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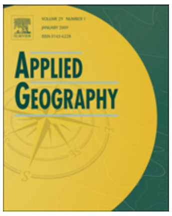

Water management and biodiversity conservation interface in Mexico: A geographical analysis

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ABSTRACT

Leading scholars and global institutions emphasize the urgency of balancing human livelihood needs with the demands of the environment, particularly for water. In Mexico, the interface between water and environmental conservation is manifested in initiatives to enlarge "natural protected areas" in order to protect both hydrological basins as water sources as well as ecosystems and the services they provide. However, the spatial overlaps, hydrological–biological interactions, and multiple stakeholder institutional interfaces between protected areas and basins remain poorly understood, particularly the ways in which conservation areas are being reconfigured by human water use. Employing spatial analysis, volumes of water concessions, and institutional mapping methods, this paper examines the policy and resource dimensions of groundwater use in the Río Cuchujaqui watershed and its implications for ecosystem services in the Sierra de Álamos protected area in northwestern Mexico. Competing water and environmental institutional mandates have prevented the formulation of a water management program for conservation purposes. Geographical expansion of the Sierra de Álamos will confront pre-existing Río Cuchujaqui groundwater uses outside the area currently protected. This impasse can only be resolved by capping groundwater at levels that permit current ecosystem function.

Introduction

In Mexico, influential scholars in environmental policy (Carabias & Landa, 2005)[1] have proposed the enlargement of the natural protected areas (NPAs) in order to protect hydrological basins. We view the intent behind these policy pronouncements to be two-fold: first, responding to the need for expanded conservation in regions facing degradation and human pressure on ecosystems, ecological–hydrological conservation would effectively bundle ecosystem services; and second, disparate institutional interests (water and environmental bureaucracies) would be better integrated. However, these initiatives inadequately account for how past water and conservation policies have interacted in protected areas and, moreover, they lack specific rationale on how NPAs have contributed to preserve hydrological basins.

It is necessary to provide an overview of institutional arrangements and agency mandates for water and environment in Mexico. The National Water Commission (CONAGUA) and the National Commission for Natural Protected Areas (CONANP), both under the Secretary of Environment and Natural Resources (SEMARNAT), are the federal agencies directly charged with managing water and NPAs. The Mexican national water law (1992 Ley de Aguas Nacionales, or LAN) grants to CONAGUA

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[1] Carabias was the first Mexican Secretary of Environment and Natural Resources (SEMARNAT) from 1994 to 2000.

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comprehensive authority over all of the nation's water resources. The LAN establishes that the federal government will protect, improve and preserve basins and aquifers, and restore the hydrological equilibrium of all waters, surface or underground. In accordance, CONAGUA grants water rights concessions (which we will rely on as a primary data source in our analysis below). CONANP focuses on biodiversity conservation within NPAs. By law, it has the authority to develop water conservation plans and ensure that water users located inside NPAs do not adversely affect the hydrological equilibrium (NPA Regulation, 2004).

The overlapping mandates of CONAGUA and CONANP are of particular concern for the use and management of water within NPAs. And the critical role that water plays in ecosystem services and habitat conservation is heightened in water-scarce regions such as northwestern Mexico where the case examined in this paper is located. To examine these issues, we analyze the case of the Sierra de Álamos-Río Cuchujaqui (SA-RC) located in the state of Sonora. A considerable area, although not all, of the SA-RC is contained within the Cuchujaqui watershed (Fig. 1). As SA-RC is enlarged to preserve multiple ecosystem services following Carabias and Landa (2005), the spatial overlap and institutional interface become more complex, with changes in the location and intensity of water use occurring inside and outside the SA-RC. Based on consideration of this case, the specific questions we address are: (1) How have distinct institutional mandates for water and environmental conservation influenced water management planning for the NPA? (2)What is the spatial distribution of water use within and outside the current NPA boundaries and how does this relate to the spatial distribution of a hypothetical expansion of the NPA (as a uniform buffer of riparian areas)?

The first part of this paper describes the Cuchujaqui watershed and the Sierra de Álamos NPA. It proceeds to examine the legal framework that shapes CONAGUA and CONANP policies in order to shed light on their institutional interaction. We base this on document review of the laws and regulations for these two agencies and interviews with key functionaries of these agencies addressing how their respective agencies work and how the two agencies interact. Next, the paper analyzes the geographical distribution of water rights in the Cuchujaqui watershed. Finally, the spatial interaction of institutions and water resources provides the evidence base to analyze policy implications particularly of expanding water use in the Cuchujaqui watershed as a potential threat to the ecosystem in the Sierra de Álamos NPA.

Study area

The SA-RC and Cuchujaqui watershed are located in the northwestern Mexican state of Sonora, specifically in the southeastern portion of the rural municipality of Álamos.

The area of overlap between the NPA and the watershed is 690 km^2, which represents 75% of the NPA and 31% of the watershed area. According to Mexico's most recent census (2005), the Cuchujaqui watershed area contains 101 human settlements encompassing a total of 14,086 inhabitants. Of these communities, the principal city of the municipality has 8201

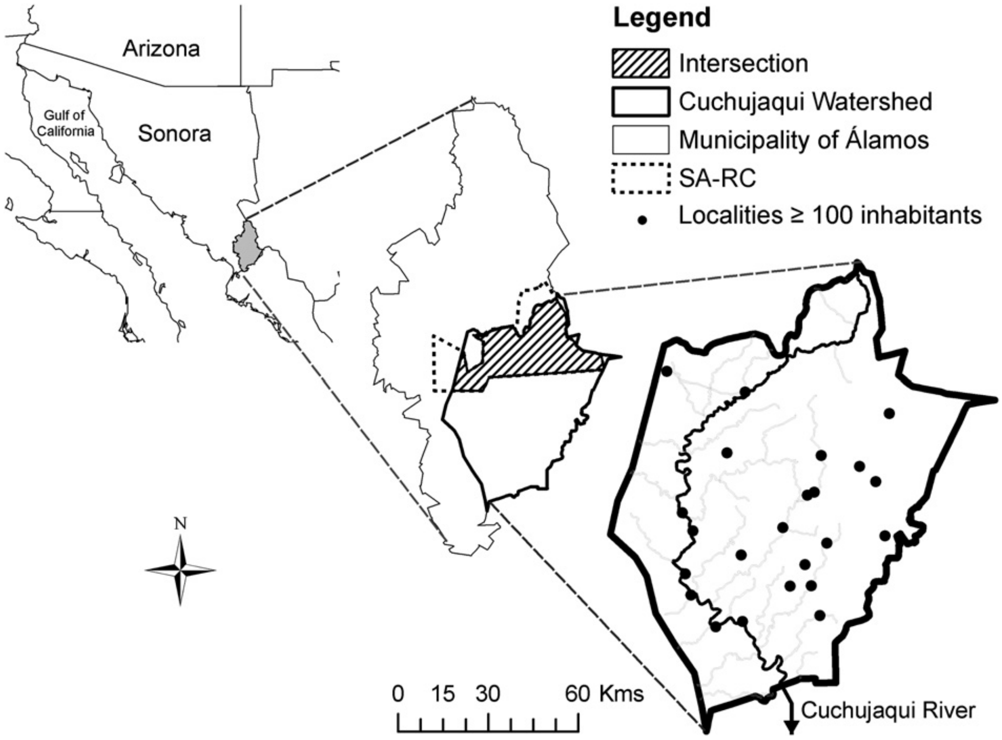

Fig. 1. Study area.

Table 1
Water use by type and source, Cuchujaqui watershed.

Uses	Surface water		Groundwater		Total	
	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)
Urban	7	85,421	124	1,335,495	131	1,420,916
Livestock	20	16,723	85	78,951	105	95,674
Agriculture	0	0	4	176,563	4	176,563
Industrial (mining)	0	0	4	1,500,000	4	1,500,000
Multiple uses	0	0	36	758,532	36	758,532
Total	27	102,144	253	3,849,541	280	3,951,685

inhabitants; 22 settlements each have between 100 and 500 inhabitants; and the remaining communities each have less than 100 inhabitants. In the 690 km^2 overlap, there are 19 communities totaling 626 inhabitants, which represent just 4.4% of the total population in the Cuchujaqui watershed (INEGI, 2005). The Río Cuchujaqui, runs from north to south, indicated by an arrow in Fig. 1.

Inside the watershed, there are 27 surface water rights (granted by CONAGUA as concession titles) with a total permissible extraction of 102,144 m^3 per year, ranging from a minimum of 274 m^3 to a maximum of 23,363 m^3 per concession. Groundwater represents the more significant use of water, with 253 concessions and total volume of 3,849,541 m^3 per year, ranging from a minimum of 55 m^3 to a maximum of 621,520 m^3. It should be pointed out that actual extractions in volumetric terms are not comprehensively monitored or reported; hence we take the volume of concessions as a proxy for extraction or use (Garduño, 2005; Moreno Vásquez, 2006). Table 1 shows the number, use type, source, and volume of water used in the watershed.

As mentioned the major source of water in the watershed is groundwater, representing 97.4% of the total volume used. The dominant types of uses are industrial (in this case mining activity) and urban, which are 38% and 33.8% of the total volume in the watershed, respectively. Because of the importance of groundwater sources in terms of both volume and number of rights, the spatial examination focuses on groundwater rights granted by CONAGUA.

The SA-RC was established as an NPA in July 1996. This area was protected because it is a transition zone between the Neoartic and Neotropical biogeographic regions, and represents the northernmost limit of the Low Deciduous Forest (World Bank, 2004). Furthermore, it is simultaneously the northernmost and southernmost distribution limit for certain species. The existence of rich and varied vegetation and wildlife has been observed with the occurrence of about 1100 species of vascular plants divided into 148 families. As a result, the principal objective of CONANP in the SA-RC is to preserve the biodiversity of flora and fauna.

The Río Cuchujaqui is an important tributary of the Josefa Ortiz de Dominguez Dam downstream on the Río Fuerte that provides water to the irrigation district of the Valle del Carrizo. In other words, the watershed provides essential ecosystem services to habitat and human uses both within and outside its boundaries.

Policy framework

Importance of water and biodiversity conservation interactions

On the one hand, considerable scholarly attention has focused on the developing "crisis" in water availability and quality, shifts in international water policy, and the increasing need for implementing water conservation strategies. In general terms, long-term population and economic growth drive this water management transformation. Increasing demand has made water a relatively scarce resource, which consequently has augmented the levels of competition among different water uses.

The World Water Vision Report states that one in five persons worldwide lacks access to safe and affordable drinking water, and one half of the world's population has no access to sanitation (Cosgrove & Rijsberman, 2000). The report also argues that without considerable innovations in technology, institutions, and investment, the world in 2025 will likely face an estimated 1.3 billon people without access to safe drinking water, and 2.6 billion without adequate sanitation (Conca, 2006).

Global water challenges have received broad international recognition since the 1990s in a series of international conferences. Particularly significant were the International Water and Environment Conference held in Dublin in 1992, and the World Water Forums held in Marrakech (1997), The Hague (2000), Kyoto (2003), Mexico City (2006), and Istanbul (2009).

On the other hand, in the last three decades, there has been a growing interest on a global scale in environmental conservation and the sustainable use of natural resources. This interest has crystallized in diverse global environmental summits such as Stockholm (1972), Rio de Janeiro (1992), and Johannesburg (2002).

Global biodiversity conservation is one of the manifestations of this international environmental concern (Brechin, 2003; Escobar, 1995; Guha, 2000; Zimmerer, 2006). In the case of Mexico, the expansion of protected areas has been coordinated and financed by global organizations. In this regard, CONANP was officially established in July of 1996. As a prominent World Bank report on Mexico's protected areas program indicates (World Bank, 1997), protected areas projects would financially be supported by global institutions such as the Global Environment Facility (GEF).

In their early stages, international water management and global conservation policy were part of different global agendas and consequently factors shaping the interface between water management and protected areas have received limited examination, with some exceptions (Gleick, Wolff, Chalecki, & Reyes, 2002; Postel & Richter, 2003; WCD, 2000). However, in the case of Mexico it is critical to evaluate the interface because influential scholars in national ecological policy recently proposed the enlargement of NPAs in order to protect the hydrological basins and the environment (Carabias & Landa, 2005). They argue that the enlargement of natural protected areas could simultaneously protect biodiversity, provide environmental services, and preserve hydrological regions. However, little is provided on which ways or to what degree NPAs have contributed to the preservation of hydrological basins and the environment or what the interaction between water and environmental conservation policy has been.

National policy frameworks

Water resources in Mexico are managed by the National Water Commission (CONAGUA) as mandated by the Law of the Nation's Waters (LAN), enacted in 1992. CONAGUA had been created three years earlier in 1989 as part of a national water planning process that gave the agency authority for the administration of water and hydraulic works. In 1994, CONAGUA was placed under the environment ministry (then SEMARNAP, currently SEMARNAT). In the 1992 LAN and its regulations, CONAGUA's authority most directly related to management in protected areas is the power to declare a banned zone for ecosystem protection. This attribution is clearly related to environmental conservation objectives; however, specific strategies for protected area conservation are unclear particularly for an agency steeped in hydraulic works development and irrigation expansion.

In 2004, the LAN was modified. One of the most significant changes was the inclusion of the environment as a discrete and autonomous water use. The 2004 LAN reform also established that CONAGUA can reassign national water to guarantee the minimum flows necessary for ecological protection and to restore vital ecosystems. These modifications likewise state that water use may be restricted when a water right "…affects the minimum ecological flows, which are part of environmental use…" (LAN, 2004, p. 52). Yet, these changes to national water law, while critical for environmental water conservation, remain indefinite on the details of how much water constitutes an ecological flow. Moreover, water resources management for environmental purposes in critical habitats (whether formally protected or not) is in its infancy (Pitt, Luecke, Cohen, Glenn, & Valdes-Casillas, 2000; Postel & Richter, 2003). According to this research, in the case of the Cuchujaqui watershed the reallocation of water concessions to be used for environmental purposes has never taken place.

Based on this, we assert that the LAN and its regulations are too broad and do not provide the mechanics of implementation of water and conservation policies for the specific problems and characteristics of NPAs, and therefore do not offer specific solutions required by water users in these zones. The development of management plans tailored to location-specific conservation goals is essential.

As stated above, under the support of the GEF, CONANP was established in 1996, during the administration of President Zedillo and under the regulation of the Secretary of Environment and Natural Resources (SEMARNAT) directed by Julia Carabias Lillo. At the outset in 1996, ten NPAs were proposed (World Bank, 1997), but now there are 166, classified mainly in six different categories: biosphere reserves, national parks, natural monuments, natural resources protected areas, flora and fauna protected areas, and natural sanctuaries. Currently these NPAs cover 23,148,432 ha (CONANP, 2009).

Regulation of NPAs is framed in the legal authority of the Mexican General Law of Ecological Equilibrium and Environmental Protection (LGEEPA), enacted by the federal government in January 1988. In this regard, the second step is to examine NPA regulations in order to ascertain whether there are legal constraints involving water management. In our examination, we found that the NPA regulations recognize two significant objectives regarding water resources. One is related to the practice of water conservation; another, possibly more significant, is the requirement that there be no significant effect on hydrological equilibrium or ecosystems in the NPA (NPA Regulation, 2004, pp. 28–29). From our interest in institutional interfaces, there is a gap in the regulations regarding how CONANP will fulfill these objectives because this agency has no authority to deny or modify water concessions. According to the law, the sole agency with that authority is CONAGUA.

This significant gap in the formal legal framework introduces a disjuncture in the institutional authority structure. On the one hand, legally the LAN does not consider specific attributes for the natural protected areas, and on the other, CONANP does not have sufficient authority over water resources. To address the institutional disjuncture between competing agencies, we conducted interviews with key governmental agents and environmental practitioners working in the study area. In this regard, CONAGUA functionaries interviewed emphatically stated that acquiring a water concession or extracting water inside the NPA did not require CONANP authorization. In granting new concessions in the Cuchujaqui watershed, CONAGUA does not take into account if the location is inside or outside the NPA. The process of applying for a water right consists of three steps: the identification of the potential water use, the location of the water right, and the volume of water to be extracted (CONAGUA, 2009). The principal criteria to approve or deny the spatial location of a proposed groundwater concession are: a) the well may not be located in a banned zone (*zona de veda*) determined by CONAGUA,[2] and b) the aquifer is not considered overexploited by CONAGUA's water balance studies (*estudios de disponibilidad*). According to CONAGUA, the Cuchujaqui aquifer, which shares almost the same area as the watershed, was considered by CONAGUA as a banned zone since 1956.

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[2] The banned zones were determined by CONAGUA or its predecessors with similar federal mandates.

However, according to a water balance study conducted in 2005, CONAGUA determined that the aquifer had an annual volumetric water availability of 22.16 million m^3 (CONAGUA, 2005).

To substantiate CONAGUA's position on whether CONANP authorization is required to acquire a water concession within the SA-RC, two prominent CONANP agents were interviewed two times each one. They verified that for CONAGUA, granting water rights inside the NPA does not need CONANP approval. They stated that CONAGUA's decision, by law, must be based on the banned zones determined by CONAGUA. They said that they have interacted with CONAGUA's river basin council[3] to determine the validity of water harvesting projects. Over the past five years, CONANP has established check dams to restore damage caused by soil erosion and to recharge the aquifer. They said that in 2007 the river basin council approved this kind of project. Following this, in an interview we asked a CONAGUA agent who is directly involved in the river basin council about how CONAGUA and CONANP have interacted over water management inside the SA-RC. He said that the principal project in which they have worked together is check dam construction within the SA-RC. When questioned if CONANP needed to authorize proposed water concessions inside the SA-RC, he responded that this process is independent of CONANP. In a separate interview, we asked another CONAGUA employee responsible for starting the process of granting new water concessions in the Cuchujaqui aquifer whether extracting water inside the protected area would require authorization from CONANP. His response was that CONANP approval is not a requirement for obtaining a water right. What is clear from these interviews is that CONAGUA and CONANP interaction is based on personal goodwill, but is non-mandatory institutionally.

Geographical analysis

From the institutional point of view, then, there is an important disjuncture at the interface between CONAGUA and CONANP inside the SA-RC. Of particular importance is the fact that the banned zone is the principal criteria to restrict or allow water concessions, but the NPA delimitation appears to play no role. To return to our two principal questions posed in the introduction on formal institutional mandates and the spatial nature of water use, the incongruous nature of formal legal provisions and institutional authority on the ground raises the need for a closer examination of the geographical interface between water use and conservation areas. This we achieve through analysis of the geographical distribution of groundwater use (location and volume) in relation to the SA-RC limits and the riparian area inside the watershed.[4]

Data and methods

For the geographical analysis we used the following data:

(1) The volume and location of groundwater concessions as registered by REPDA in July 2008 in the Cuchujaqui watershed,[5]

(2) the streams of first order and second order of the Cuchujaqui drainage system established by the National Institute for Statistics, Geography and Information Science (Instituto Nacional de Estadística, Geografía e Informática, INEGI),

(3) the geographical boundaries of the Cuchujaqui watershed established by CONAGUA, and

(4) the geographical delimitation of the natural protected area established by CONANP.

Three methods are used to analyze the spatial distribution of groundwater rights: Kernel density function, Chi-square and Cramer's *V*. As will be presented below, these distributions are related to the geographical domains of the watershed and NPA corresponding to CONAGUA and CONANP, respectively.

Kernel density function

We first carry out exploratory spatial data analysis (ESDA) by examining the spatial intensity of groundwater use using kernel density, in which point data (individual wells) are converted to fields (Baxter & Beardah, 1997). This transformation allows us to create an integrated area of influence for water use and visualize how they are related with other spatial units, particularly the NPA and riparian areas within the Cuchujaqui watershed.

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[3] For further details on river basin councils and their functioning, refer to Scott and Banister (2008).

[4] Using Geographic Information Systems (GIS) to examine groundwater conditions has been a significant concern by scholars (Al-Adamat, Foster, & Baban, 2003; Dixon, 2005; Rahman, 2008).

[5] REPDA (the Mexican Public Register of Water Rights) codifies water rights as mandated by LAN and overseen by CONAGUA. Although the LAN was promulgated in 1992, the REPDA has only recently become operational as a reliable database and has been used in spatial analysis studies (Scott et al., forthcoming). REPDA officially records 1997 as the earliest date that water rights in the study area were granted. However, anecdotal evidence from rights-holders and agency staff indicate that some of 1997 water rights were granted to pre-existing rights, i.e., from before 1996. Because the NPA was established in 1996, in this 1997 revalidation of pre-existing rights CONANP could have been consulted. On the other hand, some rights, which play a central role in the analysis of this paper, were granted more recently, particularly the mining water rights granted in 2005.

The kernel method assigns a value based on sampling the surrounding neighborhood and computing the "intensity" of observations around the element. A kernel function is used to fit a smoothly tapered surface to each point, and the density is calculated from the overlap of multiple surfaces in the output grid cell. ArcGIS uses a quadratic kernel function (Silverman, 1986, p. 76), which is as follows:

$$D(s) = \sum_{i=1}^{n} S_i\left(3/\pi\tau^2\right)\left[1 - (h_i^2/\tau^2)\right]^2 \tag{1}$$

where:

τ = radius of circle neighborhood
h_i = distance between the point s and the observation point S_i
n = number of observation points
$D(s)$ = density (intensity) at point s (grid cell center)
S_i = observation point i (water right volume of use)

One of the advantages of using kernel density mapping is the possibility of comparing weighted and un-weighted attributes, which allows comparison of how the same observation might be affected by the attribute. For example, here we compare the density maps of groundwater rights with and without the attribute of volume used.

The kernel method permits us to visualize the contours of the densest zones in the area of study. However, because it is a method that measures the interrelation of the observations, sometimes high values of weighted attributes are located where there are no observations. Due to this disadvantage, kernels are not useful to quantify differences. Additionally, the density of groundwater use assumes two-dimensional spatial homogeneity of intensity. In reality, the water availability or depletion implications of groundwater wells are related not just to their spatial density but to aquifer characteristics.

Chi-square and Cramer's V

Chi-square and Cramer's *V* are complementary methods. Chi-square is a well-know method to measure the strength of association between two variables (Bonham-Carter, 1994; Shaw & Wheeler, 1994). This paper examines two spatial associations: between groundwater use volumes and the boundaries of the SA-RC, and between groundwater use and the riparian area of the Río Cuchujaqui. The Chi-square (χ^2) statistic is computed using the following equation:

$$\chi^2 = \sum\left(\frac{(O_i - E_i)^2}{E_i}\right) \tag{2}$$

where:

O_i = number of the observed sites in the row
E_i = number of expected sites in the row

The null hypothesis in Chi-square is always that the frequencies of observations found in the rows are independent of the frequencies of observations found in the columns (Zar, 1999). This study evaluates two rows: one row with the registered distribution of groundwater volume used and the other with the expected distribution of groundwater volume used in random space. The interpretation of Chi-square consists of comparing the results with a table of significance to determine if the specific value is statistically significance.

The Chi-square test is useful to determine if a significant relationship exists, but this does not necessarily suggest that there is a strong association between two variables because the results are influenced by the sizes of the sample used (Blalock, 1979, p. 300). Thus, in order to determine the strength of the spatial association Cramer's *V* is used (Bonham-Carter, 1994). Cramer's *V* is computed using the equation:

$$V = \sqrt{\frac{\chi^2}{T(q-1)}} \tag{3}$$

where:

T = sample size
q = the smaller number of rows or columns

Cramer's *V* coefficient is a well-known measure used in geography and natural resources spatial association analysis (Apan & Peterson, 1998; Millward & Kraft, 2004; Morris, Ross, & Johannsen, 2008; Stueve, Lafon, & Isaacs, 2007). Cramer's *V* is a method that simplifies and makes comparable the results obtained by Chi-square because it ranges just

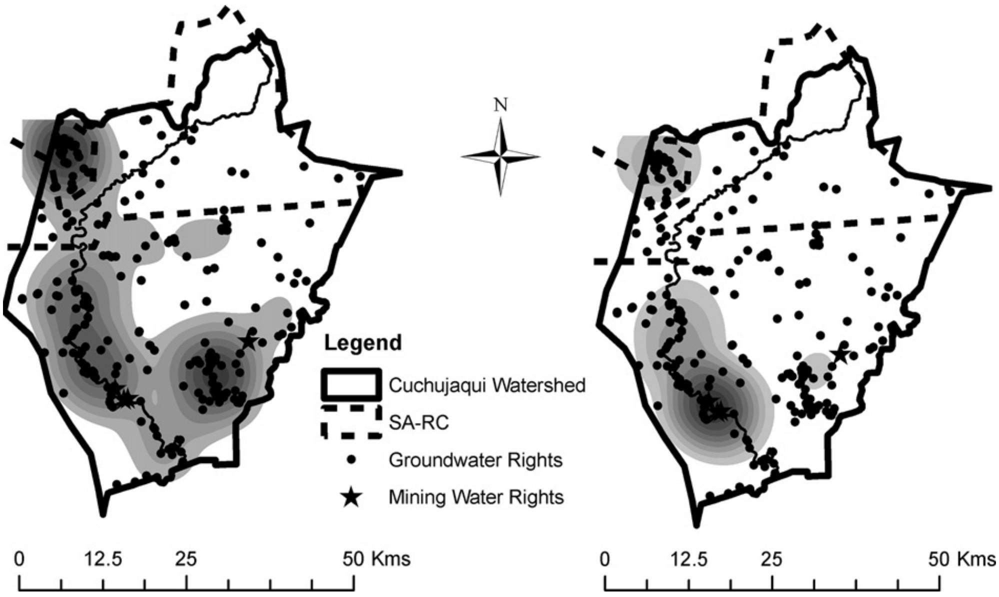

Fig. 2. Kernel density maps.

from 0 to 1. A coefficient of 0 signifies the observed frequencies are all equal to the expected frequencies, and as a result, the variables are statistically independent. A coefficient of 0.3 and above indicates a strong association; 0.1–0.3 points out a moderate relationship; and below 0.1 indicates a weak association (Millward & Kraft, 2004; Morris et al., 2008; Stueve et al., 2007).

Results

Kernel density function

The first step consisted of using ArcGIS to compute the kernel density map of the groundwater rights in the Cuchujaqui watershed (Fig. 2). This density map was obtained using a radius of a circle neighborhood of ten km, which is the radius from which large dense areas can be adequately geovisualized.[6] Fig. 2a shows the density map for an un-weighted attribute; in other words, for this map just the location of the groundwater rights was taken into account regardless of the volume of water. Fig. 2b maps the density area for a weighted attribute of the annual volume of each well's groundwater extraction.

This exploratory spatial data analysis shows important groundwater intensity features. In Fig. 2a the highest density areas are in the northwest, southwest and southeast of the watershed, indicating that these areas have large numbers of wells. However, in Fig. 2b the highest density occurs in the southwest of the watershed along the main reach of the river drainage system, which conforms to hydrological processes observed in the watershed, i.e., that groundwater occurs spatially in association with river flow. This is the location where large volumes of water are extracted, and corresponds to the area of greatest expected impacts on ecological flows in the riparian corridor. Thus, this exploratory analysis shows that the Río Cuchujaqui should be also considered as a spatial feature that may explain groundwater distribution. Likewise, according to this analysis, subsequent investigation should take into account the volume of water in order to measure more accurately the relation between groundwater rights and conservation areas.

Chi-square and Cramer's V

Chi-square and Cramer's V measure the interrelation between geographical features (here wells, drainage lines, and management boundaries) regardless of whether the attribute is weighted or un-weighted. In order to take into account the annual volume of water per year granted by CONAGUA, which we showed above to be very relevant, the following logarithmic classification of groundwater volume (Q) was used:

- Very low = groundwater volume less than or equal to 1000 m^3 per year ($Q \leq 10^3$ m^3).
- Low = groundwater volume higher than 1000 and lower or equal than 10,000 m^3 per year (10^3 $m^3 < Q \leq 10^4$ m^3)
- Medium = groundwater volume higher than 10,000 and lower or equal than 100,000 m^3 per year (10^4 $m^3 < Q \leq 10^5$ m^3).
- High = groundwater volume higher than 100,000 and lower or equal than 1,000,000 m^3 per year (10^5 $m^3 < Q \leq 10^6$ m^3).

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[6] There is no single optimum radius with a specific physical basis; instead, the selection depends on the geovisualization purpose related to map scale. For this particular analysis, it is important to locate large, dense areas to differentiate the Kernel method when we use the volume used, so a larger radius of 10 km was selected.

Table 2
Spatial association between groundwater volume used and protected area.

Areas of reference	Groundwater rights				Chi-square	Cramer's V
	Classification by volume	Total by classification	Registered inside the protected area	Estimated inside the area in a random space		
SA-RC without a buffer	Very low	131	19	41.0	10.498	0.200
	Low	71	9	22.2	7.198	0.225
	Medium	45	1	14.1	13.654	0.390
	High	6	0	1.9	2.229	0.431
SA-RC with a buffer of 2 km	Very low	131	29	51.6	9.149	0.187
	Low	71	11	28.0	10.178	0.268
	Medium	45	1	17.7	18.861	0.458
	High	6	0	2.4	2.943	0.495
SA-RC with a buffer of 4 km	Very low	131	56	59.1	0.151	0.024
	Low	71	21	32.0	3.670	0.161
	Medium	45	9	20.3	6.471	0.268
	High	6	2	2.7	0.175	0.121

In order to examine the spatial association between groundwater volume used and the SA-RC, first, two areas are compared: inside the SA-RC within the watershed (called intersection in Fig. 1) and outside the SA-RC within the watershed. In addition, following Carabias and Landa's (2005) purpose of enlarging the natural protected areas, Cramer's V for assumed NPA expansion, 2 and 4 km buffers around the current SA-RC boundary are computed to examine how groundwater rights are related to the surrounding areas of the protected area. Table 2 shows the results of this analysis.

The first observation in Table 2 is that all the groundwater rights estimated inside the NPA (area of reference) in random space are higher than the groundwater volume used registered inside the protected area. Thus, Cramer's V values indicate the degree of spatial association related to the outside area. According to the table of significance, considering a degree of freedom of 1, such as this case,[7] and a probability of 0.05 we have a value of 3.841 (Blalock, 1979, p. 613). However, as stated above, Chi-square values are affected by the size of the sample used. Particularly, high groundwater (10^5 $m^3 < Q \leq 10^6$ m^3) has only six concessions. Due to this Chi-square limitation, the discussion of the results will be focused just on Cramer's V values.

Very low and low water volume extraction rights have moderate or weak spatial relationship in all the cases (V values lower than 0.3). This means that in very low and low groundwater volumes there is not a strong difference of the distribution between inside and outside the SA-RC. Medium and high groundwater volumes have a strong spatial association with the SA-RC both without a buffer and with a 2 km buffer (higher than 0.3). This indicates a strong difference in groundwater distribution between areas inside and outside the SA-RC, such that volumes outside have a density greater than the estimated random distribution. However, V values of medium and high groundwater volume change when they are compared with the 4 km buffer around the SA-RC, for which they exhibit only moderate values, indicating that if the SA-RC limits were enlarged by 4 km, medium and high groundwater volumes inside and outside the SA-RC would not be strongly differentiated.

While the actual expansion of the NPA would be based on non-uniform land acquisition we have assumed buffers of 2 or 4 km around the current NPA area. Additionally, because riparian areas are considered to be the ecosystems most affected by water human uses (Carabias & Landa, 2005; Pitt et al., 2000; Postel & Richter, 2003; WCD, 2000), our second examination considers the spatial pattern of groundwater volumes in relation to the riparian areas of the Cuchujaqui watershed, which we define in relation to the principal river (first order stream) and its direct tributaries (second order streams) as shown in Fig. 1.

Three tests of association are conducted. First, the association between the groundwater volumes and the first order stream was measured applying a buffer of 300 feet (91.4 m), which is the minimum buffer suggested as the riparian area by numerous environmental practitioners (McNaught, Rudek, & Spalt, 2003; Presumpscot River Management Plan Steering Committee, 2003; Wenger & Fowler, 2000). Second, the association between the groundwater volumes and the second order streams were tested applying the same buffer. Finally, the relation between groundwater volume used and the buffer of 300 feet of the whole drainage system (first and second order streams together) was examined. Table 3 shows the results of this analysis.

Unlike with the association with the SA-RC, the registered groundwater volumes inside the riparian area (area of reference) in all cases are higher than the estimated groundwater volume used in random space. Thus, in this case Cramer's V value is a measure of the degree of spatial association related to the area within the riparian buffer.

Almost all the cases have weak and moderate V values, which indicate the difference between the distribution inside and outside of the riparian area is not strong. However, there are two significant exceptions to this outcome. First, high groundwater volume distribution in the first and second order streams buffers has a V value of 0.793. This means a very strong

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[7] We have a 2×2 table and in Chi-square degree of freedom = (number of rows − 1)(number of columns − 1).

Table 3
Spatial association between groundwater volume used and Cuchujaqui drainage system.

Areas of reference	Groundwater rights				Chi-square	Cramer's V
	Classification by volume	Total by classification	Registered inside the riparian area	Estimated inside the area in a random space		
First order stream with a buffer of 300 feet	Very low	131	6	1.5	2.801	0.103
	Low	71	3	0.8	1.300	0.096
	Medium	45	5	0.5	3.896	0.208
	High	6	4	0.1	5.749	0.692
Second order stream with a buffer of 300 feet	Very low	131	12	4.5	3.580	0.117
	Low	71	5	2.5	0.908	0.080
	Medium	45	5	1.6	1.942	0.147
	High	6	1	0.2	0.577	0.219
First and second order stream with a buffer of 300 feet	Very low	131	17	6.0	5.722	0.148
	Low	71	8	3.3	2.155	0.123
	Medium	45	10	2.1	6.010	0.258
	High	6	5	0.3	7.547	0.793

relationship. In the same way, high groundwater volume used distribution in the first order stream has a V value of 0.692 (whereas this water right class for the second order stream is 0.219). This shows that the high V value of the whole riparian area is explained predominantly by the strong relationship with the first order stream riparian buffer.

Discussion

Groundwater rights and the current SA-RC delimitation

The results of the spatial relation test between groundwater volume used and the boundaries of the SA-RC show us that in the cases the groundwater volume used inside the SA-RC is less than estimated for a random distribution, which is in accordance with conservation policy. In Table 4, the current distribution of groundwater use, by water source, inside and outside the protected area is shown.

Inside the SA-RC, most of the groundwater use is destined to provide water for human use in the rural communities. This follows the LAN 2004, which grants urban/domestic use of water higher priority than environmental purposes. However, as Table 4 shows, environmental water is not formally accounted for in the Cuchujaqui watershed. In this regard, a member of a Mexican environmental non-governmental organization who works in the SA-RC claimed in an interview that although the LAN 2004 considers the environment as a separate water use, in practice CONAGUA has not established the criteria to identify, much less allocate, water for the environment. He argued that this water use is particularly critical for the ecosystem services provided by NPAs and therefore, by law, environmental water use should be recognized and enforced at least inside these areas. This opinion of environmental groups points to the need for CONAGUA and CONANP to interact more actively in managing water for biodiversity conservation.

At the beginning of this paper a significant disjuncture in the legal framework between CONAGUA and CONANP was presented. Nonetheless, the spatial analysis shows that in the ultimate instance, the groundwater use distribution conforms to a policy favoring environmental conservation. As demonstrated in the results, within the current boundaries of the SA-RC, although in very low and low groundwater use volumes there is not a strong difference of distribution between inside and outside the SA-RC, in medium and high water use (highest impact) are more strongly concentrated outside the SA-RC. One way to explain the low concentration of groundwater volume used inside the natural protected area is the proportion of population located in this area, which in 2005 was just 4.4% of the total Cuchujaqui watershed population.

Another factor to explain the low occurrence of groundwater inside the natural protected area is the declaration of the Cuchujaqui aquifer as a banned zone in 1956. This official decision changed when a Canadian mining company hired a Mexican institution of higher education that determined that the aquifer had an annual volumetric water availability of

Table 4
Groundwater use inside and outside the SA-RC.

Uses	Groundwater inside		Groundwater outside	
	Number	Volume (m^3)	Number	Volume (m^3)
Urban	21	30,853	103	1,304,642
Livestock	5	8,761	80	70,190
Agriculture	0	0	4	176,563
Industrial (Mining)	0	0	4	1,500,000
Multiple uses	3	5,499	33	753,033
Total	29	45,113	224	3,804,428

22.16 million m^3 (CONAGUA, 2005). In 2006, this company acquired the right to 1.5 million m^3, located outside of the SA-RC, at the southwest of the watershed (densest zone in Fig. 2b). This recent and unexpected change in CONAGUA's classifying the aquifer from a banned zone to a water-available aquifer also explains why high groundwater use volumes are more concentrated in the area outside the SA-RC.

Groundwater rights and an expanded SA-RC

As established in the introduction, one of the objectives is to examine the spatial distribution of groundwater rights of a hypothetical NPA expansion. For this purpose, we first examine buffers of 2 and 4 km around the current SA-RC limits as the expected expansion of the NPA (Table 2). This analysis indicates that if the area of the SA-RC was enlarged by a 4 km buffer, high groundwater volume distribution would not be strongly differentiated between areas inside and outside the SA-RC (V value of 0.121). This is because, if extended, the SA-RC would encompass two urban water rights with a total volume of 305,384 m^3 per year that supply water to the principal city of the municipality. This fact would complicate conservation goals if the NPA were enlarged.

A second hypothetical expansion of the NPA through the riparian areas of the watershed is examined. This geographical analysis shows a high spatial association between groundwater volume used and the riparian area (Table 2). A buffer of 300 feet around the first order stream shows weak and moderate spatial association with very low, low and medium groundwater volumes. However, high groundwater volume shows a very strong relationship with the riparian area of first order stream. This has several implications.

While dams' impact on the environment has received significant consideration among scholars and practitioners, less attention has been paid to groundwater extraction impacts on the environment. As an illustration of this worldwide dam attention is the formation of the World Commission of Dams, which pointed out the importance of releasing tailor-made environmental flows to maintain downstream ecosystems (WCD, 2000). However, the case of the SA-RC aims to highlight the importance of examining the interrelation between sustaining rivers and groundwater extractions (noted for the Colorado River by Pitt et al., 2000), rather than only dam impacts. In this regard, one implication of the spatial association between high groundwater volume used and the riparian area concerns watershed-wide ecosystem services.

The distribution of water rights affects the interrelation between upper and lower basin users. According to Shah (2009), in South Asia, before the appearance of water extraction mechanisms such as electric or diesel pumps, the layout of hydraulic infrastructure of large irrigation projects was essentially time invariant. However, with the pump irrigation revolution this state of affairs underwent drastic change because as a final stage is possible that only a fraction of planned water inflows to the lower irrigated area is received due to dispersed groundwater extraction (Shah, 2009). As stated above, the Río Cuchujaqui is an important tributary of the Josefa Ortiz de Dominguez Dam, which supplies water to the Valle del Carrizo irrigation district. In an interview, a CONAGUA employee who works in this irrigation district said that the water users complain about the check dams constructed by ranchers for livestock water provision in the upper watershed area of the Río Cuchujaqui. However, perhaps more important are the groundwater extractions from the riparian area, particularly the high groundwater rights of around 2 million m^3 per year located in the first order stream buffer. Lower basin users complain about the more visible water reconfiguration, which is the check dams in the upper basin; however, they may not realize the non-tangible use of groundwater.

Equity and interaction between upstream and downstream users is a recurrent topic among water management scholars (Shah, 2009; Van der Zaag, 2007). In Asia, Shah (2009) establishes that the spread of pump irrigation markets produced powerful and large-scale beneficial equity impact by spreading irrigation benefits among smallholders throughout the catchment area. Unlike the Asian case, a mining company rather than smallholders owns most of the high groundwater volumes in the Cuchujaqui aquifer. Moreover, as the CONANP's director of the SA-RC established, this company is the beneficiary by the water-environmental services provided by the SA-RC (Rojero Díaz, 2008, p. 21).

Conclusions

Globally there is growing recognition that environmental conservation protects habitat and other ecological values while also enhancing the ecosystem services that watersheds provide for human populations. The proposal of enlarging natural protected areas may produce important benefits for conservation of both water and ecosystem services. However, these benefits are not merely additive; tradeoffs must be considered to understand the full import of this proposal. The case considered in this paper bears lessons that are illustrative beyond the specific region. The spatial and institutional analyses demonstrate that there exists a significant disjuncture between the formal, legally mandated functions of different governmental agencies, which is a concern more generally in Mexico and other countries. In the Sierra de Álamos-Río Cuchujaqui study area, the federal water and protected area agencies (CONAGUA and CONANP, respectively) are not obligated or able to formulate an integrated, long-term water conservation program. Questions remain on the benefit of enlarging NPAs if the policies between the two involved agencies are not integrated.

The geographical analysis results show that the spatial distribution of groundwater use largely supports conservation goals; this may be explained more by demographic factors (absence of human settlements) than by a coherent and integrated management framework between the two agencies. However, it is unclear what will happen in the hypothetical case that the NPA is enlarged to the Cuchujaqui aquifer. As established, high groundwater uses (up to 2 million m^3 per year) are located in the watershed's riparian area. In the hypothetical case that SA-RC is enlarged, CONANP would have to address this fact. Thus, the task of enlarging environmental conservation goals would be more difficult, and the interface of CONAGUA and CONANP would be all the more critical in order to preserve the riparian ecosystem.

Groundwater extractions reconfigure watersheds. On the one hand, upper and lower watershed relations are reconfigured and possibly become more equitable; however, this case shows that it is necessary to analyze the internal differentiation of access to water in the upper watershed before assuming a more equitable distribution of water benefits between upper and lower users. On the other hand, this case exposes the necessity of studying the ecological reconfiguration produced by groundwater extractions. Particularly problematic, as this paper established, is if groundwater extractions directly affect the riparian area, its associated habitats, and the ecosystem services it provides.

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