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Hydrological Sciences Journal

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/thsj20

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To cite this article: B. Lopez-Alvarez , M. A. Urbano-Peña , J. Moran-Ramírez , J. A. Ramos-Leal & J. Tuxpan-Vargas (2020): Environment component estimation via remote sensing in the water poverty index in semi-arid zones, Hydrological Sciences Journal, DOI: 10.1080/02626667.2020.1839081

To link to this article: https://doi.org/10.1080/02626667.2020.1839081

Publisher: Taylor & Francis & IAHS

Journal: *Hydrological Sciences Journal*

DOI: 10.1080/02626667.2020.1839081

Environment component estimation via remote sensing in the water poverty index in semi-arid zones

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Abstract Groundwater has become an alternative of water supply for various sectors of the population and the economy, and its extraction is increasingly large worldwide. The water poverty index (WPI) is a holistic tool that enables the establishment of links between poverty, social marginalization, environmental integrity, water availability and health. The index includes five components: Water Resources, Access, Capacity, Environment and Use, which are evaluated on a scale of 0 to 100. The objective of this research is to calculate the WPI by applying remote perception techniques to the Environment component. Through multi-temporal analysis, we estimate the variability of soil cover in a semi-arid area of San Luis Potosí in Mexico, whose availability of surface water and groundwater is mainly for agriculture. The overall result was a WPI for the studied area of 56, which reflects contradictions in the management of the resource that is abundant.

Keywords: water poverty index environment, resource, soil adjusted vegetation index (SAVI), normalized difference vegetation index (NDVI), foliar area index (LAI), CIgreen, socio-hydrology

Introduction

Global population dynamics, which have led more than half of the world's 7 billion people to live in urban areas (UN 2014), have resulted in pressure on water resources and different types of users (public-urban, agricultural and industrial) competing for their use. Governments must guarantee populations the human rights of sufficient supply of water that is healthy, acceptable, accessible, and affordable, as well as adequate food that is quantitatively and qualitatively suitable and sufficient (FAO 2010). About industrial use, both government and business people present significant challenges to ensuring a type of production that prioritizes efficiency and care of water rather than maximum production.

Given this scenario, the deterioration and reduction of water sources significantly limit access to water. For example, most wastewater is discharged directly into the environment without adequate treatment reducing the availability of surface water, in addition to generating deterioration of aquatic ecosystems, waterborne diseases, and negative repercussions on economic productivity (agriculture, for example).

For this reason, groundwater has become an alternative water supply for various social and economic sectors, providing drinking water to at least 50% of the world's population and 43% to irrigated agriculture. It is expected that by 2050, global water extraction will increase by 55% (WWDR 2017). Deficiencies in water legislation and management further exacerbate this issue. As stated in the United Nations Report on

Water Resources in the World in 2015, the global water crisis is a crisis of governance more than one of available resources (WWDR 2015).

The holistic tool called the Water Poverty Index (WPI) enables interest groups to establish direct public policies, identify where problems exist, and propose appropriate measures in the matter of water availability for different uses. The methodology under which this index was developed allows for the establishment of links between poverty, social marginalization, environmental integrity, water availability, and health. The WPI shows that it is not the quantity of available resources that determines a country's levels of poverty, but rather how effectively those resources are used (Sullivan 2001, Sullivan 2002, Sullivan et al. 2002, Sullivan *et al*. 2003).

The WPI was applied to 140 countries taking into account five components: water resources, access, capacity, use, and the environment, on a scale of 0 to 100 (Lawrence *et al*. 2002). In this study, Finland, followed by Canada and Iceland, received the highest scores of 78, 77.8 and 77.1, respectively, while Ethiopia, Niger, and Haiti obtained scores of 35 each. The highest-rated countries are rich or developed nations, and although the evaluation in the water resources component was less than 20 points, they make better use of water and pay more attention to conservation.

In the report, Mexico received 57 points, a score that can be justified by the heterogeneity of the natural availability of water that depends on rainfall and climate, but also by the way it is used and managed in the country.

The methodology has continued to be used in different parts of the world with modifications and even some simplification of the components (Abraham *et al*. 2005, Jiménez 2007, Cook *et al*. 2006, Kamal El-Din El-Gafy 2008, Gine and Pérez-Foguet 2010, Cho *et al*. 2010, Van der Vyver 2013, Jemmali and Motoussi 2013, Jemmali and

Sullivan 2014, Jemmali and Abu-Ghunmi 2016, Thakur *et al*. 2017, Pan *et al*. 2017, Kallio *et al*. 2018, Hatem 2018, Nadeem *et al*. 2018).

The WPI has been applied in different regions of the state of San Luis Potosí that vary not only in terms of climate characteristics and resource availability, but also in terms of socioeconomic conditions. The first approach was in the San Luis Potosí Valley, in the Central Region (López Álvarez *et al*. 2013); the second, in the Valles River Basin in the Huasteca Region (López Álvarez *et al*. 2015), and the third, in the Santo Domingo aquifer in the Altiplano Region (López Álvarez *et al*. 2019).

The WPI is a flexible and perfectible tool, to the extent that some authors have proposed modifications to improve and narrow down the methodology proposed by Sullivan and his collaborators. Thus, its components are going through the process of being standardized, as is the case of the WPI applied in arid zones in Mexico where water quality was added as a component (López-Álvarez *et al*. 2013, López-Álvarez *et al*. 2015, López-Álvarez *et al*. 2019).

The objective of this research is to calculate the Water Poverty Index for the Rio Verde Aquifer, located in the Middle Region of San Luis Potosí, with semi-warm climatic conditions, where surface and groundwater are highly available and are used mainly for agriculture; however, the water quality is not good enough for human consumption. In this work, one of the most important modifications is the characterization and calculation of the Environment component using remote sensing techniques. The variability of land cover is estimated through a multi-temporal analysis.

The Rio Verde Aquifer (RVA) covers an area of 2770 km^2 and is part of Hydrological Region 26 "Rio Panuco," Alto Panuco Hydrological Subregion, Tampaon river basin. Its main stem is the Rio Verde (**Figure 1**). The average annual precipitation and temperature are 668.0 mm and 21.5 ° C, respectively, and the potential evaporation is around 1685 mm per year. There are three types of climate in the aquifer: in the northern zone the climate is dry-semi-warm, while in the central region, the semi-dry-semi-warm climate predominates, and the southern zone has a semi-warm-subhumid climate. All three receive rainfall in summer (CONAGUA 2015).

Within the RVA are the municipalities of Rioverde and Ciudad Fernández (RV-CF), as well as small regions of Cerritos, Villa Juárez, Ciudad del Maíz, Alaquines, and Cárdenas. The municipalities of RV-CF and their surrounding areas (127 thousand inhabitants) make use of most of the hydrogeological unit of the Rio Verde and, therefore, these municipalities will be considered for the calculation of the WPI.

Materials and methods

The composite index approach is based on the premise that a combination of relevant variables can provide a more complete perspective in a situation than one can by itself. The variables that make up the WPI are represented mathematically as follows:

$$\mathrm{WPI_i} = \frac{\sum_{i=1}^{N} w_{Xi} X_i}{\sum_{i=1}^{N} w_{Xi}} \tag{1}$$

where WPI$_i$, is the Water Poverty Index, resulting from multiparametric expression with a value between 0 and 1, weighted by the six components: Resources (R); Access (A); Use (U); Capacity (C); Environment (E) and Water Quality (Q) (see Table 1). The components of the WPI are weighted based on their relative importance, using functions of weight w, applied to each component X$_i$. Equation (1) is expressed in a developed form as:

$$\mathrm{WPI_i} = \frac{w_c C + w_r R + w_a A + w_u U + w_e E + w_q Q}{w_c + w_r + w_a + w_u + w_e + w_q} \tag{2}$$

This method in a certain iterative way enables the validation and evaluation of the consistency of the analytical results and provides the basis to modify and reevaluate the weights assigned to the parameters. Each component influences the WPI, expressed in effective weights. The effective weight Wx_i can be calculated for each component according to Equation (3) (Ramos 2002):

$$Wx_i = \frac{Xr_i * Xw_i}{\sum_{i=1}^{N} W_i} \tag{3}$$

Where Xr_i and Xw_i are the scores for each component X_i and their theoretical weights and W_i is the sum of theoretical weights.

Comparison of the values of the different variables that make up the subcomponents can be done through normalization, in this case with the minimum-maximum method used in different studies (Sullivan and Meigh 2003, van Ty et al. 2010, Jemmali and Abu-Ghunmi 2016). Normalization allows comparable data to be obtained in a standard range of 0 to 1.

The results of each component are plotted on a polygon, where the edges represent 100% of each component. With normalization, the maximum value is 1 and the minimum is 0 (in the middle); therefore, the ideal polygon is the one where all the components of the WPI reach values of 1 and form a hexagon. Conversely, values less than 1 move away from the hexagon and form an irregular polygon, representing deficiencies in the components.

Environment (E)

Water, as mentioned by Scoones (1998), is a key component of the natural capital rights of households, but also of healthy ecosystems, and little attention has been paid to the water needs of nature itself (Sullivan 2002). In this sense, economic development has been boosted by promoting agricultural or industrial production, causing disturbances to water systems, generating not only their deterioration but also their depletion.

In this case, agricultural development has expanded the extension of farmland at different times; in this area, irrigation practices have their roots in the 17th century (Escobar-Ohmstede 2013) and are currently the main user of water resources. One way to evaluate the impact these practices have had is by using vegetation indexes.

The purpose is to evaluate the Environment Component with remote sensing techniques, which is a novel proposal that is efficient, fast, and affordable. The new estimate allows constant monitoring of changes that occur in large areas of land due to the use of satellite data and implementation of vegetation coverage indices. The advantage of applying remote sensors is that they increase the capacity for monitoring and analyzing spatio-temporal transformations, giving the possibility, even, of making forecasts based on patterns identified, for example, by the loss of natural plant coverage due to land use changes.

In different investigations, the normalized difference vegetation index (NDVI, Rouse et al. 1974) or soil adjusted vegetation index (SAVI, Huete 1988) have been used; this research proposes an integrative methodology of four spectral indices for characterizing plant cover: the NDVI, SAVI, the foliar area index (LAI, Breda 2003), and the chlorophyll index (CIgreen, Gitelson and Merzlyak 2003).

The spectral indices (NDVI, SAVI, LAI, and CIgreen) were selected due to (a) their ability to detect vegetation cover and (b) their complementary capacities that enable increasing the level of detection certainty. Each of those indices provides information to the base index. The NDVI was used as a reference index to identify the distribution of vegetation as well as differentiate other types of surface coverage such as soil and water. The SAVI supports correcting spectral values according to the effects of soil reflection.

For its part, the LAI provides the density of the vegetation present; that is, it is an indicator of the amount of biomass per area, while CIgreen is a parameter that specifies the amount of chlorophyll in the leaves and the tree canopy. The satellite data used was acquired by the Landsat 7 platform through the US Geological Survey portal (https://earthexplorer.usgs.gov/).

The images correspond to the period of study between 2006 and 2016 in the months of February. Radiometric and atmospheric corrections were applied according to Chandler (2009) and Chuvieco (1991). Finally, indices were calculated as follows: NDVI = (NIR – Red) / (NIR + Red); SAVI = ((NIR – Red)/(NIR + Red) + L) × (1 + L), with $L = 0.5$; LAI = 1/0.91 × (ln (0.69 – SAVI)/0.59); and CIgreen = (Red/Green) – 1. The spectral bands used for land cover estimation were: Band 2 or Green (0.52–0.60 μm), Band 3 or Red (0.63–0.69 μm) and Band 4 or near infrared (NIR, 0.77–0.90 μm).

The integration of the indices was done using weighted of weights (Urbano-Peña 2017) as follows:

$$\mathrm{E} = \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{INDEX_i}) * \mathrm{fac_i}, \qquad (4)$$

where E represents the result of the component; n indicates the total number of indices; i is the index (1, NDVI; 2, SAVI; 3, LAI; 4, CIgreen); $\mathrm{fac_i}$ is the weighting factor for the index map; and $\mathrm{INDEX_i}$, represents the map of the calculated index. The values of $\mathrm{fac_i}$, are calculated semi-empirically from the correlation matrix of the normalized indices and, based on their variability, the weighting of each index is assigned. The evaluation scale of E is from 0 to 1.

Resource (R)

The resource component is constituted considering the sources of surface and groundwater that are available in the study area. An annual volume of 231.1 $\mathrm{hm^3}$ of groundwater is harvested, made up of 95.8 $\mathrm{hm^3}$ of extraction of the RVA, of which 81.9

hm^3 (85.5%) are for agricultural use, and 13.9 hm^3 (14.5%) are destined to urban use. An annual volume of 135.3 hm^3 of water from the Media Luna Spring is added to the extracted volume, and it is used by the DR-049, in the Municipality of Rioverde (DOF 2014), which constitutes one of the most important agricultural regions of the state of San Luis Potosí and the main economic activity in the study area (CONAGUA 2015).

In terms of surface water, the main tributary streams in the El Refugio-Ciudad Fernández region are Arroyo Morales, Arroyo Grande, Arroyo El Sauz and Arroyo San Rafael. The volume used from this source is 3.8 hm^3 per year, with just over 90% used for agriculture (Urbano-Peña 2017).

For this component, surface water (Ws) and groundwater (Gw) are considered as subcomponents. The weight assigned to each subcomponent is related to the percentage of use, as seen in the following mathematical expression:

$$\mathrm{R} = 0.2\mathrm{Ws} + 0.8\mathrm{AGw} \tag{5}$$

$$\mathrm{Ws} = \frac{\mathrm{StoredVol}}{\mathrm{AnnualPrecipitationVol}} \tag{5.a}$$

$$\mathrm{Gw} = \frac{\mathrm{Recharge} - \mathrm{Extraction}}{2\mathrm{Extraction}} \tag{5.b}$$

Access (A)

The RVA concentrates 67.67% of population, while RV-CF holds the remaining 33.33% of inhabitants. In Rioverde, 90% of inhabitants have access to drinking water, while Ciudad Fernández’s drinking water only reaches 78% of the population; 85% of the population has Access to drinking water (Urbano-Peña 2017). In terms of access to sanitation, the population has a drainage coverage of 84%. Also, there is a wastewater treatment plant in Rioverde that also receives wastewater from Ciudad Fernández. The percentage of treatment is 84% (Urbano-Peña 2017).

This subcomponent is calculated based on the hectares destined for crops in the area and the number of them that have access to water for irrigation. The arable land in the RVA is 44,347 ha, of which 32% has access to irrigation water (Urbano-Peña 2017). In this way, the component considers the percentage of the population that has access to safe water for their basic needs (A_{ap}); the percentage of water receiving sanitation (A_s) and agriculture with irrigation (A_i). The expression that defines this component is:

$$\mathrm{A} = 0.5\mathrm{A}_{\mathrm{ap}} + 0.25\mathrm{A}_{\mathrm{s}} + 0.25\mathrm{A}_{\mathrm{i}} \tag{6}$$

The allocation of weights for the subcomponents was obtained through a weight analysis (Ramos, 2002; Urbano-Peña, 2017).

Capacity (C)

The basis for the development of the Capacity component is the human development index (HDI) because its variables have a direct influence on water access and quality. The HDI in the research area (UNDP / Mexico 2014) was applied at the municipal level; however, in lieu of the municipal Gross Domestic Product per capita which is unavailable, the total net income per capita per household is used, based on the National Household Income and Expenditure Survey of 2017 of the National Institute of Statistics and Geography.

Both Rioverde and Ciudad Fernández are classified as medium-sized urban municipalities. The former concentrates 57.8% of its population in its municipal seat and the latter 73.5%. The rest of its inhabitants reside in towns with populations of less than 2,500 people. Both municipalities have a high degree of migration to the United States, which provides remittance income for 18.7% of households (CONABIO 2015).

Other sources of income for the population of these municipalities include the provision of services and commerce (due to tourism activity) and agricultural activity. Regarding education, the population receives only 7.1 years of schooling, and 76.7% of the population has not concluded its primary education.

The Capacity component is made up of the Income Index (Ii); the mortality rate of children under five years of age (Mi); the education index (Ie) and the Gini coefficient (CG). The capacity is evaluated through the expression:

Use (U)

The Use component considers three subcomponents: water for domestic use (U_d), water for industrial use (U_i) and water for agricultural use (U_a). However, within the RVA, there is no significant industrial activity; the main economic activity that has a major influence on the development of the RVA municipalities is agriculture.

Thus, agricultural use represents a volume of 81.9 hm^3 (85.5%), and 13.9 hm^3 (14.5%) go to public-urban use, with an average drinking water supply to inhabitants of 200 liters/inhabitant/day (Urban-Peña 2017). This component is determined based on the following equation:

$$\mathrm{U} = 0.15\mathrm{U_d} + 0.0\mathrm{U_i} + 0.85\mathrm{U_a} \tag{8}$$

The weight assigned for the subcomponents is based on the percentage of water use that is counted in the study area.

Water quality (Q)

Water quality has become a factor directly related to availability; physical surface water or groundwater availability is not enough; today more than ever, quality must be an attribute to consider in order to manage the risks associated with it. Although quality depends on natural and anthropogenic factors, the contamination of water by human action is the main cause of the degradation of water quality throughout the world.

In the region studied, geology has a significant impact on water quality and soil type due to the evaporite formations that generate a large amount of sulphates and hardness in the water. This condition causes the eastern portion of the RVA to have issues with high salinity concentrations (Ballín-Cortés *et al*. 2004, Hernández-Martínez 2008). In addition to this, the lack of capacity for wastewater treatment in the municipalities of this area increases the problems of contamination in the bodies of water (Hernández-Martínez 2008).

For the Quality component, water quality was evaluated based on the water quality index (WQI) for human consumption and the sodium adsorption ratio (SAR) as an indicator of water quality for agriculture. The WQI is a tool that enables the level of water contamination for human consumption to be determined, and it is evaluated based on the reference levels of Official Mexican Standard 127 (NOM-127-SSA1-1994). This index is the weighted sum of physicochemical parameters (Brown and Mccleland 1974). Its value ranges from 0 to 100; the closer this value is to 100, the better the water quality. Its mathematical expression is defined by:

$$\mathrm{WQI} = \mathrm{k}\frac{\sum \mathrm{C_i P_i}}{\sum \mathrm{P_i}} \qquad (9)$$

where C_i is the percentage value assigned to the parameters due to their concentration; P_i, the weight assigned to each parameter; k, the constant that takes the value of 1 for clear waters without apparent contamination; 0.75, clear waters with slight colour, foam, slight unnatural turbidity; 0.50, waters with the appearance of being contaminated; 0.25, black water that presents fermentations and odors. Overall, it is evaluated on a scale of 0 to 1, where 1 represents excellent quality and values less than 0.5 represent serious pollution problems.

To evaluate the quality of agricultural use, the Wilcox diagram (Ayers and Westcot 1985) was used. The construction of the diagram considers the electrical conductivity (EC) and the SAR (Richards 1973) for each of the samples. EC indicates the risk of soil salinity; that is, the greater the salt concentration in the soil, the higher the osmotic pressure and the lower the capacity of the plant to absorb water due to the excess of ions. The SAR (Equation (10)) reflects the exchange of sodium ions (Na^+) with calcium (Ca^{2+}) and magnesium ions (Mg^{2+}), and a high concentration of sodium in the water would result in the loss of structure and permeability of the soil (Pérez León 2011):

$$\mathrm{SAR} = \frac{\mathrm{Na^+}}{\sqrt{\frac{\mathrm{Ca^{2+}+Mg^{2+}}}{2}}} \tag{10}$$

The waters can be grouped according to their sodium content in percentage (% Na). Below 20% is considered excellent for use in agricultural irrigation, 20–40% is good, 40–60% is admissible, and 60–80% is doubtful. Values higher than 80% are considered inadequate (Wilcox 1956). The Quality component is evaluated with both the WQI for domestic use (WQI_d) and the WQI for agricultural use (WQI_{agr}), whose weights are considered based on the percentage of use:

$$\mathrm{Q} = 0.15\mathrm{WQI_d} + 0.85\mathrm{WQI_{agr}} \tag{11}$$

For this component, 44 water samples were collected and analyzed from wells, dug wells, and springs distributed in the study area, to determine the cations of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+) and boron (B^{3+}) and major anions of chlorides (Cl^-), sulphates ($SO_4^=$), phosphates (PO_4^{3-}) and nitrates (NO_3^-). The pH, EC, temperature, redox potential (PR), dissolved oxygen (DO) and alkalinity were measured in each sample *in situ*.

Results and discussion

Environment component

Human activities generate changes in land use, directly impacting natural cycles such as water and vegetation. The environmental services offered by nature directly related to water have a vital impact on soils, vegetation cover, surface runoff, catchment and recharge for water tables. The methodology proposed for the evaluation of this component allows the comparison of vegetation indexes and their spatial-temporal change. Table 2 displays the average values of each index, which show an increase over the course of the evaluation period (10 years). This suggests an increase in plant cover that can be attributed to the increase in vegetation and agricultural area.

Subsequently, through a linear correlation, a matrix was obtained (Table 3) that indicated the degree of relationship between each vegetation index and its degree of influence for the allocation of the weights for the normalized weighting (fac_i) of each index. Finally, Equation (4) was applied to calculate the value of the environment component. The value of this component is 0.49, and the spatial distribution of the resulting Component E is shown in Figure 2.

Resource component

The study area benefits from its climatic and topographic conditions, as well as geohydrological features leading to water resource availability and distribution. Karsticity in the RVA gives origin to the water of the existent springs; recharge comes from the mountainous areas to the north and west, and in the plains, they circulate through the karstic environment, and in some areas, they pass to the granular medium (Ballín-Cortés *et al*. 2004).

This condition generates a physical availability of water in such a way that it makes agricultural activity viable without generating a competition until the present with the demand for water for the population. This condition is reflected in the evaluation of this component with a score of 0.68.

Access component

Adequate access to drinking water and sanitation is a decisive factor in reducing mortality and morbidity among the population under five years of age and in reducing the incidence of water-borne diseases (CONAGUA 2011). On the other hand, it is important to ensure access to water for irrigation, since this favors the increase of income to producers and the decrease in the cost of food for all consumers (FAO 2001).

The Access component registered a value of 0.72 due to the high drinking water and sanitation coverage provided by the RV-CF conurbation’s hydro-sanitary infrastructure. Just over a third of agricultural land has access to water for irrigation.

Capacity component

In general, the RV-CF population shows a condition of medium marginalization and low economic well-being, since 73.3% of the population has incomes below the poverty line in order to satisfactorily access food, education, health, housing, transportation, and recreation (CONABIO 2015). The Ii for the studied population is 0.65; the Mi is 0.01; the Ie is 0.58 and the CG reported 0.42 (Urbano-Peña 2017).

The resulting value for the Capacity component was 0.52. This value can be explained from the fact that the population has a medium degree of marginalization and low social backwardness; however, 61.80% of the population lives in poverty (CONABIO 2015).

Use component

The study area is known for protected agriculture, horticulture, and fruit growing (COPLADE 2016); the primary sector in the Middle Zone contributes 34.5% of the regional GDP, a situation that is possible due to the availability of water for irrigation and that makes it the main consumer of surface and ground water.

In the RVA, 85% of the population has access to drinking water; however, the rest of the population that is dispersed outside the conurbation has a poor supply, which is reflected in the score of 0.38 for the Use component.

Quality component

Availability is not only limited in quantity but in the quality of water that can be used for consumption and food production. With the analysis of the 44 water samples, water quality indices for human consumption and agricultural use were calculated. In the first case, Equation 9 was applied. In the case of quality for human consumption, we obtained a maximum value of 84.8, for Samples 14 and 15 corresponding to the San Diego dam and the El Nacimiento spring, respectively. The minimum values were 7.8 and 7.3, for Samples 29 and 39, which correspond to two wells for agricultural use.

Figure 3 shows that 70% of the samples have quality with restrictions for their use. The water that is extracted in these points belongs to the granular aquifer, where evaporites (gypsum, anhydrite, and dolomite) are predominant, while the best water quality is in the southwest, close to the mountain area, where recharge influences the quality of the water that is extracted.

In the case of calculating water quality for agricultural use, the total of the sampled sites is within the S1 classification (Figure 3), that is, with low sodicity hazard since they have a SAR of less than 10 meq/L. In the case of the EC classification, the samples show a differentiated behavior; two groups can be observed, the first of which falls between C1 and C2, which represents 25% of the samples with low to medium sodicity hazard (Figure 3).

The other group is between C3 and C5, from high to excessive EC, the sodicity hazard. The water quality of this group of samples is related to the interaction with evaporite rocks in which the groundwater circulates. By substituting the values in equation (11) and solving it, the resulting final value is 0.51.

Once the value for each component of the WPI has been calculated, each component's score and assigned weight is presented in Table 4. The overall result of the

Water Poverty Index for the RVA in the Middle Zone of San Luis Potosí was 56 points plotted in the resulting polygon (Figure 4).

As can be seen, the components with the highest scores are Resource and Access; while the lowest are Environment and Use. Quality and Capacity are around the average. From this, it is deduced that the resource administrators must work on the Capacity and Use components for better management of the Resource towards the Population. On the other hand, although the Environment was relatively low, it is necessary to consider that any modification to the use of the soil can cause deterioration to the environment; however, it has been observed that agriculture has increased in recent years except for adding fertile soil, which has increased vegetation.

Conclusions

This study shows the development and application of WPI in a semi-arid zone in the central part of Mexico. In this work, the methodology for evaluating the Environment component was improved, allowing for the comparison of vegetation indices and their spatial-temporal changes.

The main advantage of applying the WPI methodology is to simplify, quantify and communicate key information; however, its main limitation is access to data. In this case, the information to evaluate the index was obtained by searching government or official sources, or they were constructed empirically, as is the case of the Quality and Environment components.

The results show an increase in plant cover over a 10-year evaluation period; however, this can also be attributed to the increase in agricultural area, a situation that is not favorable for the environment, since agriculture has historically displaced natural vegetation, a situation that is reflected with the resulting value of 0.461.

The recharge to the hydrogeological system comes from the mountain ranges of the north and west in a karstic environment, and the flow is directed towards the center of the valley, preferably by the granular medium through which it emerges as springs in the zone of the Media Luna. This availability favors agricultural activity, without creating competition with population water demand; this is consistent with the measurement of the Resource component with a score of 0.68.

The conurbation of RV-CF concentrates the hydro-sanitary infrastructure and registers a high coverage; while in the case of agricultural land just over a third of the agricultural area has access to water for irrigation, which is why the Access component received a score of 0.72.

In general, the population has a medium degree of marginalization and low social backwardness; however, 61.80% of the population lives in poverty, so the resulting value for the Capacity component was 0.52.

The study area’s economic activities are mainly protected agriculture, horticulture and fruit growing; the primary sector in the Middle Zone contributes 34.5% of the regional GDP, a situation that is possible due to irrigation water availability and that makes it the main consumer of surface and underground. 85% of the population has access to drinking water, while the remaining population dispersed outside the conurbation has a poor supply, a situation that is reflected in the score of 0.38 for the Use component.

In terms of quality, a maximum value of WQI of 84.8 was obtained for samples from the San Diego dam and the El Nacimiento spring. Scores of <8 were recorded for two wells for agricultural use. In the northeast, 70% of the samples have quality with restrictions for human consumption, due to interaction with evaporites. The best water quality is in the southwest, close to the recharge zone in the mountains composed mainly of limestone.

Water quality for the valley's agricultural use is classified as S-1 with low sodicity hazard. In the case of the CE classification, two groups can be observed, one between C1 and C2, which represent 25% of the samples with low to medium sodicity hazard. 75% of the samples are classified C-3 and C-5 in a range of high to the excessive sodicity hazard. In general, the quality of water for human use and agricultural irrigation obtained a final score of 0.51.

The overall result of the WPI for the RVA in the Middle Zone of San Luis Potosí was 56 points, which reflects some contradictions in the management of this resource.

The WPI polygon shows that, although there is an abundant resource and the population has access to water, the environment has deteriorated, the resource's quality is not good enough for human consumption, and it is limited for agricultural use. This situation suggests the establishment of systematic water quality monitoring to identify fluctuations in physical, chemical, and even biological parameters, since this is an area is a major economic hub for agribusiness, maquiladoras, and tourism.

On the other hand, it is important to establish that the physical availability of water does not depend on its presence per se, but also on socioeconomic aspects, public policy, legislation, environmental factors; in other words, the problem of water scarcity for both domestic and productive use is one of poor water governance. The United Nations Development Program (UNDP) assures that to improve water governance it is essential to break the vicious circle of world poverty.

The Middle Zone of San Luis Potosí obtained a score of 56 points, reflecting the fact that the majority of the population lives in a medium degree of poverty, marginalization, and is dispersed outside the metropolitan area where supply is deficient. In other words, given that it is the result of poor management of the resource, possible solutions must consider the different dimensions, scales, and stakeholders involved in water issues.

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Table 1. Key Components in the WPI (Adapted from Lawrence *et al*. 2002).

WPI Component	Definition	Sub-components
Environment (*E*)	Evaluation of environmental integrity related to water.	Spatial-temporal analysis of vegetation cover through vegetation indexes from satellite data:* NDVI SAVI LAI CIgreen
Resource (*R*)	Physical availability of surface and groundwater, considering its use and water balance	Surface water Groundwater Volume used
Access (*A*)	Level of access to safe water for human use	% of the population with access to drinking water % of population with access to water treatment. % of agricultural land with access to irrigation.
Capacity (*C*)	Efficacy of the population's capacity to manage water	Income. Mortality rate of children under 5 years of age Education index Gini coefficient
Use (*U*)	Ways in which water is used for different purposes, including domestic, agricultural and industrial uses.	Domestic water use, liters per day. Percentage of water used for agriculture, adjusted based on the sector's contribution to the GDP
Water quality (*Q*)	Evaluation of water quality for human use	Water quality for domestic and agricultural use WQI SAR

* Vegetation indices NDVI, SAVI, LAI and CIgreen are incorporated for the first time in the IPA assessment in this research.

Table 2. Changes in vegetation indexes NDVI, SAVI, LAI and CIgreen in the period from 2006 to 2016.

	NDVI		SAVI		LAI		CIgreen	
	2006	2016	2006	2016	2006	2016	2006	2016
Average	0.047	0.107	0.024	0.058	0.164	0.147	0.081	0.248

Table 3. Correlation matrix of the NDVI, SAVI, LAI, and CIgreen indices

	NDVI	SAVI	LAI	Cigreen
NDVI	1.00			
SAVI	0.97	1.00		
LAI	0.01	0.02	1.00	
Cigreen	0.82	0.85	0.32	1.000

Weights: $fac_{SAVI} = 0.35$; $fac_{Cigreen} = 0.35$; $fac_{NDVI} = 0.25$; $facS_{LAI} = 0.05$

Table 4. Water poverty index values obtained for each component for the Rio Verde Aquifer

Component	X	w	WPI
Environment	0.49	10	56
Resource	0.68	25	
Quality	0.51	20	
Use	0.38	15	
Access	0.72	15	
Capacity	0.52	15	

Figure captions

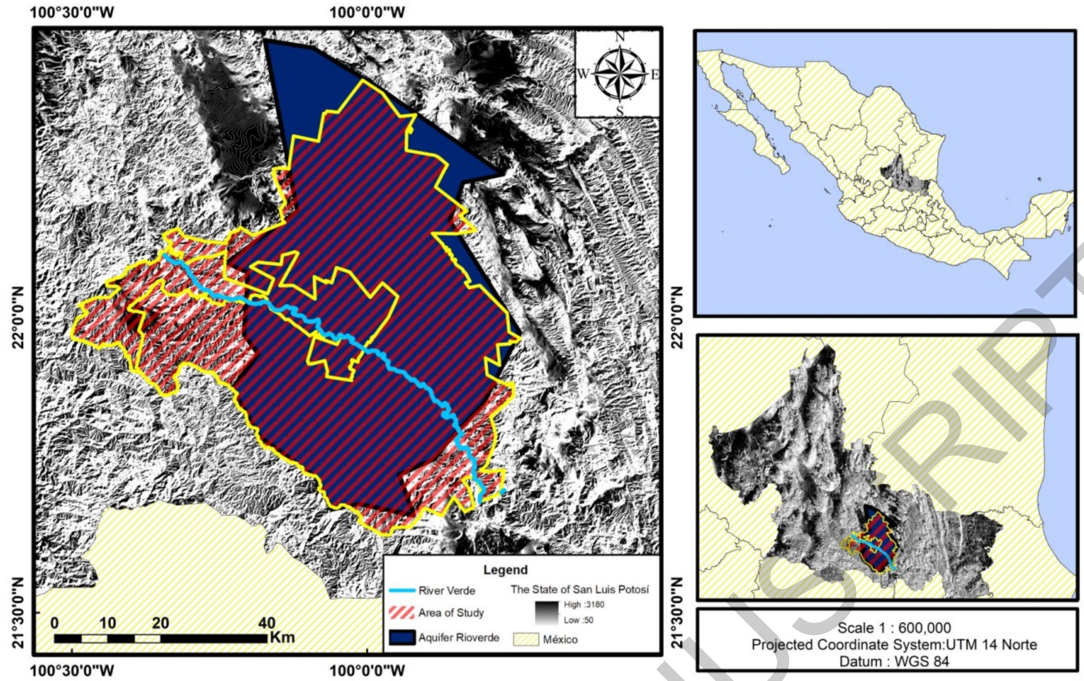

Figure 1. Location of the Río Verde aquifer, San Luis Potosí.

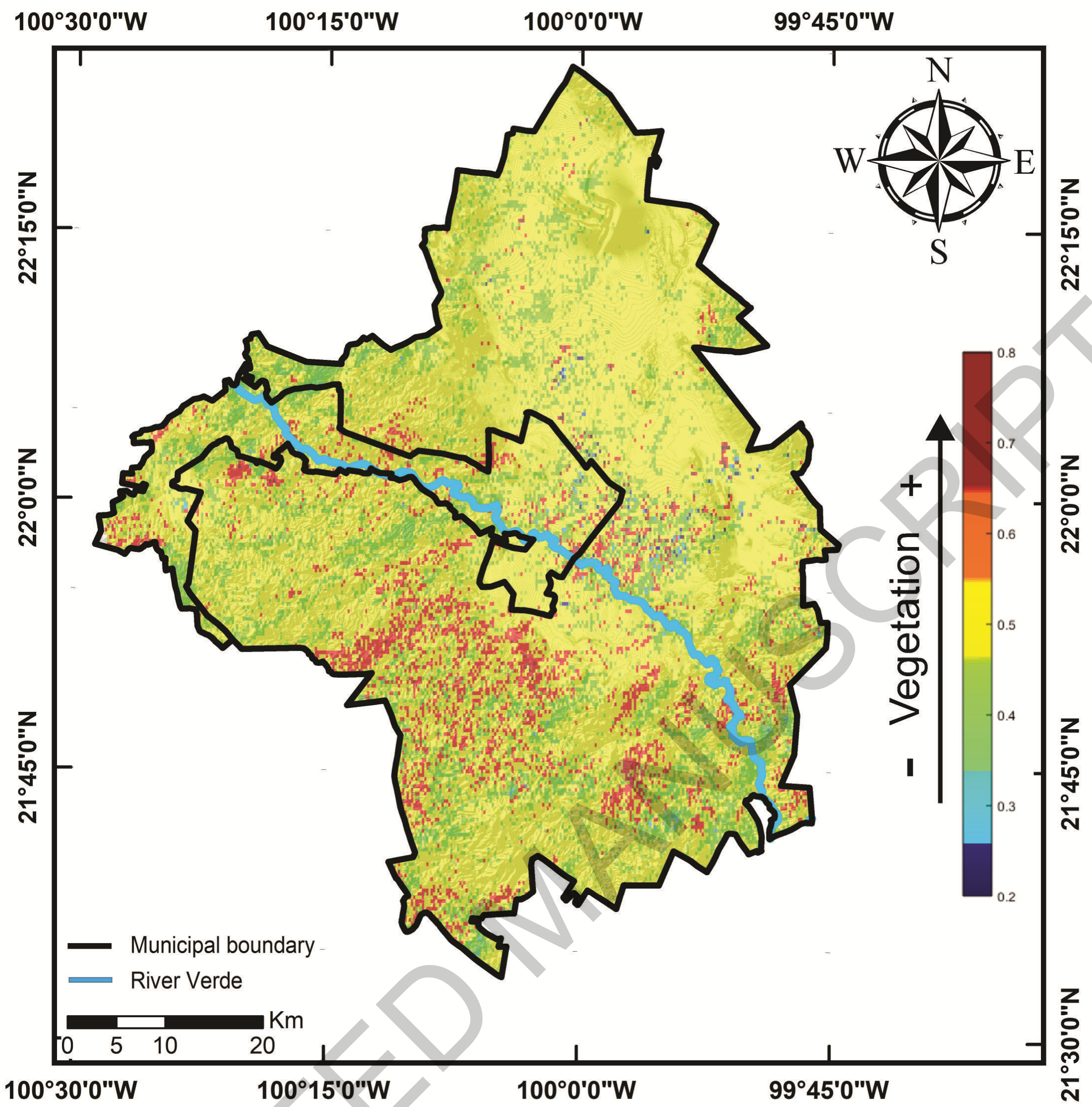

Figure 2. Spatial distribution, resulting from Component E of the study area.

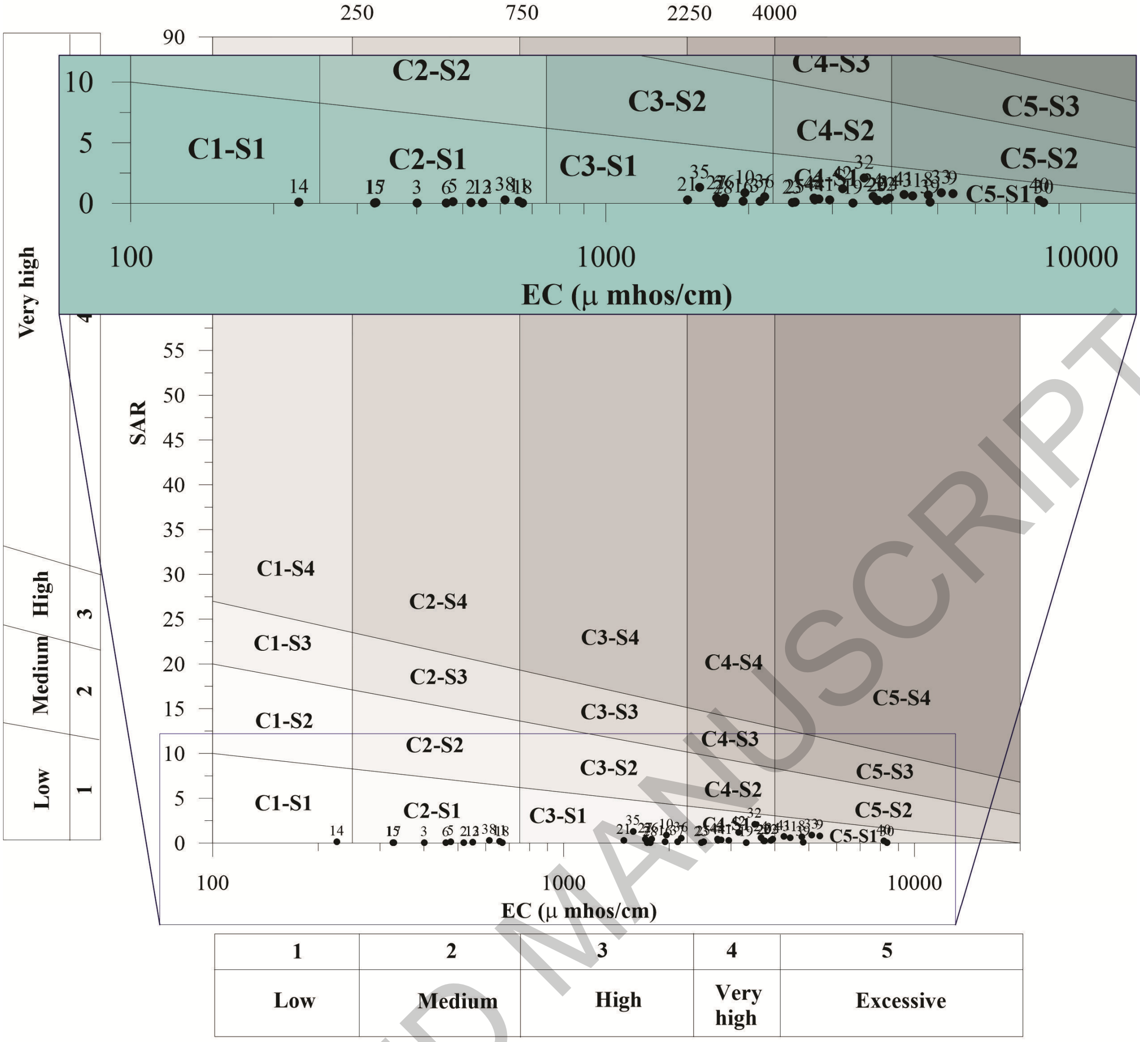

Figure 3. Classification of water according to Wilcox.

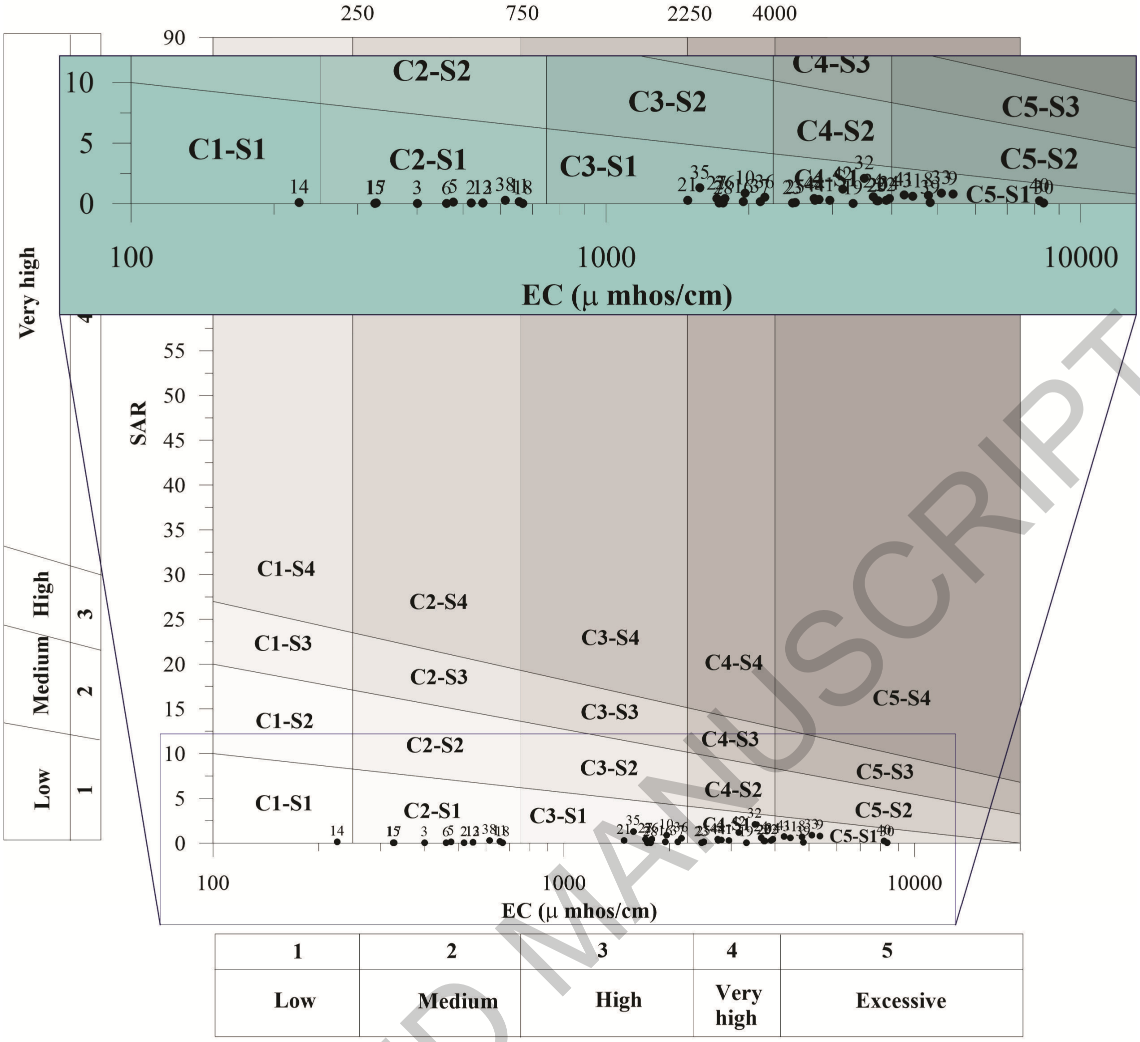

Figure 4. Hexagon of the standard WPI of the Rio Verde aquifer.