A spatial application of the water poverty index (WPI) in the State of Chihuahua, Mexico

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Abstract

The Water Poverty Index (WPI) standardizes water scarcity diagnostics by considering natural, environmental, and socioeconomic factors which reduce, facilitate, or prevent water access. To integrate these factors, the WPI includes five components: resource, environment (negatively affected by development), capacity, access, and use (positively affected by development). Nevertheless, the place granted to hydrological factors is questioned, and many studies insist on the problematic correlation of WPI with the well-known Human Development Index (HDI). Calculating WPI in the socially heterogeneous and semi-arid context of the State of Chihuahua (Mexico), adapting traditional methodology thanks to geographic information systems (GIS) tools and the corresponding databases, allows discussion of those points. This study uses multi-criteria evaluations from TerrSet software to calculate WPI while preserving specific data precision. In this process, scale calculation and indicator normalization are adapted through raster maps and fuzzy techniques to valorize specific hydrological data. This opens interesting discussions for multidimensional water scarcity diagnostics, since they increase the visibility of diverse water scarcity issues in WPI results. In fact, concentrating socioeconomic factors in corresponding components and valuing GIS alternatives provides a diagnostic different from the HDI and sensitive to hydrological factors.

Keywords: Chihuahua; Decision-making; Desert; Development; GIS; MCE; Mexico; Water management; Water scarcity; WPI


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Introduction

In a global context where water resources are affected by qualitative and quantitative degradations, access to water has become a major challenge for decision-making (Anju et al., 2017). With the aim of helping the decision-making process, water scarcity studies determine the situations in which water resources are insufficient to answer water demands on a given territory (Fenwick, 2010; Jemmali & Matoussi, 2013). Those studies focus on both factors that increase water scarcity, such as climate change and population growth, and factors that reduce it, such as the application of water management technology. Factors that affect water scarcity fall into two categories: natural or environmental, and socioeconomic factors which facilitate or prevent water access (Sullivan et al., 2002). Within this framework, the Water Poverty Index (WPI) has been designed to standardize water scarcity diagnostics.

The WPI adapts the concept of poverty – usually reserved for material and economic conditions – to water access. Then, the traditional WPI calculation rests on associating available statistical data, selected as scarcity indicators, and analyzing them through five components (resource, environment, use, capacity, and access) (Lawrence et al., 2003). Components and indicators are statistically analyzed, weighted, and finally integrated. The WPI method has been used in many countries and at many scales, raising debates about the integration of resource components, and the WPI correlations with the Human Development Index (HDI) (Lawrence et al., 2003; Fenwick, 2010; Gong et al., 2017). The use of geographical information can complement the usual components of the WPI and address some of the limitations in the WPI that have been previously highlighted by statistical analyses.

Geographic information systems (GIS) were developed to elaborate useful cartographical diagnostics for territorial decision-making processes (Joerin & Musy, 2000). Considering that they associate ecologic and socioeconomic factors as the WPI does, they could be relevant to discuss the index. Cartographical studies offer a range of particularly rich and detailed environmental and hydrological indicators (Cullis & O'Regan, 2004; Nihila, 2012). Moreover, multi-criteria evaluations (MCE) allow charting statistical analyses through a series of transparent and repeatable operations similar to the traditional WPI methodology (Yager, 1995; Jiang & Eastman, 2010). Those strengths of MCE methodology make it relevant for the discussions mentioned.

To feed discussions concerning resource component integration and WPI correlation with HDI, GIS tools are applied to calculate a GIS-WPI. This study specifically focuses on indicator selection and cartographic representation, operating normalization and aggregation through a specialized software called TerrSet. This also leads to adapting the WPI’s final representation, and discussing its accuracy and
clarity. With that purpose, WPI is calculated in the State of Chihuahua in northern Mexico, its environmental and socioeconomic heterogeneity being convenient for the discussion of environmental and socioeconomic integration in water scarcity diagnostics (CONABIO, 2012).

**Presentation of WPI methodology and challenges**

*An standardization tool for multidisciplinary water scarcity diagnostics*

The WPI synthesizes the scarcities that lead to insufficient water availability, because water scarcity compromises economic development and the well-being of the population. This index is elaborated from five components related to natural, physical, monetary, human, and social capitals: environment, resources, access, use, capacity. Sullivan *et al.* (2002) noticed that development – defined as the creation of physical and financial capitals – positively affects the components of access, capacity, and use, while negatively affecting the components that depend on natural and physical capitals (the components of resource and environment).

Concretely, each component includes various indicators – detailed below – which are integrated through a multi-criteria analysis formed by two analysis steps (Lawrence *et al.*, 2003). First, all data are analyzed separately through a normalization step. This initial interpretation consists of defining the optimal and minimal conditions for the indicator and spreading out data between them. This is traditionally done through the following equation:

\[
I_{qc} = \frac{x_{qc} - \min_c(x_q)}{\max_c(x_q) - \min_c(x_q)}
\]

where \(X_{qc}\) is the indicator for a generic territory \(c\), and \(\min_c(x_q)\) and \(\max_c(x_q)\) are the minimal and optimal values of \(X_{qc}\), respectively.

This first step leads to various series of numbers, from 0 to 1 (or 100), where 0 represents the most unfavorable hydro-socio-system for humans, and 1 represents the optimal one. Next, those results are integrated in an aggregation step. This second step consists of statistical treatments, which include weighting and calculation operations. Values obtained for each indicator of a component are integrated in a weighted average. The WPI finally results in a single number, obtained using the following equation (Sullivan *et al.*, 2002):

\[
WPI = 0.20*R + 0.20*C + 0.20*A + 0.20*U + 0.20*E
\]

where \(R\) is the result obtained for resource component; \(C\) is the result obtained for the component capacity; \(A\) is the result obtained for the access component; \(U\) is the result obtained for the use component; and \(E\) is the result obtained for the environment component.

This WPI statistical method is interesting because of its multidimensional and synthetic characteristics. That is why it has been used in several countries and scales (Anju *et al.*, 2017). However, it has been discussed in many ways.

**Challenges associated with environmental and socioeconomic integration in water scarcity diagnostics at regional and national scales**

Since its conception, WPI structure has raised many questions, in particular about the capacity and resource components. The capacity component is traditionally elaborated with the four indicators used in HDI calculation (see Table 1). The problem is many studies have demonstrated that WPI
The final results are strongly correlated with the capacity component, and then, with HDI results (Lawrence et al., 2003; Fenwick, 2010; Garriga & Foguet, 2010). Since the final results of the WPI are supposed to integrate environmental dimensions that have no place in the HDI, this correlation is all the more striking. Simultaneously, the integration of hydrological issues is debated. Some authors propose removing the resource component, questioning the WPI multidisciplinary conception (Fenwick, 2010; Jemmali & Matoussi, 2013). Also, the resource component is constructed in two different ways: through m³/capita (Lawrence et al., 2003; Fenwick, 2010; Jemmali & Matoussi, 2013) or with m³/year (Anju et al., 2017; Gong et al., 2017; Maheswari et al., 2017). The hydrologic option (m³/year) is increasingly used in WPI calculation, but without being formally debated. In fact, it must be mentioned that some authors valued cartographical databases in WPI elaboration (Cullis & O’Regan, 2004; Nihila, 2012). Those are indeed more specific than statistical databases for environmental and hydrological diagnostics. Nevertheless, this strategy has not been applied in a systematic way in WPI calculation.

Those two fundamental discussions proceed together, and can lead to questioning of indicator selections. The indicators proposed by Sullivan et al. (2002) are usually adapted according to public statistical data availability (Lawrence et al., 2003; Anju et al., 2017). This leads to a large diversity of indicators that slows down discussions and even causes paradoxes. For example, Rentería Flores & Pérez Arredondo’s (2010) WPI calculation confers to Chihuahua a very low water poverty yet it is situated in semi-arid northern Mexico (CONABIO, 2012). Those authors built the resource component from administrative indicators which present a positive evolution while development increases. According to Sullivan et al. (2002), this evolution should be negative and not positive. In view of these comments, the place granted to hydrological factors through WPI indicator selection should be questioned.

As a contribution to WPI indicator selection discussion, this study concentrates socioeconomic factors in access, capacity, and use components, creating, when possible, resource and environment components from public cartographical databases. With that aim, WPI is calculated using GIS tools, just as Sullivan et al. (2002) suggested. Those tools lead to adapting WPI calculation units, normalization, and aggregation steps.

**Employing GIS tools and transforming both WPI calculation and final representations at regional scale**

At non-local scale, WPI is traditionally calculated for administrative units such as countries, states, or municipalities (Lawrence et al., 2003; Fenwick, 2010; Rentería Flores & Pérez Arredondo, 2010; Gong et al., 2017). Applying the traditional statistical index method, those calculation units are supposed to
sacrifice some data precision since they cannot be attributed diverse values for the same indicator. This limits the benefits of using specific environmental and hydrological databases, since it implies averaging them, standardizing territorial diversity. Considering this methodological constraint, Abraham et al. (2002) divided them to improve WPI territorial representativeness. However, their strategy was developed at local scale and needs to be adapted for larger ones.

With that aim, GIS analyses can preserve data precision during the aggregation process, replacing traditional statistical databases with raster maps. In those maps, each pixel represents a singular geometric entity that receives its associated value, just as statistical databases attributed a specific value to their calculation units in the WPI calculations in Sullivan et al. (2002) and Abraham et al. (2002). With raster maps, administrative units are divided into many geometric entities and can be given different values for the same indicator. Specialized software enable applying statistical operations to each entity (as is done when calculating indexes), and developing a transparent and repeatable aggregation method similar to the traditional WPI one (Jiang & Eastman, 2010).

It should be noted that the WPI is used to classify territories and societies according to their water poverty, but also to identify the main factors of water poverty in the studied territories (Sullivan et al., 2002). Therefore, the final results often lead to cartographic transcriptions in which territorial classifications are easy to compare (Garriga & Foguet, 2010; Jemmali & Matoussi, 2013; Maheswari et al., 2017). However at the same time, many authors underline that representing the WPI by a single number is too synthetic (Anju et al., 2017). Thus, the index is often presented through an extended version, detailing the scores obtained for each component, in order to support the WPI analyses. By definition, using GIS tools leads to a final cartographic representation. This alternative fits both in continuity and adaptation of these final representations, so it appears all the more interesting to analyze and discuss.

Thus, this research explores GIS-WPI calculation using ArcGis and TerrSet. The first one both values specific environmental and hydric data, and converts all the indicators to raster format. Then, TerrSet multicriteria evaluation (MCE) is operated to normalize and aggregate the charted indicators (Jiang & Eastman, 2010). Two adaptations of traditional WPI calculation must be noted in the present MCE elaboration. First, if raster maps’ analyses enable valorization of the cartographical indicators’ precision, the others must also be charted in order to be integrated through MCE. Thus, it implies another analysis step for non-cartographical indicators, which must be processed with transparency. Moreover, the normalization process must be adapted because the min–max approach cannot be applied to all cartographical indicators. With MCE, actually, normalization is performed through fuzzy membership functions which allow normalizing heterogeneous indicators such as statistical and cartographical ones (Yager, 1995; Jiang & Eastman, 2010). Since it consists of a standardization operation the fuzzy technique is particularly similar to the min–max strategy (OECD & JRC, 2008). Consequently, the fuzzy technique and MCE seem interesting to elaborate GIS-WPI calculations.

Those alternatives are presently applied in the State of Chihuahua, Mexico. The corresponding results are commented on and compared with the territory characterization and HDI, in order to feed the discussions concerning WPI structure, calculation, and final representation.

**Methods: build a GIS-WPI choosing indicators and interpretation methods in the State of Chihuahua**

WPI is calculated for the municipalities included in the State of Chihuahua. This scale allows observation of several local variations in water management and could thus constitute an interesting basis to
calculate the WPI at larger scale (Fenwick, 2010). In addition, the availability of numerous uniform public data across Mexican territory favors the WPI reproduction and allows interesting applications and discussions.

The WPI socioeconomic factors: which data and scale are available in Mexico?

The WPI socioeconomic indicators are quite similar in all the specialized literature (Sullivan et al., 2002; Fenwick, 2010; Maheswari et al., 2017). This study uses traditional indicators even if some restrictions and specific charting strategies must be noted (Table 1).

First, no Mexican public databases incorporate the per capita irrigation access rate, which is traditionally used to develop the irrigation indicator (Lawrence et al., 2003; Jemmali & Matoussi, 2013). However, they summarize the technical development of agricultural production units at municipal scale (INEGI, 2018). Associating these data with land use maps, it makes it possible to distinguish between irrigated and non-irrigated areas, and to represent the major agricultural technologies used in each municipal irrigated area. Second, the gross domestic product (GDP) is traditionally used in the capacity component as well as to elaborate agricultural and industrial uses indicators. However, Mexican GDP values are not available at municipal scale. In the capacity component, GDP is replaced by the current total income per capita (ICTPC), which includes non-monetary income while GDP does not (CONEVAL, 2010). In agricultural uses, GDP is replaced by the production value that represents the theoretical crop value supposing all the crop is sold at market value (INEGI, 2018). For industrial uses, GDP is replaced by the industrial total gross production (PBT); it includes economic production made by Mexican people outside Mexico, while GDP does not. Also, the industrial PBT does not include economic production made in Mexico by non-Mexican people, which the GDP does.

Charting municipal data in raster format is simple thanks to their precise influence area, but education level and water and sanitation access are presented at local scale (INEGI, 2013). The question is: how to preserve this data precision? The National Statistic and Geographic Institute (INEGI) indeed identifies two demographical units: rural communities under 2,500 inhabitants and cities having more than 2,500 inhabitants. This strategy echoes Sullivan et al. (2002), who separately value urban and rural water access data through two different indicators. Moreover, CONABIO’s (2012) maps include irrigated and non-irrigated agricultural areas in which municipal membership is used to chart agricultural census.

Hydrological and environmental water scarcity indicators: identifying guidelines in the various alternatives

Excluding socioeconomic data, the resource and environmental components concentrate on three sets of data: water quantity, water quality, and what Garriga & Foguet (2010) call ‘environmental conservation’. Hydrological approaches have been adopted to evaluate the water quantities, focusing on meteorological, superficial, and subterranean water volumes and time periods (Anju et al., 2017; Gong et al., 2017). Then, following Lawrence et al. (2003), water quality indicators are developed by analyzing various physical and chemical characteristics of the resource, while water stress indicators evaluate the amounts of fertilizers or pesticides used in agriculture.

As per Gong et al. (2017), wastewater treatment is included in the Water Stress Index. With regard to agricultural pollution, there are no data specifically related to fertilizer or insecticide use in Mexico. The indicator is therefore constructed as a single indicator of extreme water poverty for all irrigated areas and
high water poverty for areas fed by rainwater only. This strategy distinguishes agricultural areas negatively from the rest of the territory and focuses on an important issue.

Finally, the wide variety of language conventions used to describe environmental preservation indicators makes it particularly difficult to define guidelines: for example, there are sometimes references to soil degradation, or a characterization of tree cover (Cullis & O’Regan, 2004). In addition, every biodiversity, land use, and vegetation data also represent the state of preservation of natural habitats. In view of these remarks, the indicators are elaborated as mentioned in Table 2, including an indicator of overexploitation of aquifers, as done by Rentería Flores & Pérez Arredondo (2010).

The MCE approach: WPI data and component integration alternatives

This study uses MCE for WPI calculation. Then, normalization is operated by applying fuzzy membership functions, which convert the indicator values into suitability levels through membership functions (Yager, 1995; Jiang & Eastman, 2010). These classify the values into four types of sets: the suitable, unsuitable, and respectively, increasing or decreasing sets (Figure 1). In this process some thresholds determine when suitability becomes maximum, minimum, or in some cases, medium.

In fact, some thresholds coincide with the limits of the indicator itself. For example, the household clean water access being a percentage, the minimum suitability is set to 0% while the maximum is set to 100%. In the same way, most of the WPI indicators used in this study have pre-established thresholds: access to sanitation (0 to 100), access to irrigation (none to technical), average level of education (none to PhD), climate (very arid and variable to very humid and constant), overexploitation of aquifers (null to extreme), erosion (null to extreme), degradation of tree cover (conservation to extreme), agricultural contamination (none to extreme), water treatment (0 to 100), and the chemical quality of the water (extremely contaminated to good quality).

However, other indicators are constructed in such a way that they have no bounds (agricultural use), or even if they do, those bounds are not relevant (child mortality being unsuitable before it reaches 1,000‰). In these cases, thresholds are defined through two strategies (Table 3).

Table 2. Hydrological and environmental indicators.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Measures</th>
<th>Sources</th>
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<tbody>
<tr>
<td>Resource</td>
<td></td>
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<tr>
<td>Subterranean water</td>
<td>Medium annual aquifer recharge (10^6 m^3/year)</td>
<td>CONAGUA (2015)</td>
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<tr>
<td>quantity</td>
<td></td>
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<tr>
<td>Superficial water</td>
<td>Superficial streams quantification (10^{-3} m)</td>
<td>CONABIO (2012)</td>
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<tr>
<td>quantity</td>
<td></td>
<td></td>
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<tr>
<td>Meteorological water</td>
<td>Climate characterization according to humidity and seasonal variation</td>
<td></td>
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<tr>
<td>quantity and variability</td>
<td></td>
<td></td>
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<tr>
<td>Water quality</td>
<td>Water Quality Index</td>
<td>CONAGUA &amp; SEMARNAT (2015)</td>
</tr>
<tr>
<td>Wastewater treatment</td>
<td>Waste water treated (%)</td>
<td>CONABIO (2012)</td>
</tr>
<tr>
<td>Environment: water</td>
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<tr>
<td>quality, and water</td>
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<tr>
<td>stress</td>
<td></td>
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<tr>
<td>Agricultural</td>
<td>Agricultural contamination index, according to quantities and product</td>
<td>CONABIO (2012)</td>
</tr>
<tr>
<td>contamination</td>
<td>recommendations</td>
<td></td>
</tr>
<tr>
<td>Vegetal cover</td>
<td>Analysis of land use changes</td>
<td></td>
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<tr>
<td>degradation</td>
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<tr>
<td>Soil erosion</td>
<td>Characterization of wind and hydric erosion, according to their forms and</td>
<td></td>
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<tr>
<td>Aquifer overexploitation</td>
<td>calculated according to aquifer availability</td>
<td>CONAGUA (2015)</td>
</tr>
</tbody>
</table>
Three of those indicators are developed on global models. Consecutively, the global maximal, medium, and minimum thresholds are used to construct the fuzzy analysis for: Gini coefficient (Banque Mondiale, 2016), child mortality (Banque Mondiale, 2013), and public use (Howard & Bartram, 2003). On the other hand, five other indicators are designed through specific methodologies (income, agricultural uses, industrial uses, surface runoff, and quantity of groundwater), so they do not allow such a global comparison. In these cases, the maximum and minimum Mexican values are used. Concretely, indicators are calculated at the state or hydrographic region scales to determine which territories present the largest and lowest values. Within them, the same approach is repeated at the specific calculation scale.

Being normalized that way, indicators and then components are aggregated through equally weighted averages in accordance with the traditional WPI method (Lawrence et al., 2003). To discuss the interest of the WPI, its results are also compared with those of the HDI. HDI is charted just as WPI and rests on indicators used for capacity component WPI calculation too. Then, the comparison is developed analyzing the map obtained, subtracting WPI results from HDI ones.
Presentation of the study area

Chihuahua State is located on the border with the United States, and is divided into three very different regions: the Sierra, characterized by its canyons and beneficial mountains; desert, characterized by its hostile ecosystem; and development corridors, situated in the semi-arid ecosystem of the desert (Figure 2).

The heart of the state’s development is situated in the urban agricultural regions of Cuauhtémoc, Chihuahua, and Delicias: those urbanized regions are favored by the streams flowing down from the Sierra, as well as dense and structured communication networks which facilitate the connections with the United States and the rest of the country. Two other municipalities, Juárez and Ojinaga, rely on water resources and transportation facilities as well thanks to border rivers and transactions. Finally, Jiménez and Parral are southern territories, respectively characterized by agricultural and mining activities. These seven municipalities structure the state in the middle of Chihuahua’s Sierra and the deserts, while economic and demographic dynamics are much more restricted.

This research expects WPI to reveal hydrologic scarcity in the desert, socioeconomic marginalization in the Sierra, and a balanced diagnosis in the development corridors where the environment and hydrological context should be problematic, but socioeconomic factors should not.

Fig. 2. Delimitation of three geographic units in Chihuahua. Source: (CONABIO, 2012). Chihuahua State stretches across the Sierra Madre Occidental to the south and west and the desert. In the Sierra, urbanization is weak, mining activities are scattered (Guachochi, Uruachi, etc.), and agriculture is seasonal and this territory is marginalized in contrast with the rest of the state (CONABIO, 2012). Now, because the Chihuahuan desert is depopulated, the state has a very low density of 14 inhabitants/ km² (INEGI, 2018). The population is mainly concentrated in kinds of development corridors whose productivity is noted. At national level, Chihuahua in some years has the highest production of fodder oats, green peppers, apples, nuts, quince; the second highest production of onions, green alfalfa; and the fourth highest for beef cattle in sheds (INEGI, 2018). This leads to massive overexploitation of the development corridors’ aquifers (CONAGUA, 2015).
Results and discussion: potentials and limits of GIS-WPI to associate first- and second-order water scarcity diagnostics in Chihuahua

This section analyzes and discusses the interest of GIS-WPI calculation, focusing on how it opens up a range of useful environmental and hydrological indicators and MCE aggregation methods for WPI. Figure (map) comparison supports these analyses and discussions.

Using MCE to aggregate WPI indicators and components

The data compilation and MCE operations applied for the State of Chihuahua actually make it possible to construct a GIS-WPI (Figure 3). The results obtained reflect the different water scarcities associated with the three geographic units identified in Chihuahua. These results, then, seem to integrate environmental and socioeconomic factors with relevance. In addition, other relevant differences appear

Fig. 3. GIS-WPI results applied to Chihuahua. WPI results lie between 0 and 1, 0 being the highest water poverty since it corresponds to the lowest suitability. Figure 3 shows that applying a GIS-WPI in Chihuahua State’s suitabilities stronger than 0.55 are actually localized and do not pass 0.60. The most visible correspond to the cities of Chihuahua, Juárez, Delicias and some agricultural parcels and cities of Cuauhtémoc region. In Chihuahua’s Sierra, the socioeconomic problems are mitigated by a favorable physical context; moreover, the best-connected municipalities’ scores are closer to the average than the others. Sierra’s suitabilities are stronger than in the desert, whose semi-arid context and desertification process seem to give more visible results. Finally, the highest suitabilities are concentrated in development corridors.
between rural and urban areas, the cities obtaining greater suitability than rural areas. Finally, both Ascen-
ción and some southern municipalities (in the vicinities of Jiménez, Parral, Guachochi, and Uruachi) stand
out for their low water poverty (with suitabilities higher than 0.48). They are actually productive munici-
palities characterized by agricultural or mining activities and connectivity infrastructures.

However, the preponderance of municipal variations is to be noted. Few socioeconomic indicators are, in
fact, available at local scale, and two water quality indicators are also elaborated at municipal scale. Some
non-municipal limits appear as shadows or points, but those results are limited compared to municipal ones.
Besides, only precise examination of the indicator (or component) maps makes them interpretable. They are
environmental in the desert, due to its hydrological context but also to the vegetation degradation and aquifer
overexploitation (in the agricultural region located between Delicias and Jiménez). In the Sierras and devel-
opment corridors, they correspond to both climate variations and agricultural practices. All urban areas get
finally similar WPI, so comparison possibilities are limited for those units.

The results obtained for GIS-WPI calculation appear noticeably nuanced and accurate in the State of
Chihuahua. Nevertheless, their contributions are limited by some data scale availability and clarity con-
siderations. The next section comments on how those contributions and limitations impact the WPI
relevance compared to HDI ones.

Comparing the GIS-WPI with HDI

Figure 4 is elaborated by subtracting WPI results from HDI ones. Much of the figure’s score is
between −0.04 and 0.09. This means the differences between HDI and WPI are tiny, and a correlation
exists between the two indexes. In this context, urban areas are not quite so visible: they get almost the
same scores as their corresponding rural areas. Therefore the HDI – included in the capacity component
– appears noticeably responsible for the urban/rural variations in WPI results. Indeed, the access com-
ponent also distinguishes those areas and accentuates those variations.

However, it should be noted that Figure 4 goes up to 0.33. This means a relevant difference between the
two indexes: the HDI being higher. The biggest differences (scoring above 0.25) are situated in the municip-
ality of Chihuahua and the urbanized territories included in the region of Delicias. Those areas are indeed
categorized by high demographic densities and agricultural activities in semi-arid ecosystems. This problem-
etic juxtaposition of heterogeneous issues is reflected in WPI calculation through low suitabilities for
hydrological and environmental components, but also water and sanitation access and public use.

Now, excluding Chihuahua and Delicias, the highest scores (higher than 0.25) are concentrated in the
deserts. For those territories, hydrological factors included in the resource component cause the indexes
to be different. Climatic variations indeed appear as shadows on the map, and jointly highlight a
regional behavior. In a similar way, some shadows emerge and mark out some no-municipal limits
in the agricultural regions of Delicias and Ojinaga (from development corridors). They correspond to
aquifer areas, and generate specific hydrological and management issues.

Finally, the heterogeneity of HDI and WPI behaviors observed in development corridors make visible
the impact of the environmental and two others socioeconomic components in the WPI results. Figure 4
indicates that their combination reduces the municipal suitabilities, but only the precise analysis of indi-
cator (or component maps) allows their singular impact to be specified. This observation indicates that
HDI and WPI correlations are not totally redundant.

This map highlights slight but significant differences between the HDI and WPI calculated in the
State of Chihuahua. In particular, WPI insists on regional variations mostly linked with hydrologic
context, but also with infrastructure and environmental management. Those results are particularly interesting for nuanced and accurate water poverty diagnostics, but they could – and should – be stronger.

Discussing WPI calculation methods through MCE

In order to feed a formalized discussion about WPI indicators and multidisciplinary construction, this study aimed to strictly elaborate the resource and environmental component from specific cartographical databases in the State of Chihuahua. First it is to be mentioned that both WPI literature and Mexican public databases allow this target to be achieved in a satisfactory way. In fact, cartographical databases have been used to construct all the hydrological indicators and almost all the environmental ones (agricultural and water quality indicators presenting important deficiencies even if they are in the past). Also, the WPI traditional calculation units have been transformed using GIS tools and aggregation
methods. The objective was to preserve data precision and make the results more sensitive to the resource component and distinct from HDI diagnostics.

In fact, the GIS-WPI results obtained identify various issues in the heterogeneous territory considered. As with the results obtained by Rentería Flores & Pérez Arredondo (2010) or Gong et al. (2017), Figure 3 highlights less water poverty in the most productive and inter-connected territories (i.e., urban areas or mining or modernized agricultural municipalities). But these results also mitigate and complete Rentería Flores & Pérez Arredondo’s (2010) results evidencing other water scarcity factors such as hydrologic and environmental ones. Thus, the GIS tools and databases used in this study appear to be relevant for multidisciplinary WPI calculation. In particular, discussing the construction of hydrologic and environmental components seems interesting even if complicated. The hydrological indicators indeed result in a significant part of the differences between WPI and HDI diagnostics: that confirms the importance of the debated resource component (Fenwick, 2010; Anju et al., 2017).

In addition, the GIS-WPI generates results at pixel units. Those scale calculations adapt the suggestion from Abraham et al. (2002) to regional studies: the authors targeted territorial representativeness, dividing the heterogeneous administrative entities into more homogeneous units. Indeed, urban and rural areas can be distinguished in the results, as can some agricultural areas and hydro-environmental delimitations. The rural/urban distinction is a relevant contribution for WPI calculation (Sullivan et al., 2002; Fenwick, 2010). However, even if it feeds interesting analyses on rural situations, the urban water poverty is quite the same throughout the State of Chihuahua. This point leads to questioning the capacity of WPI to make relevant diagnostics for both rural and urban areas. Moreover, despite the GIS methodology, the results are mostly interpretable at municipal scale, making visible relative regional variations: strong and multidimensional water scarcity in the desert, and mitigated scarcity in the Sierra and development corridors. Thus, local issues and variations still do not clearly appear without analyzing the indicator (or component) maps.

Actually, the WPI reflects complex juxtapositions of socioeconomic and hydro-environmental factors throughout the State of Chihuahua, which is still difficult to identify in GIS-WPI final results. This limitation is part of the discussion about WPI and indexes (OECD & JRC, 2008; Anju et al., 2017). And even if the GIS-WPI feeds the discussion (highlighting some rural, agricultural, and hydrologic issues), its elaboration and final representation still deserve to be discussed. The HDI/WPI comparison confirmed this point as it underlines GIS contributions, insisting at the same time on their too slight final visibility. It highlights the redundancy between the two indexes, but also makes visible the fact that other components impact the WPI significantly. In particular, the resource component noticeably appears in the Chihuahuan desert, while the socioeconomic component mostly influences the Sierra and both the socioeconomic and environmental components impact the water poverty of development corridors. Nevertheless, according to those observations, extended WPI analyses still appear interesting.

To conclude, it must be noted that other existing MCE and WPI calculation alternatives could produce relevant results for this and other discussions. Just as the extended WPI do, associating various GIS-WPI would make the results more accurate. Such modeling would also feed the methodological WPI discussion, and strengthen it to help decision-making (Joerin & Musy, 2000).

Summary and conclusions

GIS-WPI is calculated for the municipalities of the heterogeneous State of Chihuahua to feed the discussions concerning the resource and capacity components of the model. The main methodological
adaptations are to concentrate and chart socioeconomic indicators in the capacity, access, and use components, and to valorize specific cartographical data and analyses in the environment and resource components. Using TerrSet and ArcGis, WPI calculation is adapted using an MCE approach. This one is characterized by specific scale (pixel) and normalization (fuzzy) techniques, which makes it possible to conserve data precision and obtain charted results.

The results reflect complex juxtapositions of socioeconomic and hydro-environmental factors throughout the State of Chihuahua, which present medium and high water scarcities. They highlight strong scarcities in the desert. In parallel, less water poverty appears in the most productive and inter-connected territories. The cartographic options reaffirm the relevance of both WPI, compared to HDI with regard to water poverty diagnostics, and its resource component.

However, the results presented some limitations too. Even if they evidence different issues, the synthetic GIS-WPI maps are still mainly interpretable at the municipal scale. This is partly due to the limited socioeconomic and environmental data availability at local scales. Also, although suggesting this could be reduced, the results reaffirm the well-known correlation between WPI and HDI. Finally, as in traditional WPI methodology, separate component analysis remains important to obtain precise final scores.

The combination of various diagnostics appears as a constant for truly accurate results, also being the solution adopted by MCE developers in order to confront systems as complex as water poverty. This strategy both helps decision-making and feeds the discussion concerning WPI methodology. More existing WPI and MCE alternatives could be associated in future works and feed the methodological discussions.

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