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Groundwater Rights in Mexican Agriculture: Spatial Distribution and Demographic Determinants*

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Groundwater use intensity and aquifer depletion increase from south to north with decreasing rainfall and increasing economic activity in Mexico. To heighten scholarly understanding and offer new insights that strengthen policy responses to aquifer depletion, we analyze the spatial distribution of agricultural groundwater use from irrigation well titles in 2,429 municipalities and its relation to agricultural surface water and population employed in agriculture. Exploratory spatial data analysis reveals spatial dependence among all three variables implying that policy initiatives to address intensive groundwater use must be targeted at clusters of aquifers and municipalities. Key Words: groundwater, Mexico, spatial statistics, water rights.

In Mexico, groundwater use intensity and aquifer depletion increase from south to north with decreasing rainfall and increasing economic activity. To improve understanding and offer new insights that strengthen policy responses to aquifer depletion, we analyze the spatial distribution of agricultural groundwater use from irrigation well titles in 2,429 municipalities and its relation to agricultural surface water and population employed in agriculture. Exploratory spatial data analysis reveals spatial dependence among all three variables implying that policy initiatives to address intensive groundwater use must be targeted at clusters of aquifers and municipalities.

La intensidad del uso de agua subterranea y el agotamiento de los acuiferos en Mexico se incrementan de sur a norte en relacion con la disminucion de la lluvia y el incremento de la actividad economica. Para mejorar la comprension de estos problemas y explorar nuevas ideas que fortalezcan las politicas de respuesta al agotamiento de acuiferos, analizamos la distribucion espacial del uso agricola de agua subterranea extraida de pozos autorizados en 2,429 municipios, y su relacion con el uso de agua agricola de superficie y la poblacion empleada en agricultura. El analisis exploratorio de los datos espaciales revela una dependencia espacial entre todas las tres variables, lo cual implica que las iniciativas sobre politicas que afronten el uso intensivo de agua subterranea deben concentrarse en agrupamientos especificos de acuiferos y municipalidades. Palabras clave: agua subterranea, Mexico, estadistica espacial, derechos del agua.

Land, population, and economic development are concentrated in arid and semiarid northern Mexico, whereas much of the south has abundant water supplies and is prone to flooding (witness the catastrophic late 2007 floods in Tabasco and Chiapas). Despite sustained investment in infrastructure to store surface water and in the development of groundwater, the availability of water in absolute terms or in relation to states’ economic ranking is severely limited in the north; however, due to land concentration and the

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structure of commercial farming in the north, this is where water use per person employed in agriculture tends to be the greatest. The distribution of access to water varies by use, by type of user, and spatially across the country and within regions and river basins. Throughout the twentieth-century development of water resources in Mexico, however, water use was not quantified in sufficient detail to permit assessment of socioeconomic or location-specific differences. This changed with water rights titling beginning in 1992, a process described in further detail in what follows. This process allows us to provide a detailed analysis of the distribution of groundwater across Mexican municipalities.

It was during the 1990s that groundwater received increased attention in Mexico and faced growing demand as a critical resource (Vázquez Rodríguez 1999; Marañón-Pimentel and Wester 2000). At the national level, groundwater currently accounts for two thirds of the water supplied for urban populations, half of the water for industry, and a third of the water for agriculture (Comisión Nacional del Agua [CONAGUA] 2008). Driven by rising demand and pumping of groundwater coupled with variable recharge, many regions of the country, particularly the Baja California peninsula and the adjoining northwest region of Mexico, are experiencing aquifer overexploitation, leading to depletion and deterioration of water quality in this critical resource. One hundred and four of Mexico’s principal aquifers are overexploited, up from thirty-two in 1975 (CONAGUA 2008), a trend that is seen in numerous regions around the world (Shah et al. 2003; Kettle, Harrington, and Harrington 2007; Giordano and Villholth 2007). Mexico is the largest user of groundwater in Latin America, with more than 100,000 large-capacity pumps for agriculture alone (Scott and Shah 2004). Each of these groundwater wells must be titled to the individual, commercial, or public owner, in distinction from surface water rights, which are granted to groups of users.

Spatially explicit data on groundwater titles represent an important decision-making input to address aquifer exploitation and the related policy challenge of safeguarding societal dependence on groundwater. Spatial tools for water resources management in Mexico are being developed and applied, such as canal irrigation operations and management (Ojeda-Bustamante et al. 2007) and Global Positioning System locational inventorying of infrastructure for operational purposes. However, despite innovation with spatially explicit groundwater models for decision support, for example, in the central state of Guanajuato (Sandoval-Minero 2001), the Mexican government’s official estimates of groundwater availability and depletion are estimated based on aquifer-wide average water balances of supply (recharge) and demand (pumping). Decision makers have paid inadequate attention to the potential presence of spatial dependence in the distribution of groundwater levels across municipalities, to the relationship between groundwater and population employed in agriculture, and to the conjunctive role of surface irrigation (important both for recharge of underlying aquifers and as an alternative source of irrigation water). This article presents specific spatial analyses that might permit decision makers to address these policy gaps.

The article is organized as follows. The introduction has provided a brief overview of water resources in Mexico with an emphasis on aquifer depletion and associated management and policy challenges. We augment this with a section discussing water rights, particularly in agriculture. Next we set forth our conceptual approach and specific objectives, identifying the contribution this article makes to the relevant literature as well as potential policy uptake to address aquifer depletion in Mexico. The analysis follows, with an exploratory spatial data analysis of the distribution of ground and surface water rights, coupled with labor in agriculture across Mexico’s municipalities. The article concludes with a discussion of Mexico’s intensive groundwater use and aquifer depletion challenges and highlights policy implications.

**Water Rights in Agriculture**

In Mexico, the Public Register of Water Rights (Registro Público de Derechos de Agua [REPDA] 2008) codifies water rights as mandated by the Law of the Nation’s Waters (Ley de Aguas Nacionales [LAN]) and its regulations. The REPDA is managed by CONAGUA. Although the LAN was promulgated in 1992, the REPDA has only recently become operational as a reliable database (Garduño 2005). As of the end of
over 97 percent of the water rights titling process was completed (CONAGUA 2008).

It is instructive to review other provisions of the LAN that influence water management and access, namely, the role of CONAGUA, the structure and functioning of river basin councils as a mechanism for the management of water resources, and public participation in water management. A federal agency within the environment ministry, CONAGUA is responsible for administering and managing water resources. Water is considered property of the nation; however, there is some definitional ambiguity regarding “state” waters (surface sources that originate and are depleted within a state). All groundwater is national property. During the 1990s, CONAGUA’s principal mandate was to manage surface water resources. In 1992, it initiated the transfer of large irrigation districts (3.2 million hectares in total, largely relying on surface water sources) to water users. For the purposes of our analysis, it is important to note that rights to surface water in this case were granted at the level of the water user association, which typically encompasses thousands of individual users (Rap, Wester, and Pérez-Prado 2003). Small surface water irrigation systems and some collective groundwater systems called irrigation units (unidades de riego) continued under user management with group water rights (Palerm Viqueira and Martínez Saldaña 2000; Silva-Ochoa 2000; Scott and Silva-Ochoa 2001). Water users along with federal and state agencies are represented on Mexico’s river basin councils, which have achieved considerable acclaim internationally. Representation on the councils and a series of related public participation initiatives for water management are based on the water users holding rights codified in the REPDA.

CONAGUA administers the titling and concessioning of all water rights, both to surface and groundwater sources, which are written into the REPDA. Concessions are granted for a specified annual volume over the period of the concession (typically ten years for groundwater) and must be renewed. The application process requires that no damage to third parties be substantiated; however, in practice this is just a formality. It has been noted that for some aquifers, the sum total of volumetric concession titles may exceed sustainable yield (Moreno Vásquez 2006), indicating overexploitation with negative implications for other groundwater users. In a bid to bring the actual use of groundwater in line with the concessioned volume, all agricultural titles now specify that the user must install a volumetric flow meter and report pumped volumes to CONAGUA. Our primary observations based on fieldwork in Sonora, Chihuahua, Guanajuato, and other states using large volumes of groundwater in agriculture indicate that flow meters and volumetric reporting are beginning to be enforced, but these records are not systematically kept or made available for research purposes.

The principal uses of groundwater recognized in the REPDA include public and urban, industry, aquaculture, agricultural, and livestock use. Public and urban and industrial users pay for water rights. This represents an increasingly important source of revenue for CONAGUA (Scott et al. 2004). Growth in demand must be met by acquiring additional water rights. Industrial users are similarly allotted an annual volume and must pay for water rights. Agriculture, which represents the largest share of groundwater extraction, does not have to pay CONAGUA for rights. However, individual well owners (or groups of users) must formalize their concessions with a title. In addition to specifying the annual volume concessioned based on the discharge of the well and the area of irrigable land reported, the title spells out the norms regarding repositioning of the well, cessation of rights for unutilized volumes (over three consecutive years), and the transfer (sale) of rights, among other provisions.

Irrigation plays a critical role in agricultural and livestock production, particularly in arid and semiarid regions such as northern Mexico, where rain-fed agriculture is severely constrained by soil moisture and changing climate (Loaiciga 2003). Surface water irrigation conveyed from reservoirs through canals to farmers’ fields tends to be inflexible in terms of timing and delivery; as a result, farmers’ decision making on which crops to plant, when, and in what area is limited by the supply of canal water. Groundwater irrigators, on the other hand, enjoy considerable flexibility in this regard. However, a major benefit associated with receiving surface water is that irrigation fees tend to be relatively low given that federal or state governments have incurred the cost of infrastructure development and in many cases...
continue to subsidize canal irrigation operational costs (Wester 2008).

Conceptual Approach and Objectives

Llamas and Custodio (2003, 5, 16–17) held that “intensive use of groundwater” provides better explanatory insight into the sustainability of human dependence on aquifers than “safe yield” or related extraction-to-recharge ratios. Their intensive use framework assesses human demand and technology in the contexts of physical hydrogeological process and spatial and temporal scale. Sustained “overexploitation” of aquifers that drops water levels and deteriorates water quality may only be viewed as an adaptation strategy in the short term. Intensive use of groundwater that relies on technology, such as more efficient pumps and desalination, or spatially shifts demand to other locations within the aquifer without reducing overall extraction will generate serious medium- and long-term impacts. They assess intensive groundwater use in central Spain, which they explicitly acknowledge bears similarity with northwest Mexico. For the purposes of this article, we follow Llamas and Custodio by assessing the human drivers of aquifer depletion, and we expand on their spatial characterization of intensive groundwater use by analyzing detailed data from Mexico using the tools of exploratory spatial data analysis that allow us to identify and measure spatial dependence across our observations. Whereas these authors eschew value-based judgments in assessing groundwater management in Spain and leave policy implications to national and local authorities (Llamas and Custodio 2003), we attempt to draw out specific policy implications.

To augment the intensive use framework with specific management and policy considerations, we turn to Shah (2009), who provided a nuanced and extended historical view of groundwater use in South Asia where agriculture (irrigation) represents the dominant use, similar to Mexico. Shah’s analysis of the human drivers and institutional dynamics in response to the development of aquifers with distinct hydrogeological characteristics has applicability beyond South Asia. Based on data from Mexico, we assess two of Shah’s propositions on irrigation development and the interrelation between ground and surface water. First, as distinct from South Asia, surface water remains the principal source of irrigation in Mexico in aggregate terms. However, groundwater can be intensively used instead of surface water at a specific location, although we recognize that the interactions between irrigation uses of these two sources of water are complex and depend on hydrologic, economic, and other variables not fully captured by the spatial analysis for Mexico we present in this article. Second, Shah contends that population and its spatial density drive intensive groundwater use. Although our goal here is not to assess the direction or the extent of the causality between both variables, we provide in the sections that follow a discussion of their relationship. Based on our field experience, groundwater use and socioeconomic data from Mexico, and analysis in this article, we selectively interpret relevant conceptual frameworks advanced by Llamas and Custodio (2003) and Shah (2009). As objectives, we posit that intensive use of groundwater for agriculture and livestock in Mexico follows two dependent relations.

Groundwater use tends to substitute for surface water use in Mexico; that is, areas with high access to groundwater do not necessarily have high access to surface water, in contrast to other regions in which surface water irrigation plays an important complementary role in recharging underlying groundwater aquifers through irrigation return flows (Gale 2005). Additionally, groundwater access should be clustered, with adjacent areas sharing similar characteristics in access to groundwater. Given the complexity in the human uses of ground and surface water, we expect these results to be mixed and that definitive claims will be localized based on irrigation practice and hydrological processes and must therefore be supported by field-based evidence. Access to ground and surface water is posited to increase with agrarian labor population, despite significant variation in mechanization, agricultural labor absorption, and farm enterprise scale across regions in Mexico; in other words, areas with access to water for agriculture have a high percentage of the labor force employed in agriculture. Whether labor is the determining variable, following Boserup’s (1965) contention that population pressure drives innovation in food production, or the reverse, that water availability facilitates
labor absorption in agriculture (White 1994), remains an intriguing question.

The final objective of this article is to elucidate geographical (both physical and human) drivers of aquifer depletion with a view to informing policy. We consciously employ spatial and statistical tools to analyze the large REPDA database given our intent to observe patterns across Mexico’s irrigated agricultural landscapes, identify the potential presence of spatial dependence in the distribution of the characteristics of these landscapes, and provide policy implications based on our findings. Additional analyses based on fieldwork (e.g., of aquifer properties or agrarian labor dynamics) are the necessary next step to gain a detailed contextual knowledge of the Mexican agricultural sector. In addition, we intend at a later stage to combine this approach with a formal econometric estimation of the dynamics at stake in this sector. The goal of this article, then, is to elucidate the complexities and the spatial characteristics of the Mexican agricultural landscape by means of exploratory spatial data analysis but to leave more complete exploration to future research.

Data and Methods

The municipality (municipio) is the administrative unit below the state that was chosen as the unit of analysis to permit cross-comparison of REPDA data with census data reported by the National Institute for Statistics, Geography, and Information Science (Instituto Nacional de Estadística, Geografía e Informática). The following REPDA data were downloaded in November 2006 for 423,179 records: number and volume (cubic meters per year) of water rights titles by use category (aquaculture, agriculture, agroindustrial, domestic, power generation, industrial, multiple use, livestock, public and urban, or services). Each record distinguishes groundwater or surface water as the source. Agricultural groundwater (AGW) and agricultural surface water (ASW) were summed as the respective totals of agriculture and livestock uses and were aggregated at the level of 2,429 municipalities and thirty-two states.

Results and Discussion

Figure 1 shows the states in Mexico and complements Table 1, the municipality-level summary data of the variables of primary interest for our analysis, grouped by states in northern and southern Mexico. States with high mean municipality AGW include Baja California Norte (BCN), which has the country’s largest area municipalities and high standard deviations across AGW, ASW, and PEA; Guanajuato; Baja California South (BCS); and Chihuahua, all of which are northern states facing aquifer depletion. By contrast, the states with low mean AGW are Oaxaca (with the smallest area municipalities that account for almost a quarter of the country’s total number of municipalities), Guerrero, and Veracruz in the south, leading to a principal observation that high AGW is an important driver of aquifer depletion. In fact, no southern state experiences aquifer depletion. The distribution of mean municipality ASW values presents mixed results, with neither high nor low values corresponding to aquifer depletion, with the exception of urbanized Distrito Federal (Mexico City), which has little agriculture to exert much demand for ASW or AGW, yet still experiences...
depletion. The mean AGW/ASW ratios similarly are unclear in patterns that would shed light on pressure and response to aquifer depletion. As discussed in more detail later, another finding is that across Mexico’s regions AGW appears independent of ASW; that is, AGW can be high in the presence or absence of ASW.

States with high mean municipality total population include Distrito Federal, BCN, and Mexico state, as well as agriculturally important Sinaloa, Tabasco, and Guanajuato. From our interest in agriculture and irrigation, states with high mean municipality PEA include Sinaloa, BCN, Tabasco, and Chiapas. These observations on population—total or agricultural—in themselves are not noteworthy for our analysis of intensive groundwater use, so to better understand aquifer depletion we must consider AGW and its relation to both PEA and ASW. Table 1 shows high mean municipality AGW for BCN, Guanajuato, BCS, and Chihuahua—all with recognized aquifer depletion problems. To support our hypothesis that agricultural population correlates with intensive use, an additional finding is that simple regression of mean AGW versus mean PEA yields a positive relationship significant at $p < 0.05$. The AGW/PEA ratio is highest in Chihuahua, Aguascalientes, and Sonora. Aguascalientes represents the particular case of a small area state dominated by a large city where aquifer depletion appears more related to concentrated urban and industrial groundwater pumping. Coahuila and Zacatecas have high AGW/PEA ratios and are experiencing aquifer depletion, whereas the lowest ratios are found in Guerrero, Veracruz, and Tabasco, which do not currently face depletion. We find, therefore, that high AGW with low PEA in northern Mexico corresponds to aquifer depletion.

Figures 2 through 4 show the spatial distribution of AGW, ASW, and PEA by municipality. It is apparent that AGW is concentrated in northwestern and north-central Mexico (Figure 2), with some additional AGW in the southeastern Yucatan Peninsula, largely for plantation agriculture including tropical fruits. As mentioned earlier, because rainfall declines from south to north in Mexico, in the northern areas of high AGW, agriculture is only possible
Table 1  Municipality-level water and population summary data by northern and southern states

<table>
<thead>
<tr>
<th>State</th>
<th>No. over exploited aquifers</th>
<th>municios</th>
<th>AGW (cubic meters/year)</th>
<th>ASW (cubic meters/year)</th>
<th>Population in 2000</th>
<th>PEA in 2000</th>
<th>AGW/ASW</th>
<th>ASW/PEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Mexico</td>
<td>101</td>
<td>1,324</td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
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<td>111,000,000</td>
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<td></td>
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Note: AGW = agricultural groundwater; ASW = agricultural surface water; PEA = population engaged in agriculture.
with irrigation. This raises a critical resource dependence issue: Without surface water as an alternative source, agriculture in northern Mexico is based primarily on groundwater irrigation. It should also be noted that northern Mexico’s proximity to the United States gives it a strategic commercial advantage over other regions of the country for export agriculture in the context of the North American Free Trade Agreement. We have primary evidence from the northwestern state of Sonora of agricultural investment and trade (through contract farming), not just of U.S. capital but also of Chilean investors seeking a year-round supply of table grapes for U.S. markets; that is, November and December production in Chile complemented by May and June production in Mexico. The irrigation water requirements during these summer production seasons are extremely high, and aquifers in Sonora continue to face depletion. It should also be noted that, even if surface water were available, high-precision drip irrigation is better suited to on-demand groundwater from the farms’ own pumps, whereby farmers seek to protect themselves from erratic supplies that characterize public surface irrigation systems. For example, the large ASW rights in north-central Mexico (Durango and Coahuila) are predominantly to irrigate sorghum and alfalfa as fodder for the important dairy industry in the La Laguna region. Nevertheless, there are notable examples of ASW used for high-value commercial agriculture, such as tomato and fresh vegetable farming in Sinaloa that makes significant use of ASW (Figure 3).

However, intensive farming operations of the kind already described require significant farm labor. Figure 4 shows PEA. It is evident that the spatial distribution of PEA across Mexico corresponds more closely to AGW than to ASW, suggesting that labor absorption is higher in AGW-based farming than ASW-based farming. To quantitatively analyze the data based on the spatial and demographic objectives we have set out for this article, we turn next to ESDA of spatial clustering and spatial autocorrelation of the ratios of AGW with ASW and PEA as described later. Spatial autocorrelation refers to the coincidence of attribute similarity and locational similarity (Anselin 1988). In the context of our study,
Figure 3  Agricultural surface water (volume per municipality per year).

Figure 4  Population employed in agriculture (2000).
positive spatial autocorrelation indicates that municipalities with high use of AGW relative to ASW tend to be geographically clustered, whereas municipalities with low AGW/ASW also tend to be clustered. Spatial autocorrelation may be due to (1) “substantive” factors, such as proximity to U.S. markets for agricultural exports, climatic conditions, and agricultural production structure that physically adjacent municipalities tend to share; or (2) to a “nuisance” factor due to a mismatch between the boundaries of the municipalities used to organize the data and the actual boundaries of the processes we are trying to capture (Anselin 1988).

Spatial Weight Matrix
The definition of a spatial weight matrix is necessary to carry out the successive steps of ESDA. Spatial dependence can occur in any direction, so weight matrices are computed with reference to the k = 10 nearest neighbors as follows:

\[
\begin{align*}
    w_{ij}(k) &= 0 \quad \text{if } i = j \\
    w_{ij}(k) &= 1 \quad \text{if } d_{ij} \leq D_i(k) \text{ and } w(k) = w_{ij}(k) \\
    \sum_j w_{ij}(k) &\quad \text{for } k = 10 \\
    w_{ij}(k) &= 0 \quad \text{if } d_{ij} > D_i(k)
\end{align*}
\]

where \(d_{ij}\) is the great circle (arc) distance between centroids of region \(i\) and \(j\). \(D_i(k)\) is the critical cutoff distance defined for each region \(i\), above which interactions are assumed negligible. In other words, \(D_i(k)\) is the \(k\)th-order smallest distance between regions \(i\) and \(j\) such that each region \(i\) has exactly \(k\) neighbors. Each matrix is row-standardized so that distance is relative and not absolute, yielding the matrix \(\hat{w}\). Each nonzero entry in \(\hat{w}\) is therefore 0.1. The choice of a spatial weight matrix is always somewhat arbitrary. To limit the influence of the choice of the matrix on our results, we also compute a contiguity and two distance-based matrices (with cutoffs of 320 km and 800 km) to verify whether our findings are sensitive to the choice of the weight matrix.

Spatial Autocorrelation Using Moran’s I
Based on the spatial weight matrix defined in Equation 1, we proceed to analyze the spatial distribution of our variables using Moran’s I, which captures the global spatial autocorrelation of the variables of interest; that is, for each variable, Moran’s I gives the degree of linear association between its value at one location and the spatially weighted average of neighboring values. To draw inferences, we use a random permutation procedure that recalculate the statistic to generate a reference distribution and a pseudo-significance level from 10,000 permutations (Anselin 1995). For each variable of interest, Moran’s I is given by:

\[
I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \hat{w}_{ij}(k)x_i x_j}{\sum_{i=1}^{n} \sum_{j=1}^{n} \hat{x}_i \hat{x}_j}
\]

where \(\hat{w}_{ij}\) is the (row-standardized) degree of connection between the spatial units \(i\) and \(j\), and \(x_i\) and \(x_j\) are the variable of interest in regions \(i\) and \(j\) (measured as a deviation from the mean value). Moran’s I values larger (or smaller) than the expected value \(E(I) = -1/(n-1)\) indicate positive (or negative) spatial autocorrelation. The results indicate the presence of positive spatial autocorrelation; that is, regions with high AGW/ASW (Moran’s I = 0.1151), high AGW/PEA (I = 0.3687), and high ASW/PEA (I = 0.1714) tend to be geographically clustered, whereas regions with low values tend to be close to each other as well. All the Moran’s I values just given have an expected value of -0.0004 and are significant (\(p\) value = 0.0001). These results are consistent with all the spatial weight matrices defined previously. As a result, the value of these variables in one location is significantly related to the value of the same variables in neighboring locations. If found to be significant, spatial dependence is an important factor that needs to be included in policy formulation and assessment of regulations. We recommend that groundwater management in Mexico systematically include the characteristics of the agricultural landscape and water demand of the individual municipality but also those of neighboring municipalities where the aquifer is located. Some efforts have been made in this direction in recent years (Sandoval-Minero 2001), but this is the first time that the
extent of spatial dependence across Mexican municipalities is formally measured.

Significance of Spatial Clustering Using Local Indicator of Spatial Association

Although very useful, the Moran’s $I$ does not give any indication of the significance or localization of spatial clustering. To address this problem, we continue our analysis with a local indicator of spatial association (LISA). The calculation of LISA statistics for each observation allows us to obtain an indication of significant local spatial clusters (also called hot spots) as well as for the diagnostics of local instability, significant outliers, and spatial regimes. Anselin (1995) formalizes the local Moran’s statistics for each region $i$ as:

$$I_i = \left( \frac{x_i}{m_0} \right) \sum_j w_{ij} x_j$$

with

$$m_0 = \sum_i x_i^2 / n$$

(3)

where $x_i$ and $x_j$ are the variable of interest in regions $i$ and $j$ (measured as a deviation from the mean value). As for the preceding Moran’s $I$, the significance level is based on a conditional permutation approach with 10,000 random permutations of the neighboring municipalities for each observation. Figures 5 through 7 are the LISA maps for AGW/ASW, AGW/PEA, and ASW/PEA with $k = 10$ nearest neighbors. Note that the municipalities in white are those where the Moran’s statistics are not significant at 5 percent.

Figure 5 demonstrates multiple clusters of AGW/ASW spatial association. Low values of AGW/ASW surrounded by low values of the same variable in south-central Mexico and along the Pacific Ocean and Gulf of Mexico coastal regions result from high surface water availability. The low–high cluster in north-central Chihuahua appears to derive from municipalities with ASW from the Río Conchos, a Mexican tributary to the Rio Grande that forms the border with the United States, surrounded by others that are AGW dependent. Four clusters of high–high municipalities surrounded by low–high municipalities are important for our discussion of intensive groundwater use and the targeted clusters of municipalities that require additional policy and groundwater attention as alluded to earlier. The first such hot spot is centered on

Figure 5  LISA map of agricultural groundwater/agricultural surface water.
Figure 6  LISA map of agricultural groundwater/population employed in agriculture.

Figure 7  LISA map of agricultural surface water/population employed in agriculture.
La Laguna in north-central Mexico, where Irrigation District DR017 has a concentration of surface water use from the canal system embedded with pockets of high AGW groundwater use that are resulting in aquifer depletion. The second high–high cluster surrounded by low–high municipalities is in the state of Guanajuato, also experiencing aquifer depletion. An additional hot spot is located to the southeast of Guanajuato in the Mixteca region of Puebla, which has the interesting feature of groundwater use from galerías (variants of qanats, or sloped horizontal tunnels to intercept groundwater within the hillside). The galerías are at risk from groundwater pumping that threatens to lower aquifer levels and reduce or entirely stop their flow. These three hot spots require particular emphasis to address groundwater depletion through increasing ASW or, if limited physically, through reduction in AGW. The final hot spot is in the Yucatan Peninsula, where the clustering of interest is driven by high AGW but without depletion effects mentioned for the other three clusters.

Figure 6 shows marked results of spatial clustering of AGW/PEA, which is expected from the increasing south-to-north trend of reliance on groundwater as an irrigation source with south-to-north decreases in percentage of population in agriculture. Figure 7 indicates clustering of high–high values of ASW/PEA in the north-central states of Sonora, Chihuahua, Coahuila, and Tamaulipas, where most of Mexico’s large surface water canal irrigation districts are located. As mentioned earlier, we interpret these clusters to be closely related to the physical availability of surface water for irrigation and low PEA values in the north. Uniformly, ASW/PEA clustering is low–low in the south.

Conclusions

Spatial analyses of access to groundwater and surface water for agriculture in Mexico demonstrate clear patterns of spatial dependence and north–south heterogeneity. Spatial dependence results from similar climatic conditions and agricultural production structure that physically adjacent municipalities share. In addition, we have detected the presence of several clusters of municipalities in similar agricultural landscapes. However, these clusters are not randomly distributed across the Mexican territory but are located in specific areas that reflect the heterogeneity in the country’s climatic, geographic, and economic conditions. More precisely, spatial heterogeneity takes the form of a relatively high groundwater use in proportion to population in agriculture in northern Mexico as compared to southern Mexico, whereas surface water allocation in proportion to population in agriculture is more homogeneous. As a result, the spatial distribution of access to groundwater in particular, together with evidence on aquifer depletion, demonstrates that the northern and northwestern regions represent Mexico’s major intensive use challenge. Three important hot spots in Coahuila-Durango, Guanajuato, and Puebla present particular depletion risks.

Groundwater is an important source of farm income and employment for agricultural laborers. Mexico has long experienced south-to-north agricultural labor migration within its own borders and further into the United States. This trend and the spatial data on groundwater and population in agriculture suggest that irrigated farming in the north is a labor magnet, in a manner similar to that observed by White (1994). As a result, irrigation development by commercial farmers appears to drive agricultural groundwater demand and depletion, as well as influence labor migration. Notwithstanding the results presented in this article that groundwater sustainability in southern Mexico would permit intensification as a means to relieve pressure on aquifers in the north, we do not expect the commercial interests engaged in export agriculture for North American (U.S.) markets to pursue this option, although this supposition would require further investigation.

From a policy viewpoint, the presence of spatial dependence we have highlighted in this article means that groundwater management should systematically include the characteristics of the agricultural landscape and water demand of adjacent municipalities that share access to the same aquifer. Some efforts seem to have been made in this direction: Water that is managed across municipalities requires regulatory and participatory approaches (Sandoval-Minero 2001), coupled with changes in demand
behavior of pumpers (for early literature on groundwater governance, see Blomquist 1992). Where groundwater use is largely agricultural, cropping changes and water demand can be influenced by commodity prices; however, energy pricing and supply can be determinants of pumping behavior (Scott and Shah 2004). Regionally targeted caps to limit power supply as a groundwater demand management option to address clusters of groundwater depletion can face social and political challenges. Prices must be high enough to be in the elastic range of demand response, which is taking place in Mexico as power tariffs are raised (although not in a depletion-targeted sense) and pumping depths increase. Given high latent demand, however, noncommercial smallholder farmers who are first affected might choose to sell or rent groundwater to commercial farmers (Wilder and Romero-Lankao 2006; Wester 2008) instead of shutting down (“retiring”) wells that would reduce overall demand on the aquifer. Either course of action has important agricultural production and social implications; therefore, targeted well retirement programs must be viewed from the perspective of interregional equity.

Water savings and efficiency measures through government cost-share programs (e.g., *Uso Eficiente del Agua y la Energía Eléctrica* [Efficient Water and Electrical Energy Use]) have been implemented in Mexico; however, the water saved is very often used to extend the area irrigated with little change in the amount of water extracted from the aquifer. The appropriate policy response would be to pursue efficiency with conservation of the water saved, for example, through caps on planted area.

In Mexico, regulatory approaches to groundwater management have been in place—and have been largely unsuccessful in addressing groundwater depletion—for more than fifty years (Wester, Hoogesteger, and Vincent 2009). The current well concessioning and licensing drive is important; now that this process has largely been completed, users and regulators (whether government agencies or farmers’ self-regulatory bodies) have the information required to formulate regionalized plans to address aquifer overdraft that account for, among other variables, agricultural groundwater, surface water, and population in agriculture.

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