaluated on a five-point scale: (1) EPI > 20%, (2) 20% > EPI > 10%, (3) 10% > EPI > 5%, (4) 5% > EPI > 0%, and (5) EPI < 0%. The state parameter is the percentage (Av) of the watershed surface that is still natural vegetation, and it is evaluated on a five-point scale: (1) Av < 5%, (2) 5% < Av < 10%, (3) 10% < Av < 25%, (4) 25% < Av 40%, and (5) Av > 40%. The response parameter is the evolution in protected areas (i.e., reserve areas) of the basin in the study period, and it is evaluated on a five-point scale: (1) $\Delta \leq -10\%$, (2) $-10\% < \Delta < 0\%$, (3) $0\% < \Delta < 10\%$, (4) $10\% < \Delta < 20\%$, and (5) $\Delta > 20\%$.

For the environment index, the pressure parameter was evaluated according to the EPI, which considers the variation in agricultural and urban areas. Satellite geographic data were collected from the INEGI Series database. The state parameter was evaluated according to the percentage of natural vegetation remaining, which was again determined according to satellite data from the INEGI Series database. For the response parameter, the evolution of protected areas was obtained from the State System of Natural Protected Areas [56].

3.4.4. Life

The life index represents the quality of life or human development in the basin. Human development is defined as the equitable expansion of people's freedom, and it involves increasing the options of those with fewer opportunities. It is not about the mere accumulation of resources but is also about the reduction in restrictions to pursue one's own objectives [39]. The UN uses the human development index (HDI), which has three basic components: the ability to lead a long and healthy life, which is measured by life expectancy at birth (HDI-Life Expectancy); the ability to acquire knowledge, which is measured by mean and expected years of schooling (HDI-Education); and the ability to achieve a decent standard of living, which is measured by the gross national income per capita (HDI-Income) [57]. Mexico follows UN guidelines and calculates the HDI for each municipality.

For the life index, the pressure parameter is evaluated according to the variation in HDI-Income for the study period on a five-point scale: (1) $\Delta \leq -20\%$, (2) $-20\% < \Delta < -10\%$, (3) $-10\% < \Delta < 0\%$, (4) $0\% < \Delta < 10\%$, and (5) $\Delta > 10\%$. For the state parameter, the HDI of the reference year is evaluated on a five-point scale: (1) HDI < 0.5, (2) 0.5 < HDI < 0.6, (3) 0.6 < HDI < 0.75, (4) 0.75 < HDI < 0.90, and (5) HDI > 0.90. For the response parameter, the variation in the HDI for the study period is evaluated on a five-point scale: (1) $\Delta \leq -10\%$, (2) $-10\% < \Delta < 0\%$, (3) $0\% < \Delta < 10\%$, (4) $10\% < \Delta < 20\%$, and (5) $\Delta > 20\%$.

The municipal HDI was obtained from data collected by INEGI every 5 years. However, no HDI data are available for 2020, so logarithmic extrapolations were performed instead. To estimate the HDI on each sub-basin, the same procedure followed for population was applied. There is no population center reported in the Río Chico sub-basin (numbered as 2), so its life index cannot be calculated.

3.4.5. Policy

For the policy index, the pressure parameter is evaluated according to HDI-Education, which has a positive correlation with a population's willingness to become involved in water management and exert pressure on decision makers, as stated in [15]. The state and response parameters are qualitative. The state parameter is evaluated according to the capacity of the basin to incorporate the objectives of integrated water resources management (IWRM). The response parameter is evaluated according to the resources allocated to IWRM in the study period.

The pressure parameter was obtained by interpolating HDI-Education for each sub-basin and also applying the procedure followed for the population, on a five-point scale: $\Delta \leq -20\%$, (2) $-20\% < \Delta < -10\%$, (3) $-10\% < \Delta < 0\%$, (4) $0\% < \Delta < 10\%$, and (5) $\Delta > 10\%$. The state and response parameters were obtained from the UNEPA questionnaire described hereinafter. For the state parameter, responses from the Institutions and Participation section of the questionnaire were used: (1) very low, (2) low, (3) intermediate, (4) high, and (5) very high. For the response parameter, the Financing section of the questionnaire was used because it focused on the evolution of the budget directed to IWRM objectives, again with scores (1) very low, (2) low, (3) intermediate, (4) high, and (5) very high.

3.5. About the Adaptation of the Questionnaire of the UNEP

Some state and response parameters were evaluated according to the questionnaire developed by the United Nations Environment Program (UNEP) for measuring the level of implementation of strategies aimed at meeting IWRM objectives at the national level [58]. The questionnaire was modified to be applicable to the conditions and scope of this study. It is comprised of four sections; the first one covers Enabling Environment, the second Institutions and Participation, the third Management Instruments, and the fourth Financing, all four with the IWRM perspective.

This questionnaire was then distributed to the entities responsible for water management in Mexico at the federal, state, and municipal levels: CONAGUA, CEA, and the Intermunicipal System of Water Services (SIAPA), respectively. Each entity was requested to study the questionnaire for understanding and then answer it in study groups directed by the authors. Every question had five possible answers, (1) very low, (2) low, (3) intermediate, (4) high, and (5) very high. Each answer was obtained by consensus among participating officials with a score from 0 to 100 that was then normalized between 0 and 1 to use directly in the index calculations.

4. Results and Discussions

4.1. Hydrology Index

4.1.1. Hydrology Quantity Sub-Index

Figures 8 and 9 graph the water availability per capita for the sub-basins and the entire SGRB, respectively, for the study period of 2006–2020. Water availability showed a downward trend over the years. In contrast, the population showed an upward trend for both the sub-basins and the entire SGRB, as shown in Figures 8 and 9, respectively. Seeing both at the same time shows the necessity of improving the water management in the area, with special attention to the Santa Rosa Dam–Bolaños River sub-basin (numbered 10), where the highest drop in water availability is observed. For the sub-basin numbered 2, Chico River, no population data are reported.

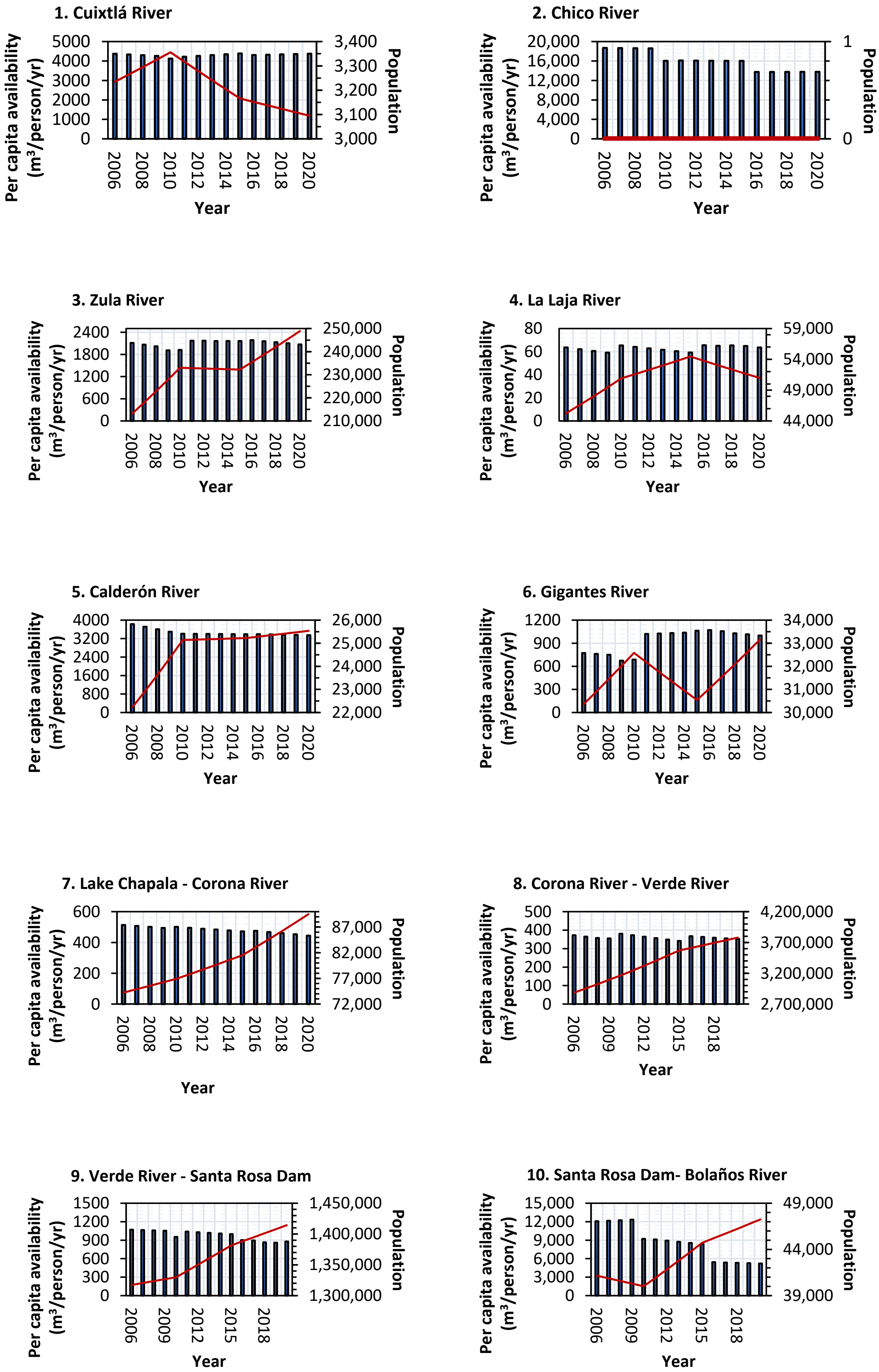

Figure 8. Average annual water availability per capita (bars) and population (solid red line) of each sub-basin from 2006 to 2020.

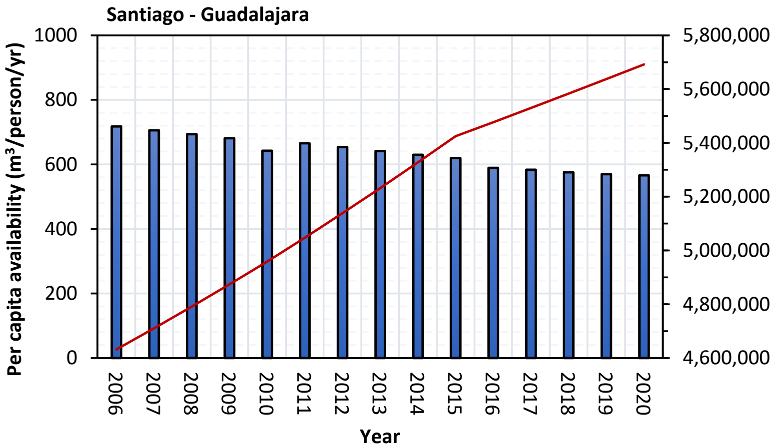

Figure 9. Average annual water availability per capita (bars) and population (solid red line) of the study area from 2006 to 2020.

The Wa showed a variation of less than 10.16% with respect to the historical average, which corresponds to a whole score of 0.25 for the pressure parameter on the SGRB. Figure 10 shows the pressure parameter for each sub-basin where it is evident that the sub-basins 10, 2, and 9, located in the lower part of the basin, obtained the lowers scores. The sub-basins 3, 5, 6, and 7 of the upper basin obtained an intermediate score, while sub-basins 1, 4, and 8 seem to be in a better situation according to the criteria. For the state parameter, the situation of the average Wa, Figure 11, is not favorable, since the scores are very low in the middle region of the basin, where the population is concentrated, while the scores are low at the east and west extremes. The average responses obtained from CONAGUA, CEA Jalisco, and SIAPA during the questionary application was 27.78 for the response parameter, which corresponds to a low score on the entire basin (Figure 12).

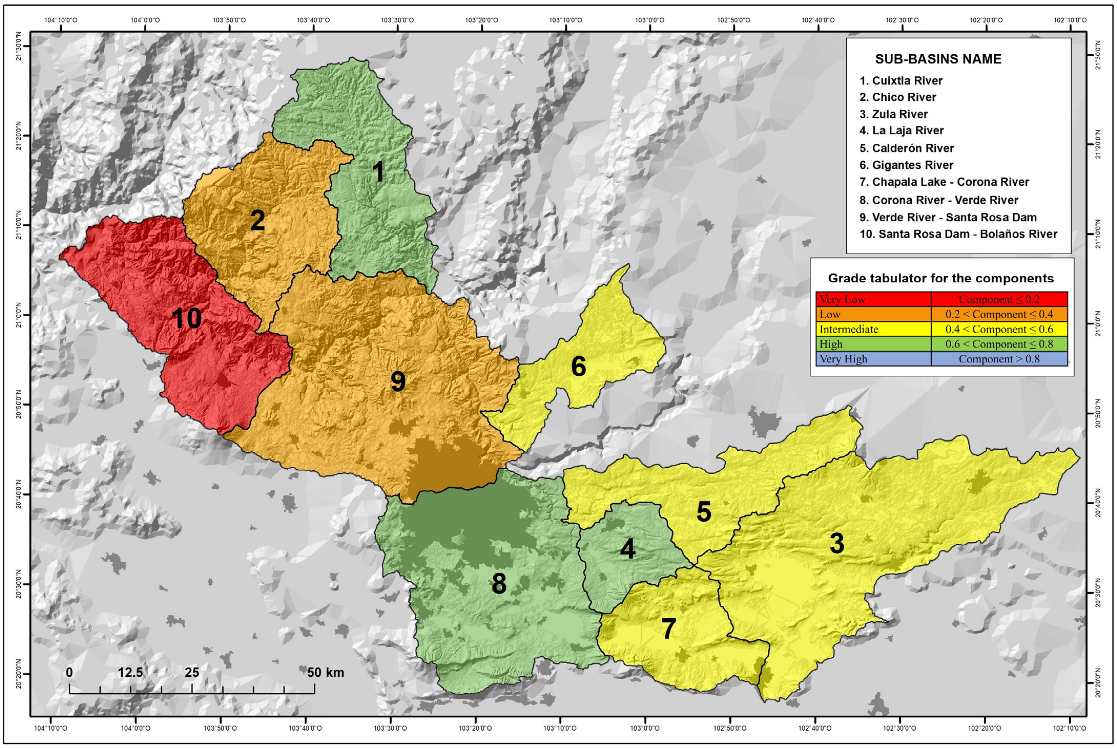

Figure 10. Scores of the hydrology (quantity) index by sub-basin: pressure.

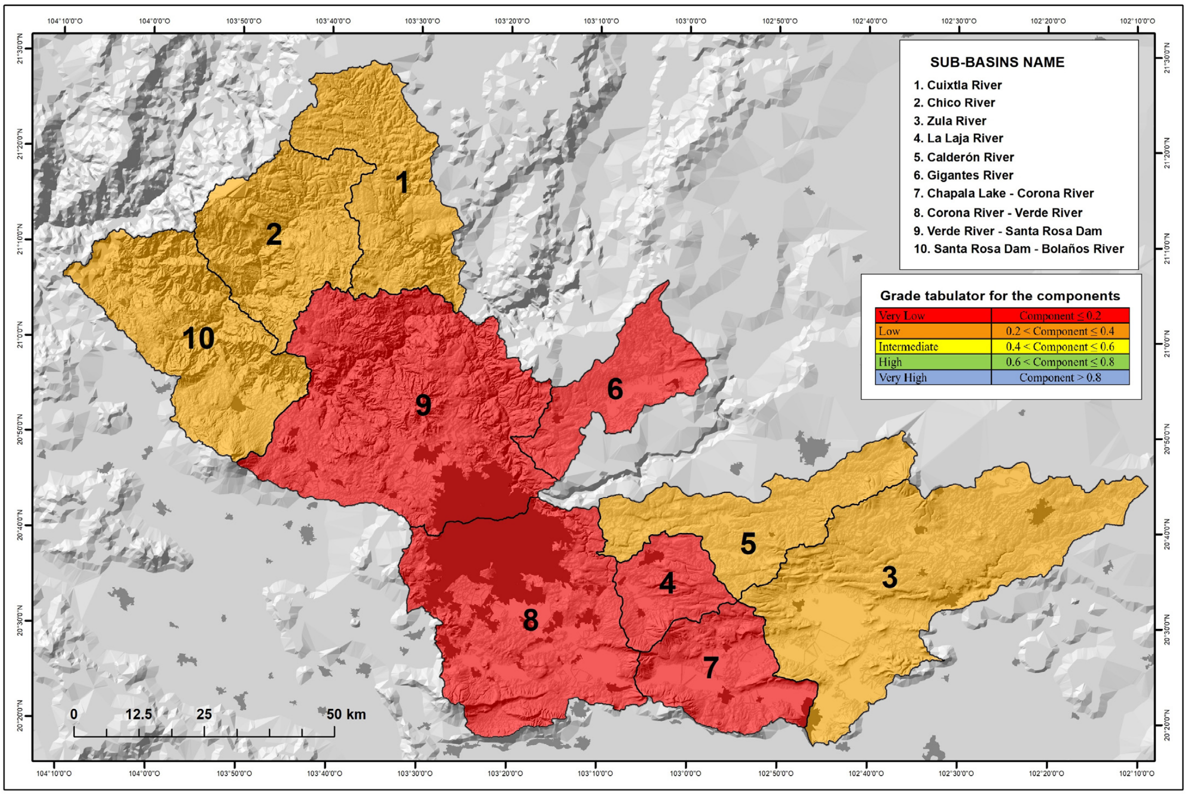

Figure 11. Scores of the hydrology (quantity) index by sub-basin: state.

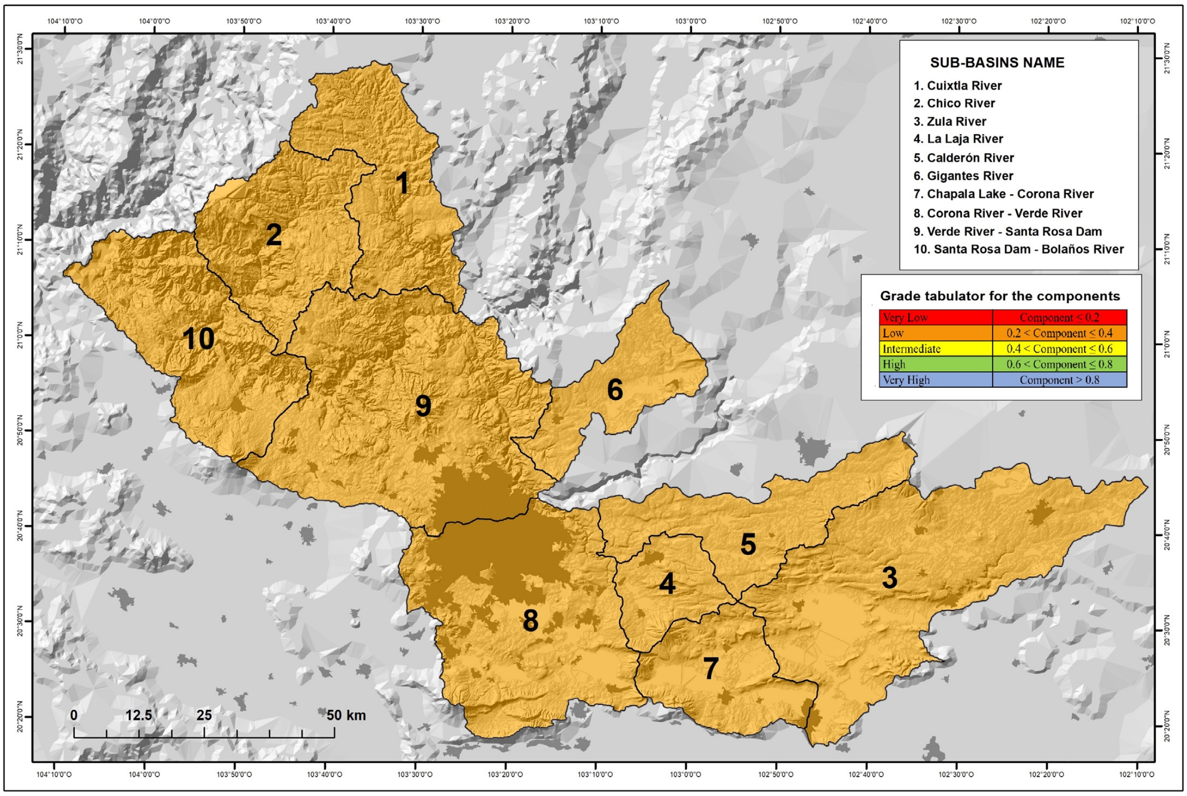

Figure 12. Scores of the hydrology (quantity) index by sub-basin: response.

4.1.2. Hydrology Quality Sub-Index

For the pressure parameter, the variation in the study period was compared against the historical average. The SGRB had a variation of −2%, which corresponds to a score of 0.75. Figure 13 shows the individual scores for each sub-basin, where one may observe that the upper basin zone, sub-basins 3, 4, and 7, has better water quality than the lower basin due to the considerable industrial activity that occurred, mainly in the sub-basin 8 Corona River–Verde River. The state parameter was represented by the long-term average, which had a value of 0.21, corresponding to a score of zero, indicating the deplorable conditions that the basin currently presents. Figure 14 shows the scores for each sub-basin where the intermediate level is predominant in the entire basin. The response parameter presents an average response of 32.22 obtained for the study area, which corresponds to a low score, showing the great opportunity for improvement in the development of regulations and their application. Figure 15 shows the scores for each sub-basin. The scores of the pressure, state, and response parameters were averaged for both the quantity and quality sub-indices. These two sub-indices were then averaged to obtain a value of 0.15 for the hydrology index.

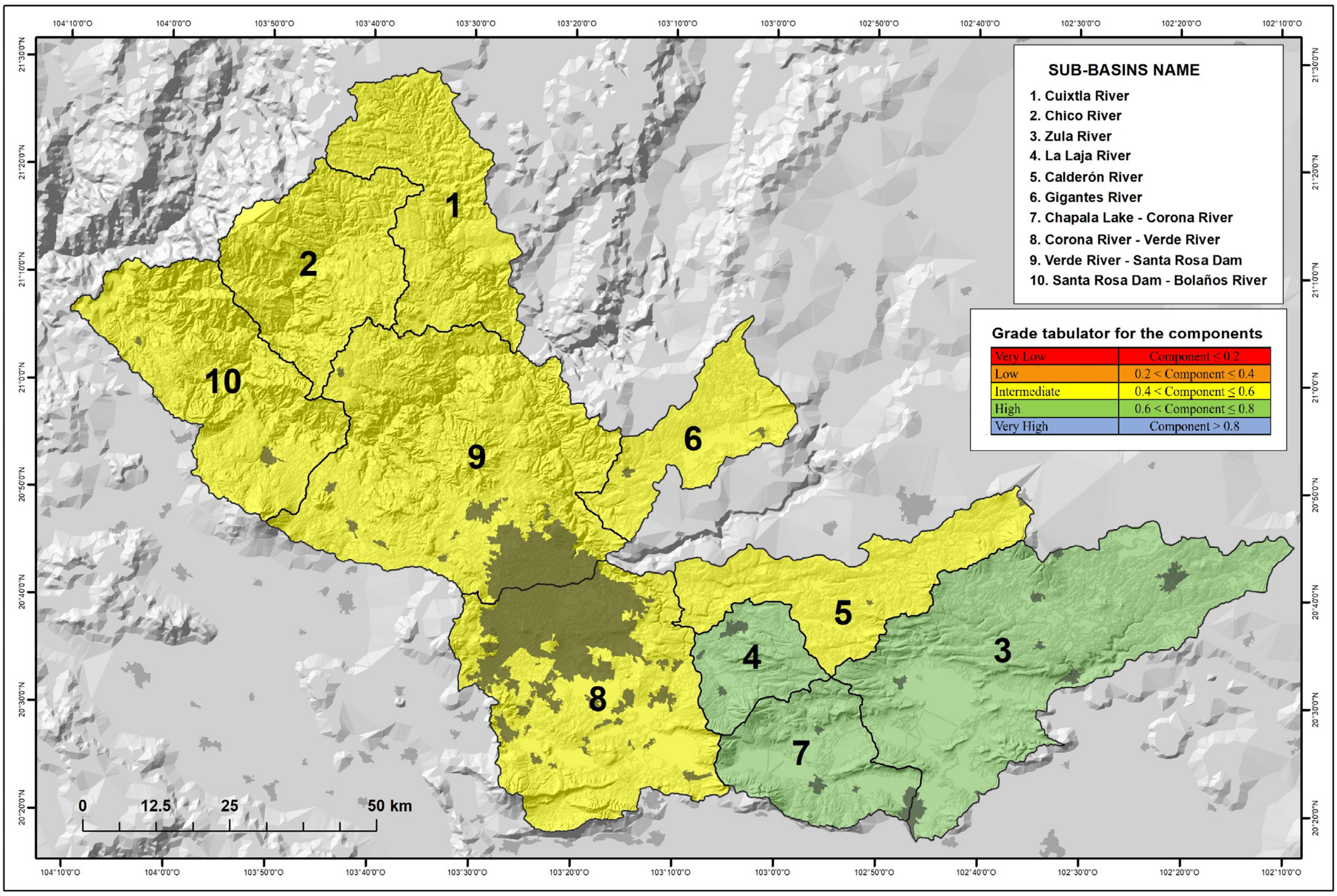

Figure 13. Scores of the hydrology (quality) index by sub-basin: pressure.

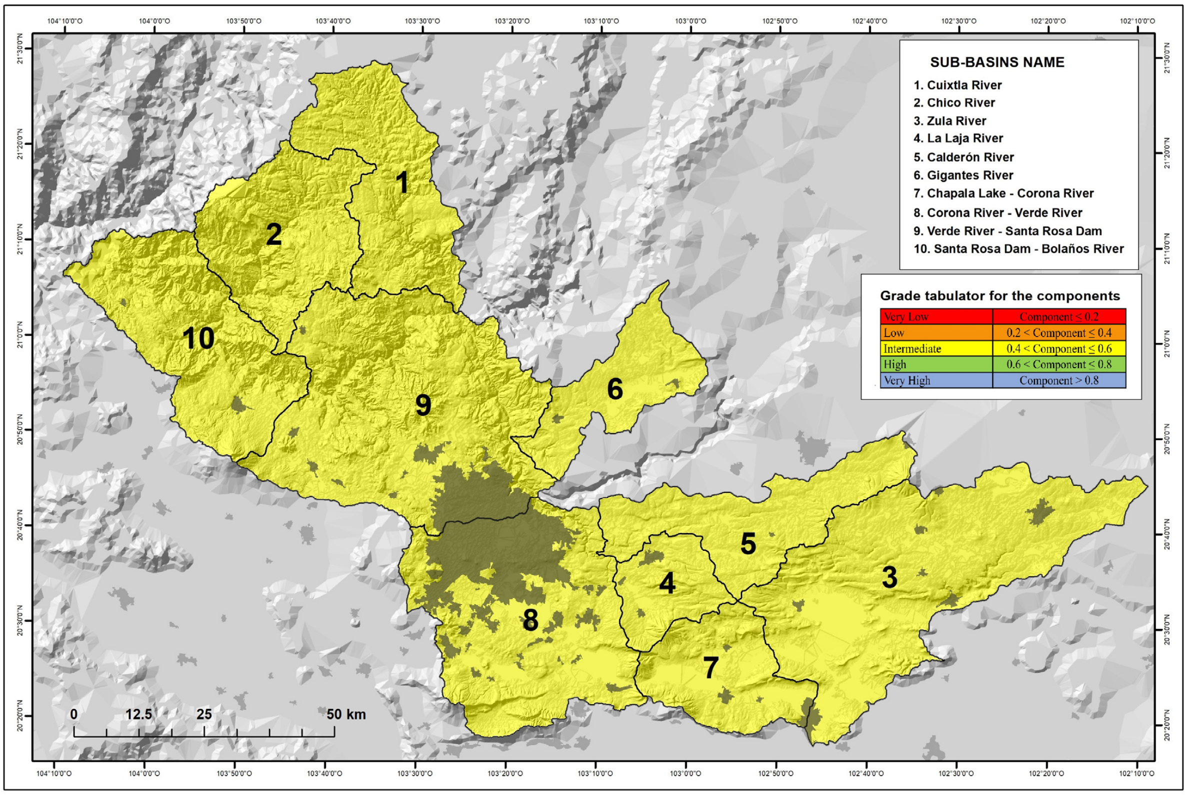

Figure 14. Scores of the hydrology (quality) index by sub-basin: state.

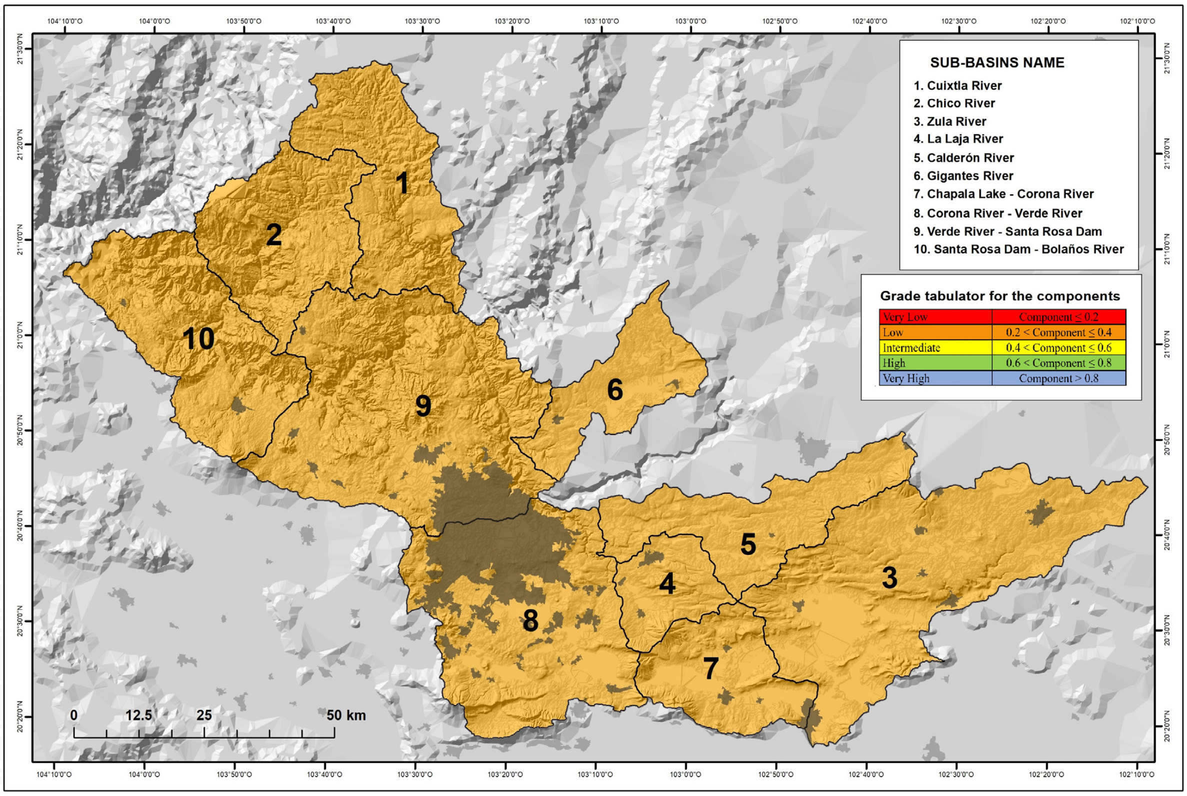

Figure 15. Scores of the hydrology (quality) index by sub-basin: response.

4.2. Environment Index

For the environment index, in the pressure parameter, an EPI of 6.16 was obtained for the entire SGRB, which corresponds to a score of 0.50. Figure 16 shows the scores for each sub-basin, where it is seen that the Chico River sub-basin (numbered 2) obtained a score of low, mainly consequence of the decrease in agricultural area. The entire SGRB had 16.53% remaining natural vegetation, which is equivalent to a score of 0.5 in the state parameter. Figure 17 shows the scores for each sub-basin for the parameter state. Despite having a low score for pressure, the Chico River sub-basin obtained a very high level in the parameter state, thanks to its current situation regarding the environment and resources. The same situation exists for the Cuixtla River sub-basin (numbered 1). The worst scenario is observed at the eastern half of the SGRB, where a very low level was estimated for the state parameter. Again, this is evidence of the present high degradation of the environment and resources in the region. For the response parameter, a percentage of 5.62% was obtained, which corresponds to a very low level. Figure 18 shows the very low scores in the entire sub-basin, which is representative of the lack of efficient policies and projects to recover the environment and resources in the SGRB. The scores of the three parameters were averaged to obtain the environment index, which had a value of 0.33. Both the state and response parameters, being as low as they are, show the need for politics that ensure the preservation of the natural ecosystem in the area.

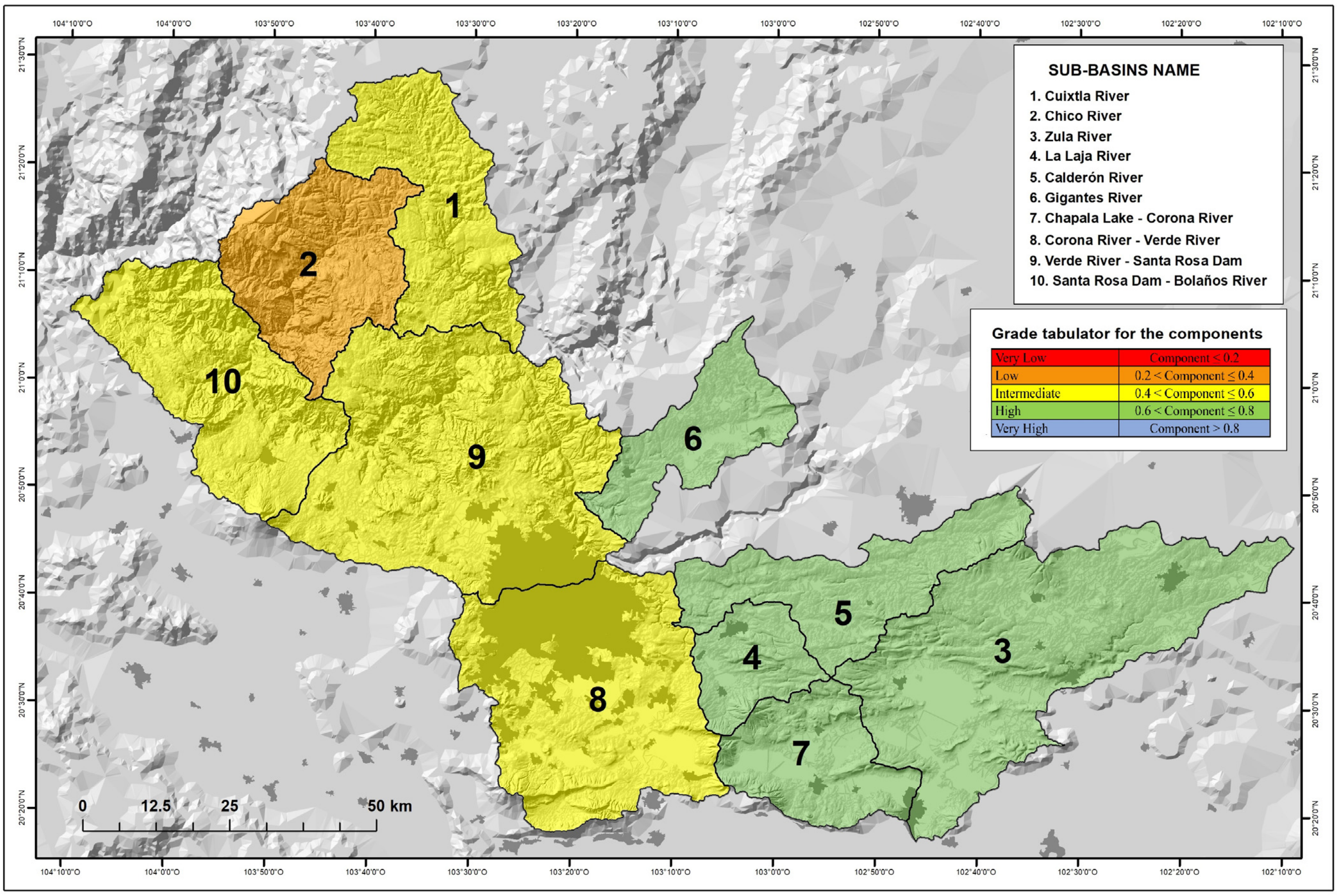

Figure 16. Scores for the environment index by sub-basin: pressure.

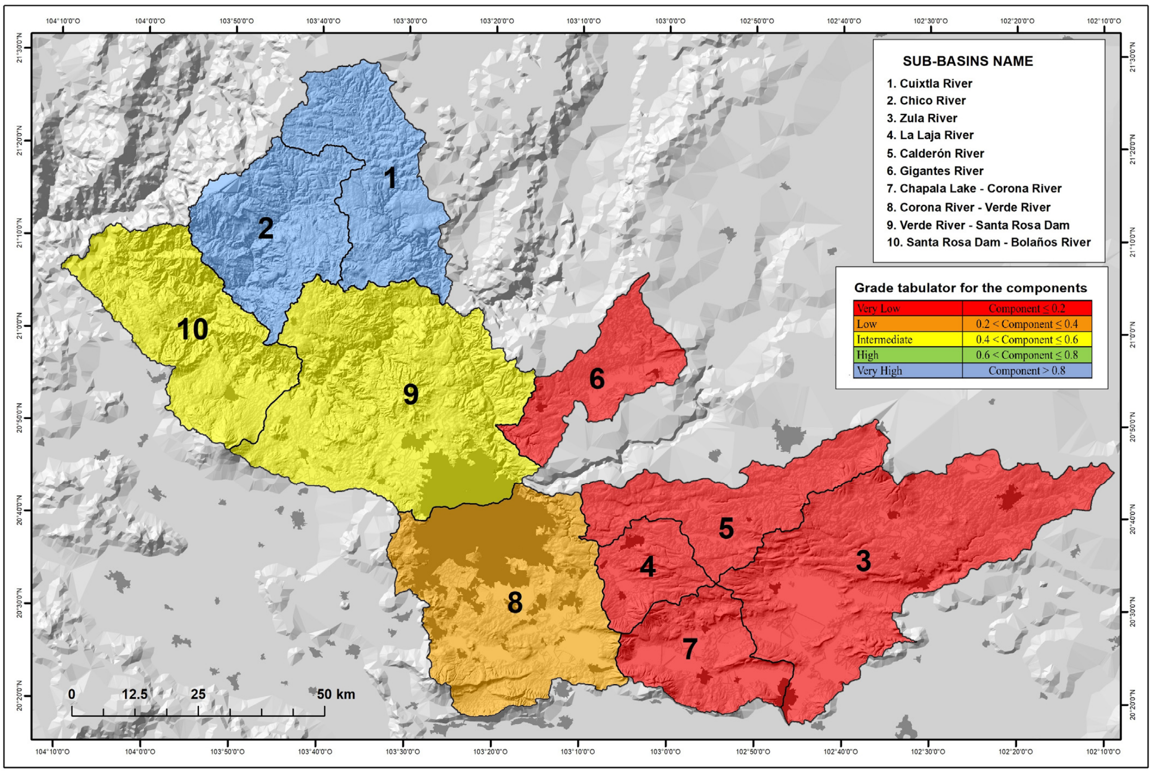

Figure 17. Scores for the environment index by sub-basin: state.

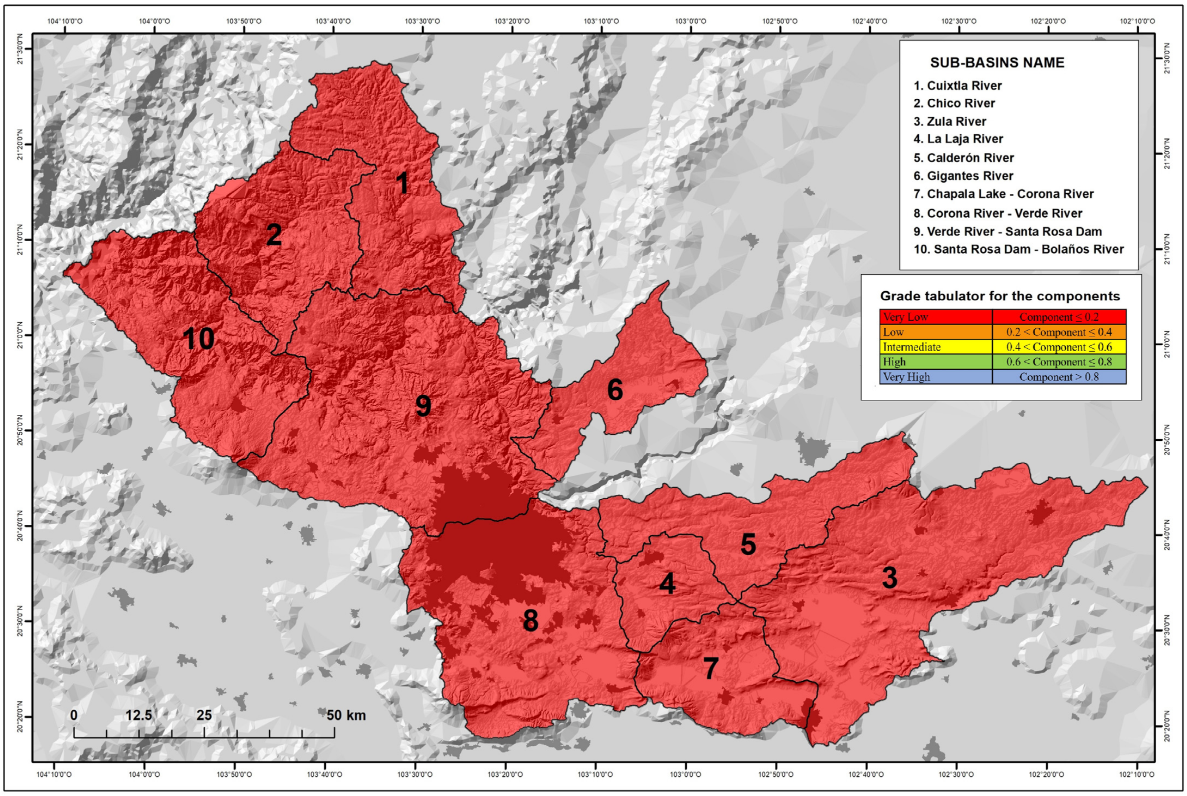

Figure 18. Scores for the environment index by sub-basin: response.

4.3. Life Index

The study period was set to 2016–2020, and the variation in HDI-Income was calculated as 2.61%. This corresponded to a pressure parameter of 0.75. Figure 19 shows the evolution of HDI-Income for each sub-basin (sub-basin 2 Chico River is missing because no population data are reported), and Figure 20 shows the evolution for the entire SGRB. The evolution of the last 20 years shows an upward trend for both the sub-basins and the entire SGRB. Figure 21 shows the scores for pressure parameters obtained at the sub-basins where a high level is evident in the entire basin. The state parameter was obtained from the weighted value of the HDI of the reference period, which was set to 2015. A value of 0.796 was obtained, which corresponds to a score of 0.75. Figure 22 shows the results for each sub-basin, with a high level at the middle region of the basin and an intermediate level at the east and west extremes.

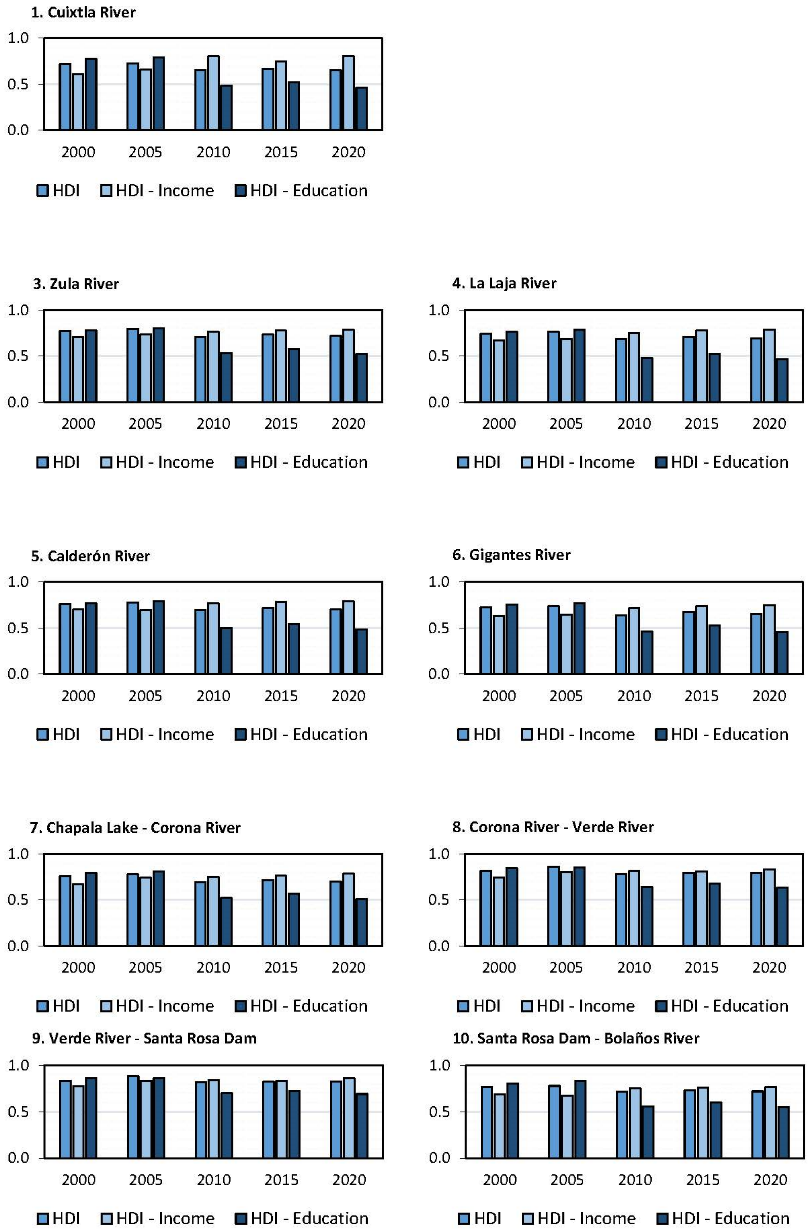

Figure 19. Evolution of the global HDI, HDI-Income, and HDI-Education in each sub-basin from 2000 to 2020.

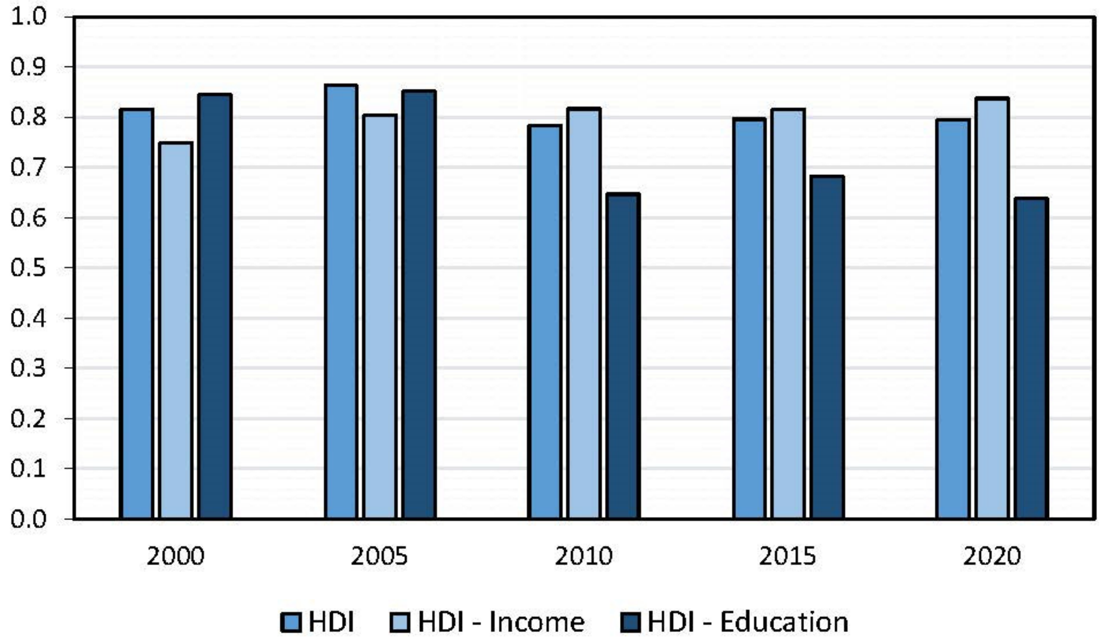

Figure 20. Evolution of the global HDI, HDI-Income, and HDI-Education in the study area from 2000 to 2020.

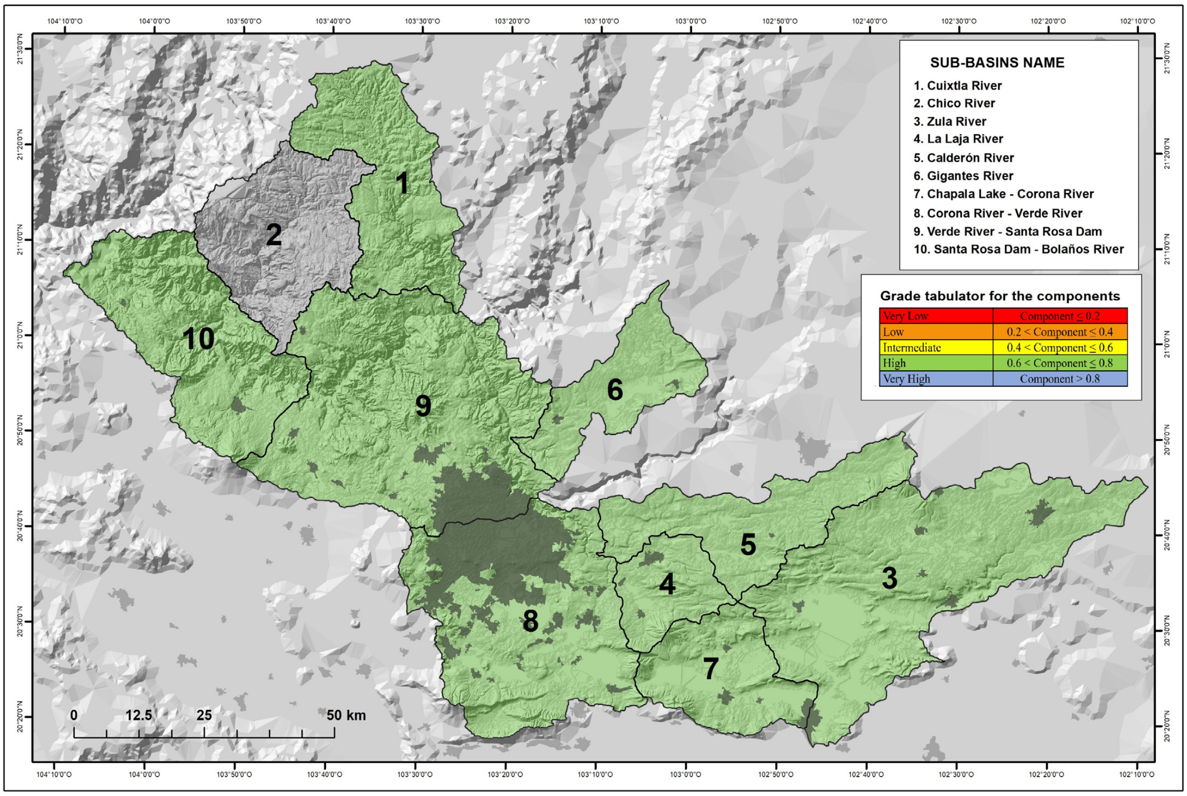

Figure 21. Scores of the life index by sub-basin: pressure.

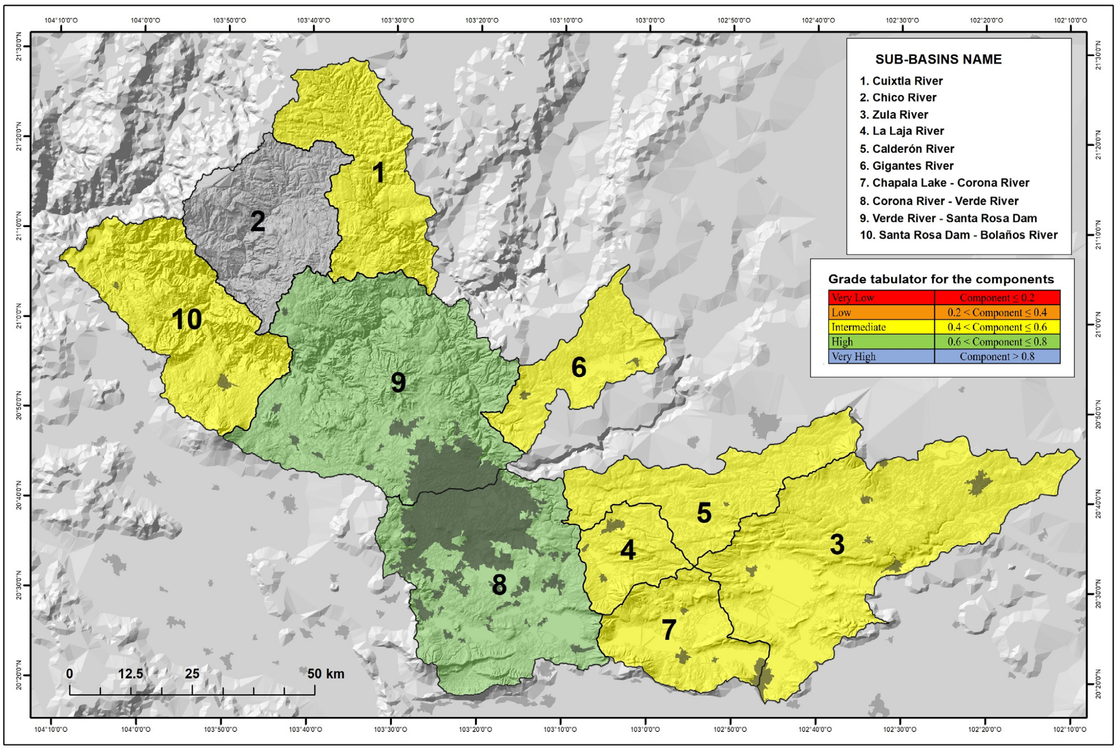

Figure 22. Scores of the life index by sub-basin: state.

The response parameter was obtained from the variation in HDI for the study period. A value of −0.11% was obtained, which corresponds to a score of 0.25. Figures 19 and 20 show the evolution of the HDI for each sub-basin and the SGRB, respectively, where no significant trend is evident, and an almost constant behavior is observed. Figure 23 shows the score for each sub-basin, where levels of low and intermediate are mainly noted.

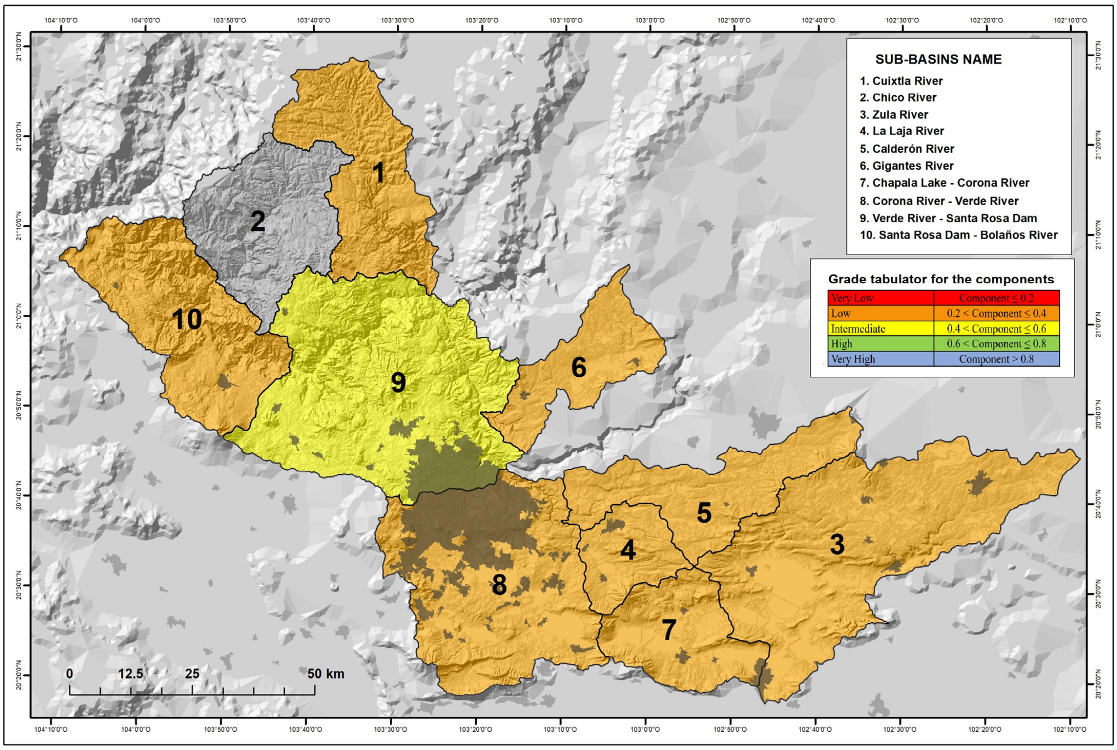

Figure 23. Scores of the life index by sub-basin: response.

The scores of the three parameters were averaged to obtain a value of 0.58 for the life index. In general, the life index shows better results in the urban area, emphasizing its population growth due to migration and, at the same time, pointing out the necessity to improve life quality in less urban and rural zones.

4.4. Policy Index

For the policy index, a variation of 6.878% was obtained, which corresponds to a score of 0.5. Figure 19 shows the evolution of HDI-Education for each sub-basin, and Figure 20 shows that for the entire SGRB, with an evident gradual decrease observed. Figure 24 shows the scores of each sub-basin, where the upper basin, sub-basins 3, 4, 5, 6, and 7, obtained a low score, while the rest obtained higher scores; intermediate and even very high scores were obtained for the Chico River sub-basin (numbered as 2). The state parameter resulted in an average value of 46, which corresponds to a score of intermediate in the whole SGRB (Figure 25). For the response parameter, a value of 15.83 was obtained, which corresponds to a score of very low (Figure 26). The scores of the three parameters were averaged to obtain a value of 0.37 for the policy index.

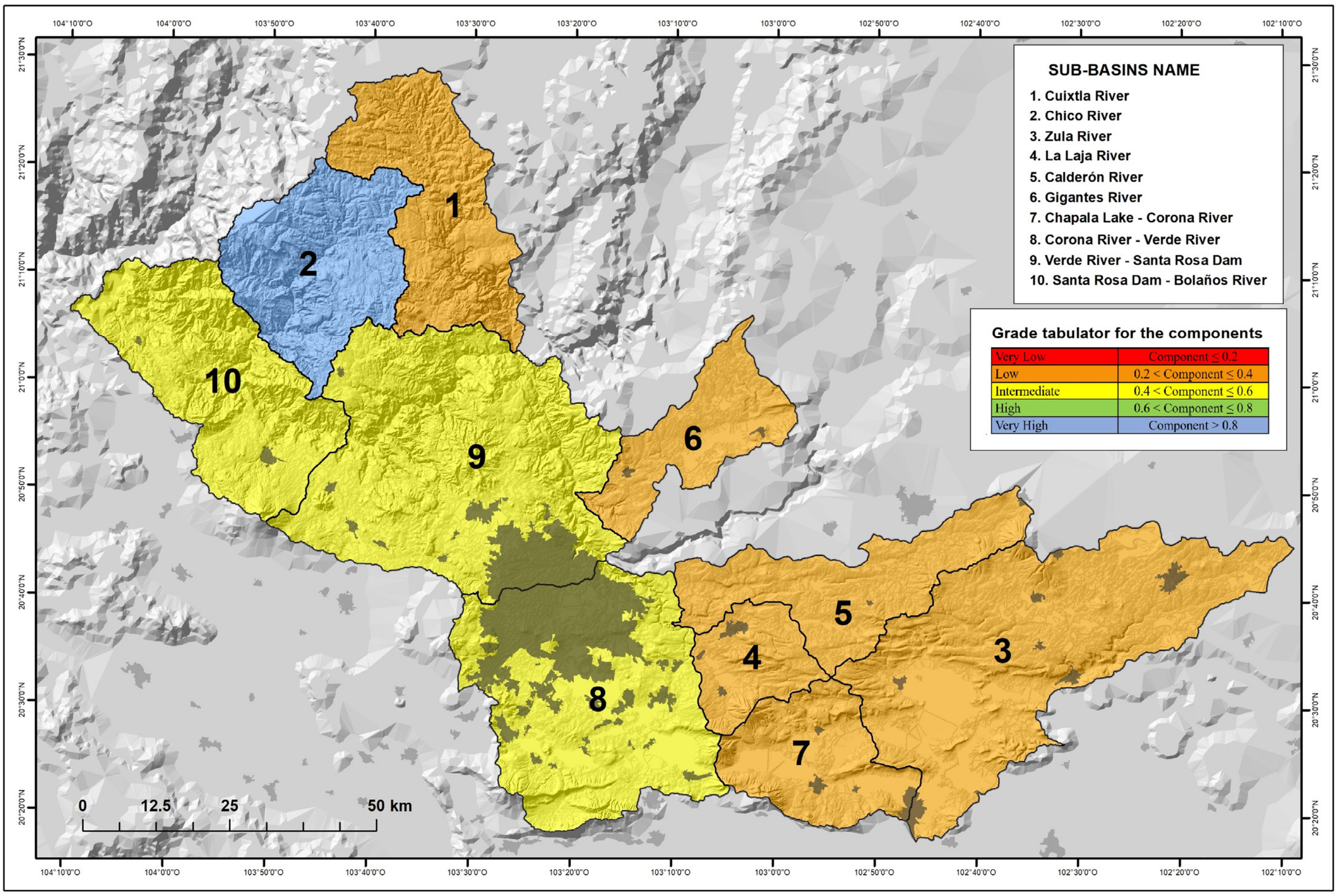

Figure 24. Scores of the policy index by sub-basin: pressure.

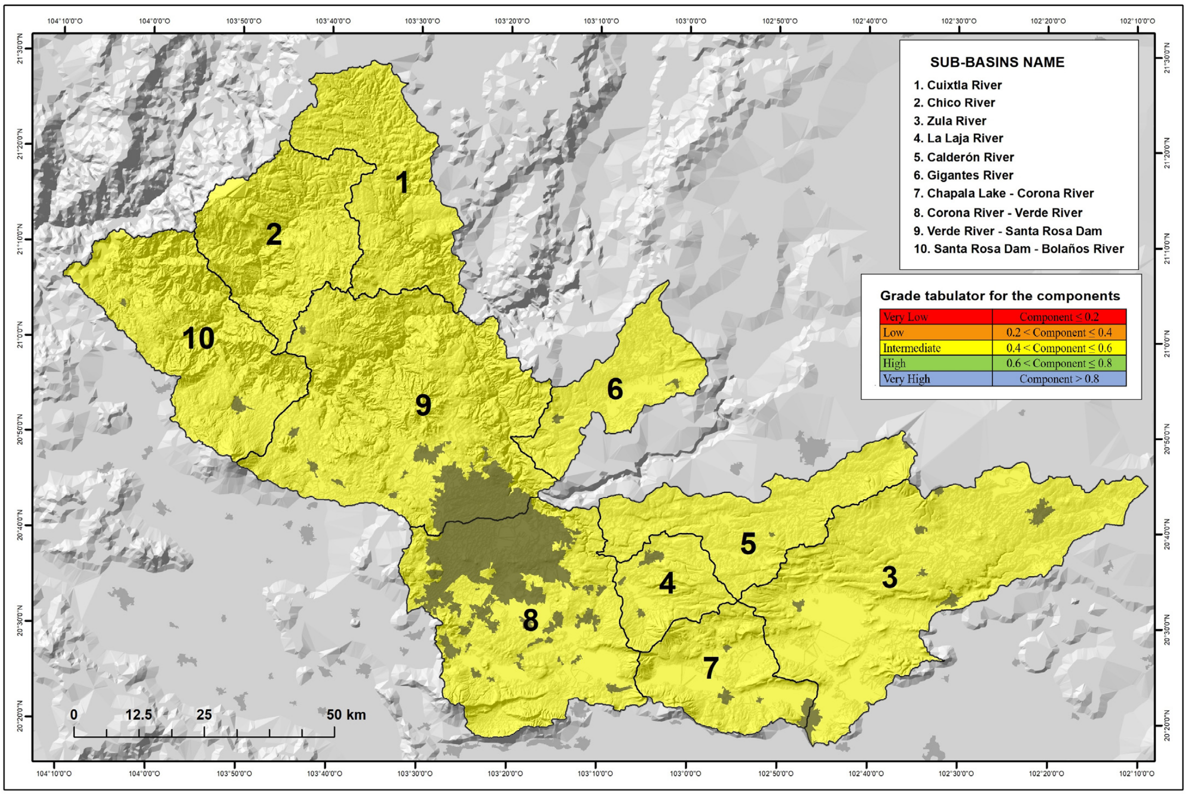

Figure 25. Scores of the policy index by sub-basin: state.

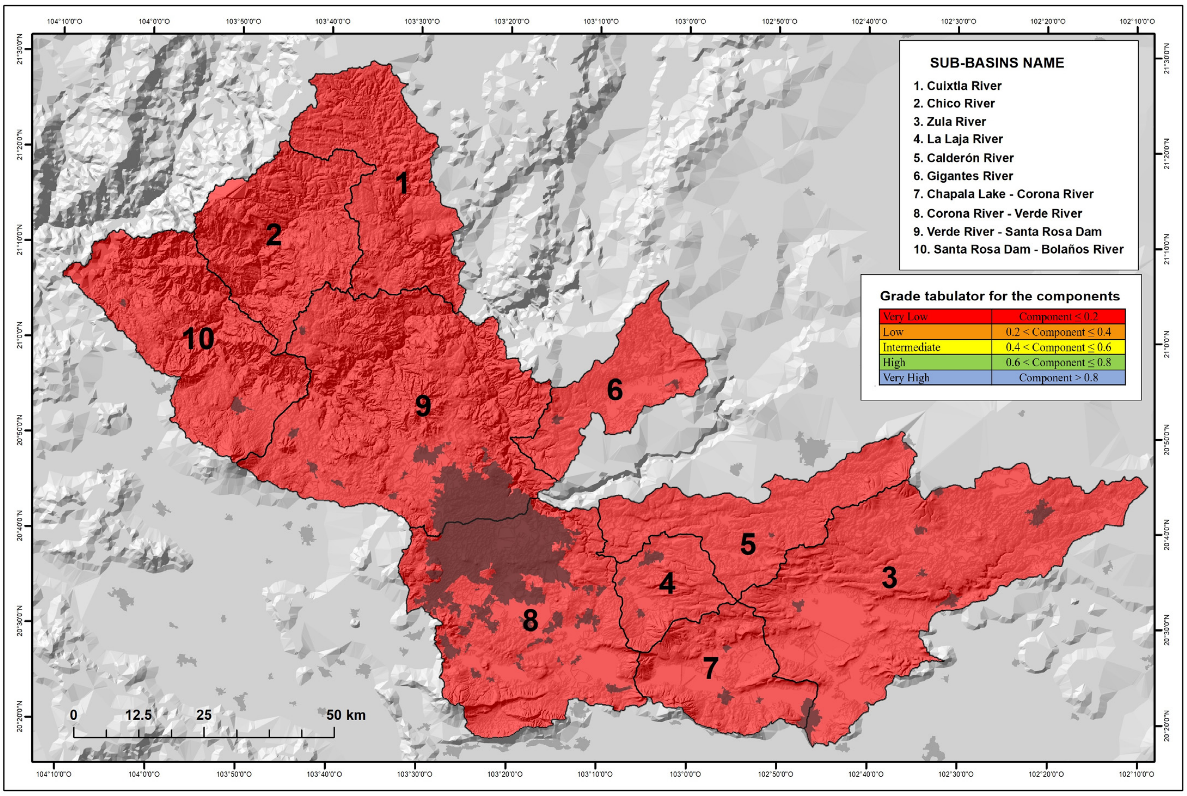

Figure 26. Scores of the policy index by sub-basin: response.

4.5. Global WSI

Figure 27 shows the WSI values calculated for each sub-basin where a predominance of intermediate levels is denoted in the middle zone of the basin, the most populated and with the greatest industrial activity, and of low levels in the extreme east and west of the basin, which are agricultural regions or forests. With the aim of estimating a unique WSI for the entire SGRB, the four component indices were averaged, getting a WSI of 0.36 for the period of 2016–2020. Figure 28 compares the WSI value of the SGRB with those of other basins around the world found in the literature.

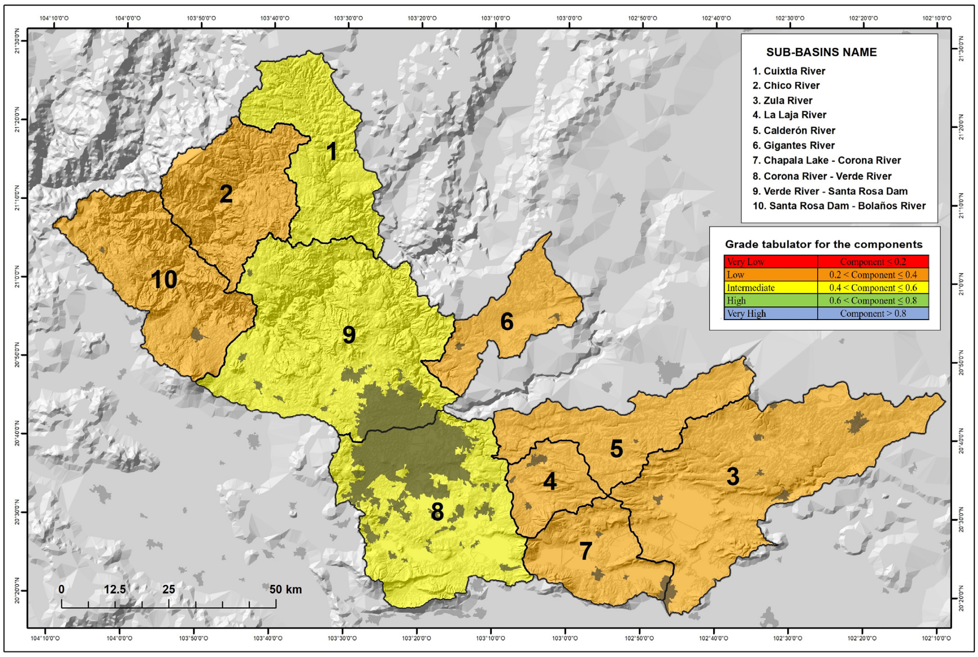

Figure 27. WSI scores for each sub-basin.

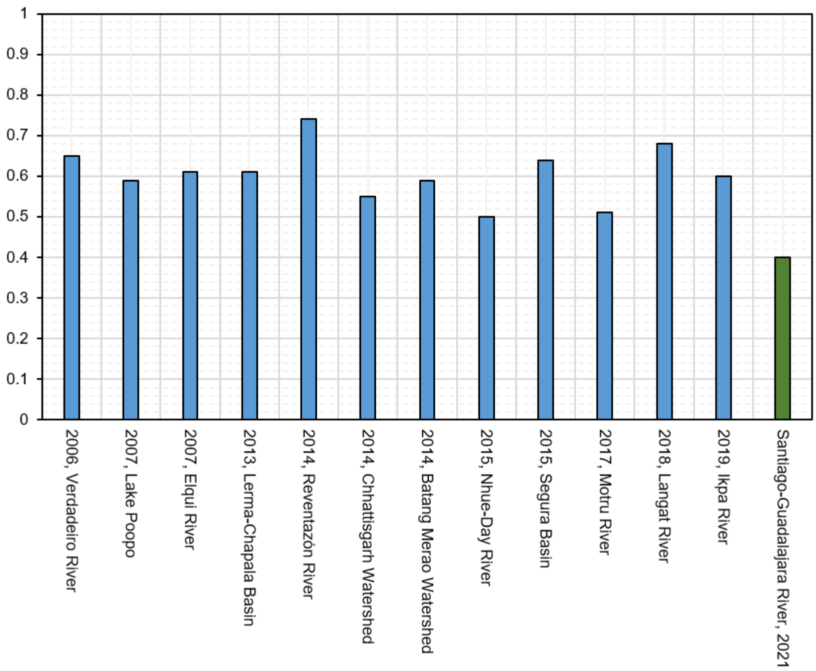

Figure 28. WSI scores for different basins around the world [8,9,15,30–38].

4.6. Discussions

The obtained WSI for the SGRB was below average, which indicates a clear need for concern. In this research, sub-basins were considered as independent units for calculations, so WSI values are available for each sub-basin.

Regarding the hydrology sub-index in terms of quantity, very low scores were obtained, especially for the state parameter in the central sub-basins of the SGRB, where there is a greater concentration of population in urban areas within the basin (Figure 11). This indicates the water stress situation that the region experiences, as the Falkenmark [40] Water Stress indicator was exceeded. Such an indicator establishes that a region is experiencing water stress when per capita availability is below 1700 m^3/year. However, the scores obtained for the pressure parameter range from low to high in the central sub-basins, which may be because water availability has remained within the same range in recent years without the possibility of further exploiting existing water sources (Figure 10). The most affected sub-basin, according to the pressure parameter, is sub-basin 10, Presa Santa Rosa–Rio Bolaños (Figure 10), where water availability has consistently decreased in recent years, in addition to a slight increase in population (Figures 8 and 9). Overall, the response parameter scores remain low in all sub-basins (Figure 12), because policies at the three levels of government do not reflect that there may be significant changes in the future for the benefit of the natural resources of the SGRB.

For the hydrology sub-index in quality, which is based on the evolution of the BOD_5 over a 10-year period, intermediate-level scores were obtained for the pressure and state parameters (Figures 13 and 14), indicating that there is a significant amount of organic matter in the water that can lead to oxygen depletion. This can have negative impacts on aquatic life and ecosystem health. As mentioned earlier, the upper sub-basins within the SGRB, sub-basins 3, 4, and 7, have a high score for the pressure parameter, indicating that the Santiago River has maintained a non-growing level of pollution in the headwater region. Again, about the response parameter, where policies or actions that benefit the water quality of the Santiago River should be reflected, the reality is that there is still much to be done, as low levels were generally obtained (Figure 15).

Regarding the environment index, the scores for the pressure parameter in the SGRB are two. In the lower basin region, intermediate scores remain, while the upper basin region presents high scores (Figure 16). The intermediate scores in the lower basin are representative of the gradual growth of the large urban areas within the basin, the main one being the Metropolitan Area of Guadalajara, with more than 5.2 million inhabitants. As mentioned earlier, only the Chico River sub-basin numbered 2 achieved a low score in the pressure parameter, due to the decrease in agricultural areas that occurred in recent years in favor of the growth of urban areas. These trends in urban growth obviously decrease the environmental conditions of the ecosystems. Although the upper region of the SGRB has an acceptable pressure parameter (high), the state parameter in that area has very low scores (Figure 17), reflecting the current state of the ecosystems and resources. This parameter is the result of the high degradation of the natural areas that still prevail in the region, according to the percentage of the basin area that still maintains a natural vegetation soil. The change in land use in the region was a determining factor in the negative result in the environment index. The response parameter is very low throughout the basin and is the result of the poor management that has been carried out in the SGRB regarding the care of protected natural areas, again due to changes in land use in the region (Figure 18).

The life index represents the quality of life or human development in the basin and was obtained from the HDI. In the case of the pressure parameter (Figure 21), the entire basin shows a high score, indicating that per capita income has increased over the past 20 years in all sub-basins, as HDI-Income values illustrate in Figures 19 and 20. This behavior is due to the economic growth that the state of Jalisco, México, has maintained above the national average. For the state parameter, the overall HDI was evaluated based on education, life expectancy, and per capita income for the year 2015, obtaining high scores in the central basins of the SGRB and intermediate scores in the upper and lower basin regions (Figure 22). For the response parameter of the life index, HDI variations in the basin were considered, which did not show significant changes in each sub-basin; in general, they maintained the same values during the 20-year analysis period (Figures 19 and 20). The stagnation in the HDI, particularly in the indices of education and life expectancy, is what leads most sub-basins to have a low response, except for the case of basin 9, Verde River–Santa Rosa Dam, where the HDI shows a slight increase between the years 2010 and 2020 (Figure 23). In conclusion, the region has maintained slight growth in terms of per capita income; however, this trend has not been capitalized on in the development of education and life expectancy of the society that inhabits the SGRS. This highlights the need to create more effective programs to promote the rise of education and well-being programs in the population.

To reinforce the final argument of the previous paragraph, it is enough to observe the results of the policy index in the pressure parameter for each sub-basin, where the variation of the HDI-Education index is precisely evaluated. The calculated scores were intermediate to low, reflecting this stagnation in the development of education in the region (Figures 19, 20 and 24). In the case of the state parameter, the answers to the UNEP questionnaire from institutions at the federal, state, and municipal levels of government demonstrate that there are still areas of opportunity in water governance, as the use of management tools is considered limited and there is only a short-term vision. In some cases, it is even considered that there are no tools that allow for sustainable river basin management. It was also evident, according to the answers of institutions, that there is no effective communication between the three levels of government. However, the score for the entire basin is intermediate (Figure 25), as there is a formal representation of authorities in the processes to contribute to decision-making, an established organizational framework, and some long-term capacity for the development of initiatives. The response parameter map reflects a very low score throughout the SGRB, as there are very limited budgets at the three levels of government to generate effective joint IWRM programs (Figure 26).

Finally, the WSI of each sub-basin places the SGRB at a sustainability level between low and intermediate (Figure 27). The sub-basins that have a low score are 2. Chico River, 3. Zula River, 4. La Laja River, 5. Calderón River, 6. Gigantes River, 7. Chapala Lake, and 10. Santa Rosa Dam–Bolaños River, while the sub-basins with intermediate scores are 1. Cuixtla River, 8. Corona River–Verde River, and 9. Verde River–Santa Rosa Dam. The sub-basins with a low sustainability level are characterized by environmental degradation due to changes in land use, which has resulted in a loss of areas with natural vegetation due to deforestation, combined with the lack of effective policies to prevent resource loss and promote ecosystem recovery. In addition, the population has been increasing in some of the sub-basins. Specifically, in the sub-basins 2. Chico River and 10. Santa Rosa Dam–Bolaños River, which are in the lower basin, there has been a gradual decrease in water availability during the analyzed period, which also has a negative effect on sub-basin sustainability. In the sub-basins with intermediate sustainability, the factor that most affects the evaluation is water availability, which places the region in a water stress situation, so efforts should focus on generating measures to make more efficient use of water, both in agricultural and urban use.

The comparison of the WSI global score of 0.36 obtained for the SGRB in the present work (Figure 28) with those that applied the same methodology in other basins of the world indicates that the SGRB is in an unfavorable situation with a low sustainability, being below all cases shown. There are basins whose WSI value is much higher, such as the Reventazón River, Costa Rica, with a value of 0.74, and the Langat River, Malaysia, with a value of 0.68, which are classified as high sustainability.

5. Conclusions

The present work focused on integrated water resources management of the study area, for which collaboration among society, academia, and government is crucial. All areas and decision makers must be considered in the decision-making area to ensure the sustainability of the SGRB. To improve the WSI score of the SGRB, public policies are needed to achieve water and sanitation goals, as well as better land-use management, decentralization of the population, allocation of water concessions, reuse of treated water, and reinforced surveillance and regulation of wastewater discharge. Indices such as the WSI are valuable for informing and educating citizens on the need to pressure politicians over issues such as water resources and sustainability. The findings of this work can be used to address areas of opportunity.

During the research for this work, the lack of systematized information was evident, making it the greatest limitation. As previously established, some data had to be extrapolated since there was no record; such was the case of water availability in the aquifers and the HDI of the last period. The use of a UNEP questionnaire in this study was a valuable contribution to evaluating areas for which numerical information is unavailable in a systematic and objective manner that avoids bias. The questionnaire required working jointly with the federal, state, and municipal governments for adaptation to the study area.

Future work may involve updating the WSI periodically to measure progress and detect new areas of opportunity to ensure the sustainability of the SGRB.

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