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The water-energy-climate nexus: Resources and policy outlook for aquifers in Mexico

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[1] Three interlinked processes drive groundwater balances in diverse regions globally: (1) groundwater-irrigation intensification, (2) electrical energy supply for agriculture, and (3) climatic variability. Mexico's water-energy-climate nexus offers generic lessons because of its water scarcity and institutional reforms followed in other emerging economies. This paper analyzes data for 280 aquifers in Mexico, all registered water users, population projections, 2010–2100 precipitation and temperature projections for A1B and A2 emissions scenarios from 15 general circulation models, and 1999–2009 agricultural electricity use. Under A2 emissions, aquifers with negative balances will increase from 92 to 130 in number between 2010 and 2100, and the national groundwater deficit will increase by 21.3 km^3. Under A2 and medium-variant population growth (which peaks midcentury), negative-balance aquifers will increase from 92 to 133, and the national groundwater deficit will increase by 22.4 km^3. Agricultural power pricing offers a nexus-based policy tool to address aquifer depletion, an opportunity that was lost with the 2003 reduction in nighttime tariffs. Under A2, medium-variant population, and simulated 2% real annual increases in agricultural power tariffs, negative-balance aquifers will increase from 92 to 111, and the national groundwater deficit will increase by 17.5 km^3 between 2010 and 2100. Regulatory and user-based groundwater management initiatives indicate growing awareness of aquifer depletion; however, the long-term outlook points to continued depletion. This raises the need to harness nexus-based policy options, i.e., increasing agricultural power tariffs, eliminating reduced nighttime tariffs, enforcing legislation linking groundwater extraction to power use, and limiting new power connections for groundwater wells.

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1. Introduction

[2] Human use of groundwater spans millennia [*Llamas and Custodio*, 2003; *Postel*, 1999] and has contributed to societal gains in public health, dispersed settlement patterns, rural livelihoods, agricultural productivity, and food security among others [*Giordano and Villholth*, 2007; *Burke and Moench*, 2000]. Factors that make groundwater preferable to surface water for human purposes include the temporal buffering capacity of aquifer storage [*Loaiciga*, 2003], the spatially distributed availability of groundwater [*Wada et al.*, 2010], and water quality that usually make it suitable for both human consumption and crop irrigation [*Zektser and Everett*, 2004]. Recent developments in technology (low-cost, reliable pumps) and energy supply (rural electrification and hydrocarbon fuel distribution networks) have significantly removed the constraints to groundwater extraction [*Scott and Sharma*, 2009], resulting in the rapid expansion and intensification of groundwater use. Human extraction of groundwater has surpassed recharge rates in numerous locations around the world [*Oki and Kanae*, 2006], specifically the Middle East and North Africa [*MacDonald et al.*, 2009], South Asia [*Shah*, 2009; *Mukherji*, 2006], northern China [*Wang et al.*, 2006], and western North America [*Megdal et al.*, 2009; *Scott et al.*, 2010; *Moreno Vázquez et al.*, 2010]. At the same time, recharge processes are influenced by climatic and hydrologic variability [*Dragoni and Sukhija*, 2010; *Loaiciga*, 2003].

[3] It has been demonstrated that human use of water is a dominant driver of the spatial distribution and timing of water resources globally [*Vörösmarty et al.*, 2000]. When coupled with the implications of climate change and variability for water resources [*Milly et al.*, 2008], expanding and intensifying human use of water raises serious management and policy challenges. Expanding water transfer schemes to meet human demands for water [*Characklis et al.*, 2006; *Brown and Carriquiry*, 2007], make policy choices all the more difficult when demand is for urban and domestic water supply purposes. The conceptual approach employed in this paper responds to calls for improved understanding of the multiple roles played by humans in the water environment [*Braden et al.*, 2009], specifically by expanding the domain of resource use beyond just water to include energy. There is growing interest in the water-energy-climate nexus by researchers [*Colby and Frisvold*, 2011; *Kenney and Wilkinson*, 2011] and policy analysts alike [*Fisher and Ackerman*, 2011; *Carter*, 2010].

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[4] Intensification of groundwater irrigation, electricity supply, and climatic variability constitute a nexus of interdependent processes, as shown schematically in Figure 1. Bidirectional causal links and mutual influences are considered for physical and human dynamics. The coupled resource-policy approach followed here aims to understand implications of physical (climatic, hydrological, and water resources) processes for management and policy making. Conversely, irrigators' behavioral choices as well as management programs have impacts on groundwater resources that are not well captured by physical water balances alone.

[5] The objectives of this paper are to quantitatively assess hydroclimatic and human use drivers of groundwater balances in Mexico and to explore energy power supply and pricing policies to address aquifer depletion. Given the complexity of that country's water, energy, and climate challenges [*Comisión Nacional del Agua* (*CONAGUA*), 2010b], the analyses presented here aim to take a step beyond case study description by elucidating drivers of aquifer depletion and opportunities to respond to this generic challenge, for example, as experienced in India and China [*Shah*, 2009]. Mexico offers lessons for other regions, especially because its agricultural groundwater use, the focus of this special section, is a pivotal driver of aquifer depletion. Other lessons include the implications of competition for groundwater by nonagricultural uses, climate change and variability that (unlike aquifer depletion) have caught policy makers' attention, and the role of electrical power supply and pricing as both drivers and responses to aquifer depletion. These generalizable features of groundwater use in Mexico are briefly contextualized here with further analyses provided below, including the institutional and regulatory environment in section 5.

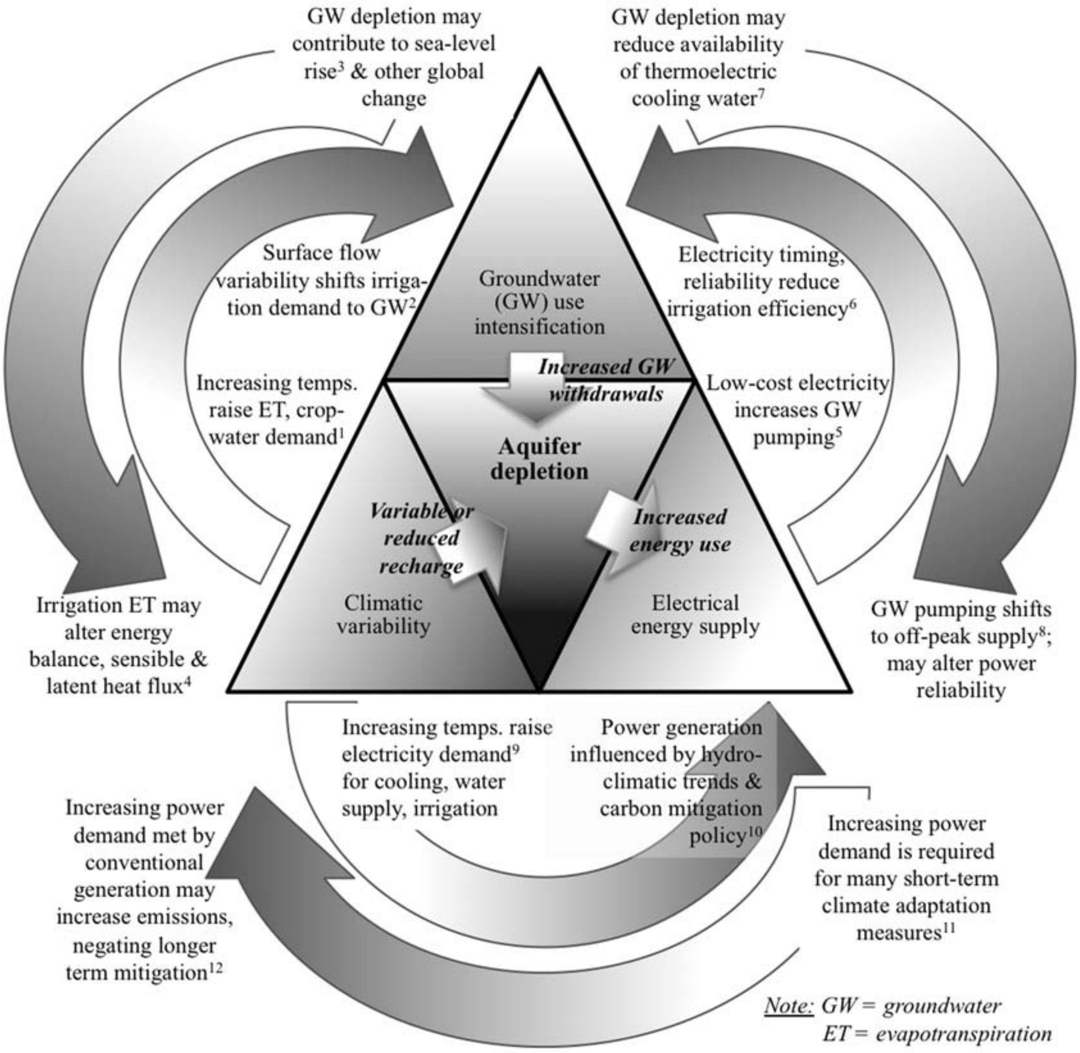

Figure 1. The (ground)water-energy-climate nexus showing causal links and mutual influences among the intensification of groundwater use, electrical energy supply to agriculture, and climatic variability. Citations for published work that illustrates the processes identified by the notes are as follows: 1, *Muñoz-Arriola et al.* [2009]; 2, *Schoups et al.* [2006]; 3, *Alley et al.* [2002]; 4, *Biggs et al.* [2008]; 5, *Ibáñez et al.* [2004]; 6, *Shah et al.* [2007]; 7, *Veil* [2007]; 8, *Scott et al.* [2010]; 9, *Colby and Frisvold* [2011]; 10, *Vassolo and Döll* [2005]; 11, *Hightower and Pierce* [2008]; 12, *Scott and Pasqualetti* [2010].

[6] Agriculture represents the largest user of groundwater in Mexico, similar to many developing countries such as India, China, and Pakistan that are globally among the largest volume pumpers of groundwater for agriculture [*Shah*, 2009]. Mexico's high per irrigated hectare use produces comparatively high crop yields [*CONAGUA*, 2010a]. However, because of the high costs of mechanization and low absorption of labor in Mexican agriculture [*Scott et al.*, 2010] overall agricultural productivity in per hectare profit terms is relatively low. Falling groundwater levels raise the costs of groundwater and further reduce agricultural profitability, particularly of low-value crops [*Ojeda-Bustamante et al.*, 2011]. This is especially true for grains (maize, wheat, sorghum, barley, and oats), beans, cotton, and other basic commodities that are primarily cultivated in Mexico's large irrigation districts (ranging in size from 25,000–200,000 hectares each) using surface water via gravity-fed canal distribution systems. The result is that farmers seek to shift from surface water to groundwater for higher-value crop production of fruits and vegetables, occasionally through conjunctive surface-groundwater irrigation within the canal command areas [e.g., *Schoups et al.*, 2006; *Muñoz-Arriola et al.*, 2009] but primarily outside of them [*Moreno Vázquez*, 2006; *Wester*, 2008]. Through a variety of contract farming or direct marketing arrangements, groundwater-irrigated production is increasingly oriented for export.

[7] Agriculture as the largest user of groundwater in Mexico [*CONAGUA*, 2010b] is key to the future of aquifer sustainability [*Moreno Vázquez et al.*, 2010]. Agriculture is sensitive to climatic change and variability [*Eakin*, 2005], both seasonal and annual temperature regimes [*Gay-Garcia et al.*, 2009] and precipitation [*Montero-Martínez et al.*, 2010]. Groundwater-based irrigation is an adaptive strategy as the reliability of canal irrigation decreases with increasing variability of surface flow [*Magaña and Conde*, 2000].

[8] The second feature of Mexico's groundwater-energy-climate nexus that offers generic lessons is that agricultural groundwater is increasingly in competition with multiple water demands including urban water supply, which has priority in Mexican water law [*Salazar and Pineda*, 2010; *Scott et al.*, 2010]. The combination of population growth and urbanization expands nonagricultural demand for groundwater.

[9] Third, the water-energy links of the nexus in Mexico, specifically electrical power supply and pricing for groundwater pumping, currently constitute enabling conditions for aquifer depletion. With appropriate policy design, however, power supply can represent a tool to manage aquifer depletion [*Scott and Shah*, 2004]. The policy dimensions of the nexus are important because Mexico is scrutinized globally because of 2 decades of efforts to navigate between free market and state-centric policy models [*Wilder et al.*, 2010; *Wester*, 2008; *Hearne*, 2004; *Easter*, 2004]. The paper concludes with an integrated prognosis for groundwater management and policy in Mexico that has broad implications beyond the country's borders.

2. Groundwater Depletion in Mexico

[10] It is important to briefly contextualize agriculture, irrigation, and groundwater use in Mexico. Water data reported here for Mexico are taken from official sources [*CONAGUA*, 2010b] unless otherwise specified. The primary sector (agriculture, ranching, forestry, and fishing) accounted for 3.8% of Mexico's gross domestic product in 2008, down from 19.2% in 1950. In 2008, an estimated 29.1 km^3 of groundwater was pumped in Mexico, with agriculture using 70.4% of this total. Groundwater accounted for 33.5% of the water used in Mexican agriculture, 50.5% of industrial water use, and 62.1% of urban municipal supply; this highlights the strategic value of groundwater for urban supply. Over 2001–2008, total groundwater use in Mexico increased 2.5% annually, led by agriculture where groundwater use increased 2.8% annually.

[11] Of the 653 aquifers in Mexico for which data are compiled and reported [*CONAGUA*, 2010b], as of 31 December 2008, 101 have reported extraction exceeding recharge by greater than 9.5%, which appears to be the criterion for listing these as "overexploited". Among these, 10 aquifers also present problems of saline intrusion, which can represent a further challenge associated with excessive groundwater use [*Zekster et al.*, 2005; *Ibáñez et al.*, 2004]. Of the aquifers listed as "underexploited," 26 have reported extraction exceeding recharge at levels between 0% and 9.4% with the remainder presenting positive water balances. Aquifer depletion is spatially concentrated in the north and central regions of the country (Figure 2), where precipitation is low and variable, agricultural demand for groundwater is high, and where urban growth exerts additional pressure on aquifer resources.

3. Methods

[12] The aquifer water balances simulated for this paper follow the three principal nexus forcings shown in Figure 1. Specifically, the following six simulated scenarios are presented and discussed: (1) A1B-AGW, carbon emissions scenario A1B precipitation-based recharge and temperature-based evapotranspirative demand for agricultural groundwater (AGW); (2) A2-AGW, which is the same as scenario 1, but under A2 emissions scenario; (3) A2-AGW-MV, emissions scenario A2–based AGW demand (same as scenario 2) plus nonagricultural demand forced by population change based on the United Nations (UN) medium-variant projections; (4) A2-AGW-CF, which is the same as scenario 3, but with UN constant-fertility population change; (5) A2-AGW-MV-E1, which is the same as scenario 3 plus 1% annual increase over 2010–2100 in electricity tariffs for groundwater pumping; and (6) A2-AGW-MV-E2, which is the same as scenario 5, but with 2% annual increase in electricity tariffs. As described in sections 5 and 6 below, the multiple water balance simulations are combined with institutional assessments in an integrated resources and policy outlook for aquifers in Mexico.

[13] The water balance calculations and estimate of depletion are as follows:

$$\Delta S_t = R_t - E_t, \tag{1}$$

where ΔS_t is change in aquifer storage, and t is the 10 year simulation time step. R_t is recharge, from

$$R_t = R_{t-1}\left[1 + \frac{P_t - P_{t-1}}{P_{t-1}}\right], \tag{2}$$

Figure 2. Map of Mexico, distinguishing northern and central states from southern states (outlined by dashed line).

and R_0 is the initial year 2010 taken as the 2008 reported recharge [*CONAGUA*, 2010b], where P_t is precipitation. Thus, the change in recharge $(R_t - R_{t-1})$ is assumed to be proportional to the change in precipitation $(P_t - P_{t-1})$, an assumption discussed following equation (7). E_t are groundwater extractions, derived from agricultural and nonagricultural extractions: $E, \text{ag}_t + E, \text{nonag}_t$. The expression

$$E, \text{ag}_t = E, \text{ag}_{t-1}\left[1 + \frac{\text{ET}_t - \text{ET}_{t-1}}{\text{ET}_{t-1}}\right] \tag{3}$$

is derived from the change in irrigated crop evapotranspiration (ET) using the Blaney-Criddle method:

$$\text{ET} = p(0.46T_{\text{mean}} + 8) \tag{4}$$

on the basis of monthly temperature in °C (T_{mean}) and latitude-derived sunshine-hour fraction (p); ET is summed for October–May (otoño-invierno and primavera-verano cropping-irrigation seasons). The assumption that E, ag_t scales linearly with ET is discussed following equation (7). The expression

$$E, \text{nonag}_t = E, \text{nonag}_{t-1}\left[1 + \frac{\text{Pop}_t - \text{Pop}_{t-1}}{\text{Pop}_{t-1}}\right] \tag{5}$$

is derived from the change in population (Pop), reported by *Instituto Nacional de Estadística, Geografía e Informática* (*INEGI*) [2005] and corrected for 2010 census data as discussed in section 3.2.

[14] $E, \text{ag}_0 + E, \text{nonag}_0$ total extraction is from *CONAGUA* [2010b] and nonhuman extractions; that is, net groundwater fluxes, surface-groundwater interactions, and freatic evaporation are considered constant over the simulation period. $\frac{E, \text{nonag}_0}{E, \text{ag}_0}$ is from the totals of user level groundwater use data reported at the municipality level (Registro Público de Derechos de Agua (REPDA), http://www.conagua.gob.mx/conagua2009/Contenido.aspx?id=ba831b70-466c-40a6-a3ad-444ccc669bfe|Informaciónestadística|0|0|35|0|0), resampled at the aquifer level.

[15] Aquifer depletion is estimated by

$$\sum_t \Delta h_t > D, \tag{6}$$

accounting for cumulative declines in water levels (Δh) that exceed reported aquifer thickness (D), where

$$\Delta h_t = \frac{\Delta S_t}{A\, S_y} \tag{7}$$

is derived from the change in storage ΔS_t from equation (1), aquifer area A, and specific yield S_y, assuming unconfined conditions. D, A, and S_y are reported in aquifer water balance reports [*CONAGUA*, 2009] downloaded from the

CONAGUA Web site (http://www.conagua.gob.mx) as referred to by *CONAGUA* [2010b].

[16] As indicated in the explanatory notes for several equations above, a number of assumptions are needed to complete national level analyses of large numbers of aquifers. An underlying assumption is that the water balance as calculated above provides a diagnostic tool to assess groundwater sustainability. It has been noted [*Bredehoeft*, 2002] that a better estimate of acceptable extraction is the share of recharge that can be captured from an aquifer under dynamic conditions. Such analysis would require process models and data [*Alley et al.*, 2002] that are beyond the scope of the national level assessment undertaken here.

[17] Several detailed assumptions are required for this analysis. First, equation (2) assumes that recharge scales linearly with annual precipitation. Constant recharge and precipitation ratios do not account for actual flow processes, multiple aquifer layers, change in recharge contributing areas in the watersheds, and other complexity that characterize hydrological processes that are better captured in process models. For the large-scale processes this paper assesses, i.e., water balance impacts of climate and human forcing over a century-long time scale, the assumption of a constant recharge/precipitation ratio is considered valid. Similar, first-order linear relations between precipitation and recharge were used in regional groundwater studies by the USGS [*Flint and Flint*, 2007].

[18] Second, equation (3) assumes that groundwater extraction scales linearly with irrigated crop ET, which in this paper is simulated from change in projected temperature using a simple Blaney-Criddle model [*Food and Agriculture Organization*, 2011]. The underlying assumption is that crop water requirements will continue to be met through groundwater irrigation over the 2010–2100 simulation period. This does not account for other effects of warming on crop yields [*Lobell and Field*, 2007], which may include damage from pests and wind. Some evidence suggests that farmers adapt to temperature changes by shifting cropping calendars, thus minimizing increases in crop water requirements; however, there are crop varietal limitations to continuing such adaptation over multiple decades. For unirrigated conditions, it has been observed that actual ET may be regulated by stomatal processes although increased growing season length as a result of climatic change may increase total ET [*Serrat-Capdevila et al.*, 2011]. However, for irrigated conditions, increasing water application in response to rising temperature remains the principal strategy employed by Mexican farmers [*Ojeda-Bustamante et al.*, 2011].

[19] Additionally, the assumptions that net fluxes, surface water interactions, and freatic evaporation are all constant over the simulation period are either neutral or conservative in their implications for groundwater balances. In other words, intensified groundwater cycling resulting from climatic processes and increased extractions may alter net fluxes [*Schaller and Fan*, 2009]. However, net inflows to aquifers experiencing declining water levels will be offset by reduced surface water recharge that results from greater hydrologic variability, i.e., heightened peaks but reduced duration of surface flows, and by reduced freatic evaporation resulting from lowered water levels.

[20] Finally, to assess aquifer depletion, equation (6) assumes that unconfined conditions apply. It should be noted that the majority of aquifers simulated here are alluvial in origin [*CONAGUA*, 2010b], which suggests the presence of unconfined conditions.

[21] The water balances of 280 of Mexico's principal aquifers resulting from multiple water-energy-climate nexus forcings were computed on a decadal time step, starting with current water balances as the 2010 base year, shown in equations (1)–(3). Detailed water balance studies, including latitude-longitude polygon limits, are publicly available for these 280 aquifers (published in the Mexican government's official gazette, *Diario Oficial de la Federación* (DOF)). It should be noted that 25 of the aquifers listed as "overexploited" (see above) did not have publicly available data; these were not included in the present analysis with the result that total numbers of aquifers experiencing depletion reported here do not match official CONAGUA tallies of overexploited aquifers. Mexico City's aquifer was excluded from the analysis because the simple recharge-extraction simulations used here do not account for the major transfers of water into and out of the basin.

3.1. Climate Drivers

[22] As noted in equations (2) and (3), the water balances are driven by precipitation (P) and temperature (T). The 2001–2100 projections for these variables were extracted from the following fifteen models of the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3): BCCR-BCM2.0, CGCM3.1, CNRM-CM3, CSIRO-Mk3.0, ECHAM5/MPI-OM, GFDL-CM2.1, ECHO-G, INM-CM3.0, IPSL-CM4, MIROC3.2, MRI-CGCM2.3.2, NCAR-CCSM3, NCAR-PCM1 UKMO-HadCM3, and UKMO-HadGEM1. As part of the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report, the multimodel ensemble has been used extensively to investigate global change processes, including effects on hydrology [*IPCC*, 2007; *Waliser et al.*, 2007]. Projections for emissions scenarios A1B (medium to high CO_2 concentration) and A2 (high) were used on a 2° grid [*Dominguez et al.*, 2010]. P and T were aggregated yearly and the 15-model ensemble means [*Annan and Hargreaves*, 2010] were computed for 69 grid cells covering the aquifers of interest and were then resampled onto the aquifers on the basis of proportional area.

3.2. Human Drivers

[23] Demographic change was incorporated in the analysis by considering population in Mexico's 2429 municipalities. The preliminary results of Mexico's 2010 census were used to correct earlier projections [*INEGI*, 2005] that had overestimated the 2010 national population. For this analysis, population for each municipality was projected to change in accordance with historical growth rates as determined from 1990–2010 data using compound growth series to determine annual growth rates r for each municipality:

$$\mathrm{Pop}_t = \mathrm{Pop}_0[1 + r]^n \tag{8}$$

Total national population projections for 2050 and 2100 were tied to two population models, the U.N. medium-variant and constant-fertility scenarios [*UN*, 2011], by proportionally adjusting all municipalities' growth. While this accounts for differential historical growth, it does not modify projected growth trends on the basis of municipality-differentiated future changes resulting from such factors such as migration, climate impacts, etc. Decadal changes in population at the municipality level were resampled onto the aquifers on the basis of proportional area, and then aquifer-based decadal rates of population change were assumed to linearly drive change in nonagricultural water demand. The share of nonagricultural groundwater use for each aquifer was assumed to vary in proportion to population growth. This assumption may be conservative because economic growth is often accompanied by disproportionate per capita agricultural and municipal use; however, industrial water use efficiency may offset municipal increases. Groundwater use for thermoelectric cooling in Mexico is estimated and reported only at the regional level [*CONAGUA*, 2010b], but this represents a potentially important nexus driver of future groundwater use [*Vassolo and Döll*, 2005].

3.3. Electrical Energy Supply and Pricing

[24] Data on 1999–2009 electrical power sales to agriculture under tariff 09 ("exclusively . . . for the pumping of water used for irrigation of agricultural crops and for lighting the pumping equipment installations" (author's translation from Spanish)) were accessed from the Web site of the Comisión Federal de Electricidad (CFE; http://www.cfe.gob.mx). Tariffs were adjusted for inflation using the national consumer price index (Banco de México, http://www.banxico.org.mx) and converted to 2010 pesos per kilowatt-hour (Mex\$ kWh^{-1}). Each Mex\$ is roughly equivalent to US\$0.085. Nighttime tariffs (09N) for pumping were introduced starting in 2003 in the states of Chihuahua, Sinaloa, and Querétaro, followed in 2004 by most of the rest. As a result, calculation of price elasticities during the transition period would provide indication of pumpers' response to the tariff shift itself and would not truly represent the demand curve, so the preshift data were used. Of the regressions considered to fit demand versus price, natural log (ln) provided the best results ($p < 0.01$); see results below. Regression results were used to estimate power demand for agricultural pumping under simulated 1% annual and 2% annual real increases in tariffs over the 2010–2100 period. The assumed 2% annual increase over the 2010–2100 period would place 2100 tariffs (in constant 2010 pesos) in the range of current 2010 tariffs for domestic high-consumption or public service users. The political feasibility of this rate of increase is discussed below. By contrast, from 1999–2009, tariffs fell at a compound rate of 0.94% annually.

4. Results

4.1. Climate Drivers

[25] Certain individual models of the CMIP3 ensemble appear to provide more robust P and T projections for specific regions in Mexico [*Montero-Martínez et al.*, 2010]; however, the multimodel ensemble means were considered to provide the best projections across Mexico's varied climatology (M. J. Montero-Martínez (Instituto Mexicano de la Tecnología del Agua, personal communication, 31 March 2009) compared historical records with 1961–1990 simulated precipitation for 15 models and found the ensemble means to provide better results than individual models). It should be noted that estimates of total precipitation and its seasonality remain uncertainties. The monsoon, a key feature of precipitation in much of central and northern Mexico, is not well represented by the models [*IPCC*, 2007].

[26] For all 280 aquifers considered in this study, the increase in temperature over the 21st century with relation to percentage change in precipitation under A1B and A2 scenarios is shown in Figure 3. For A2 in particular, temperature increases up to 5°C while precipitation declines 7%–25%. Observed CO_2 levels exceed even A2 [*Raupach et al.*, 2007]; as a result, A1B and A2 may be considered conservative climate forcings.

[27] Figure 4 and detailed tabular data in Table 1 present the A1B-AGW and A2-AGW water balance simulation results, i.e., the sum of all aquifer balances within each state, and distinguishes northern and central states in bold from southern states in italics. Dimensionless balances of the ratio between recharge and extractions are plotted on a decadal time step for northern and central states. It should be observed that the large magnitudes of the water balance results for southern states (Table 1) tend to dominate the national totals and generalizations across the country as a whole should be viewed with caution. The A1B-AGW results indicate that changes in recharge and simulated groundwater pumping shift a significant numbers of aquifers, all located in the northern and central states, from having positive to negative balances over the 2010–2100 period. The A2-AGW simulations show an even greater proportion of aquifers, with one in a southern state, shifting to negative balances. The magnitudes of difference between the simulated 2100 annual water balances and current 2010 base year balances are revealing, with the A2-AGW difference of 5.2 km^3 for central and northern states approaching on fifth of the current 29.1 km^3 total national groundwater extraction level.

4.2. Human Drivers

[28] Further attention will be paid to the water balance simulations under the high carbon emission A2 scenario because this is considered more likely to occur than A1B emissions. In fact, it should be noted that observed emissions levels appear to exceed even the A1F1 scenario [*Raupach et al.*, 2007], which has higher emissions than A2. The results of the population forcings including both

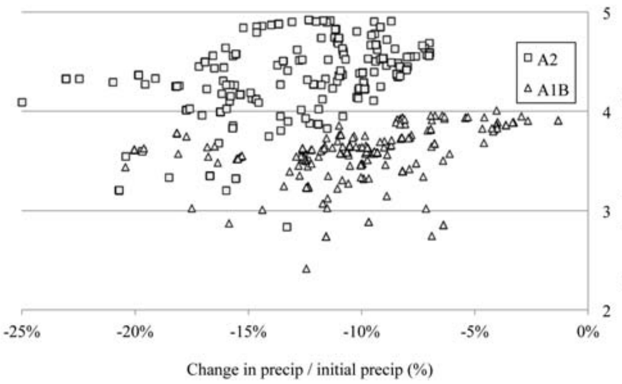

Figure 3. A1B and A2 emission scenario–based projections of 2010–2100 temperature increases and fractional change in precipitation for 280 aquifers considered in this study.

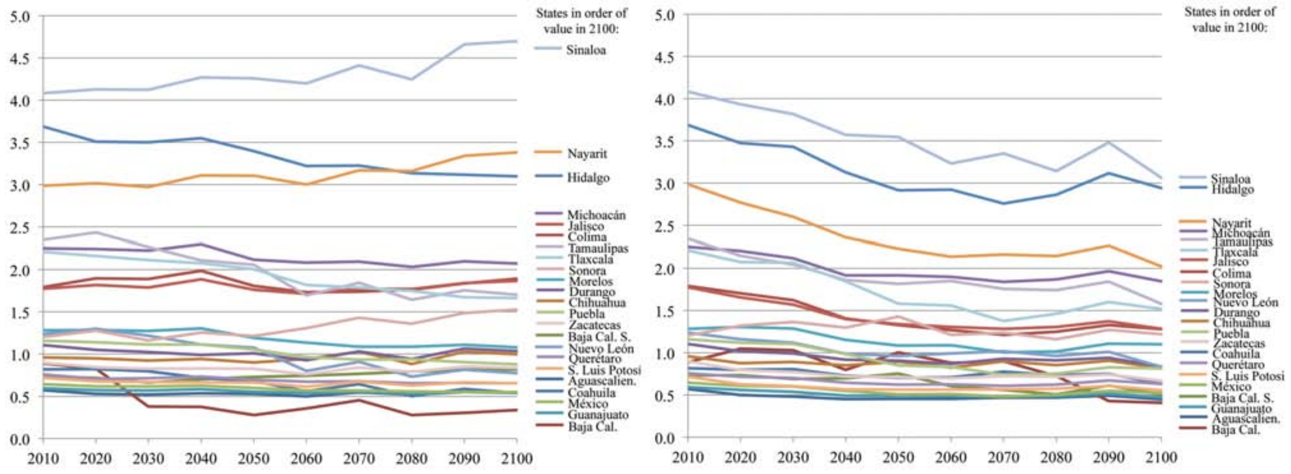

Figure 4. Dimensionless balances of the ratio of recharge to extraction for northern and central states from simulated aquifer water balances under (left) carbon emissions scenario A1B effects on recharge and agricultural groundwater demand (A1B-AGW) and (right) A2 effects (A2-AGW) for 2010–2100.

medium-variant and constant-fertility projections are shown in Figure 5 and Table 2.

[29] The difference between 2100 annual balance totals with just A2-AGW forcing of agricultural groundwater demand, on the one hand, and A2-AGW-MV with the additional nonagricultural demand is 0.56 km^3 for northern and central states (or 10.8% of A2-AGW difference of 5.2 km^3 for central and northern states; see Table 2). This incremental MV population-based demand for nonagricultural water is equivalent to water for 15.6 million people at the conservative consumption level of 100 liters per capita per day. For the constant-fertility projection, the difference is equivalent to water for 26.2 million people. The irrigation required to meet food demands of the increased population is not explicitly considered. It is likely that policy formulation combined with market forces will result in production efficiency increases, food imports, and decreased exports as mechanisms to meet this food demand. The impacts of states' differential rates of growth can be seen in the dimensionless plots. Further consideration is given to the medium-variant scenario, which projects lower future populations than the constant-fertility scenario. Mexico, like other countries, is experiencing lower rates of growth than earlier expected [*UN*, 2011], hence the medium-variant scenario is more likely to occur.

4.3. Electrical Energy Supply and Pricing

[30] Electricity is the principal energy source for pumping groundwater in Mexico; diesel engines are limited to low lifts from open water sources. Since 1962, the number of power connections for agriculture (98.8% of which are irrigation pumps; other rural connections are reported as domestic, industrial, etc.) has risen 19.6% annually to 117,084 in 2009 including almost 17,000 new connections in recent years since nighttime power tariffs were introduced beginning in 2003 (CFE, http://www.cfe.gob.mx). At the same time, energy consumption in agriculture nationally appeared to have leveled off between 7000 and 8000 GWh per year, which represents about 5% of total energy demand (Figure 6). Intensive energy use for groundwater pumping is concentrated in the central and northern parts of the country. States like Chihuahua, Guanajuato, and Sonora account for the bulk of agricultural power connections and of total agricultural demand for energy, although demand is rising rapidly in southern states. Figure 7 presents the results of deriving price elasticities by regressing electrical energy use versus price for several of the states that consume the most electricity for groundwater pumping. The simulation model, however, used unique elasticities for each state.

[31] The water balance simulations based on A2-AGW-MV as described above were expanded to consider the modified effects of tariff increases on agricultural power demand and estimated changes in the volume of groundwater each unit of power would extract, i.e., because of changing water levels as estimated by equation (6). The results are shown in Figure 8 and Table 3. Maps of aquifers at risk of depletion and the dimensionless recharge/extraction ratios simulated for the year 2100, comparing water balances without power tariff increases (A2-AGW-MV) and with power tariff increases (A2-AGW-MV-E2) are shown in Figure 9.

[32] The A2-AGW-MV-E2 results indicate reduced numbers of aquifers experiencing negative balances and fewer aquifers at risk of depletion when compared with the A2-AGW-MV simulation on which this is based. For northern and central states, the A2-AGW-MV-E2 decrease of 1.9 km^3 in water balances to 2100 is a distinct improvement over no change in power pricing. Nevertheless, among the 280 aquifers considered in this study, the total number with negative balances is simulated to increase from 92 aquifers in 2010 to 111 aquifers by the end of the century even with power tariffs that, in constant terms, would reach levels paid today by domestic high-consumption or public service users. This implies that under simulated future forcing conditions, power tariff increases alone will be insufficient to reduce aquifer depletion compared to current conditions; however, they would reduce depletion compared to future conditions without tariff increases.

[33] Other strategies to control the expansion of groundwater extraction have been adopted with little if any

Table 1. Simulated Aquifer Water Balances Summed by State Under Carbon Emissions Scenario A1B Effects on Recharge and Agricultural Groundwater Demand (A1B-AGW) and A2 Effects (A2-AGW) for 2010–2100[a]

				A1B-AGW					A2-AGW				
States[b]	Number of Aquifers Assessed	Number of Aquifers With Negative Balances, 2010	Sum of Aquifer Balances, 2010 (MCM)	Number of Aquifers With Negative Balances, 2060	Number of Aquifers With Negative Balances, 2100	Number of Aquifers With Depletion Risk, 2100	Volume (Sum) Aquifer Balances, 2100 (MCM)	Change (Volume) Annual Aquifer Balances, 2100–2010 (MCM)	Number of Aquifers With Negative Balances, 2060	Number of Aquifers With Negative Balances, 2100	Number of Aquifers With Depletion Risk, 2100	Volume (Sum) Aquifer Balances, 2100 (MCM)	Change (Volume) Annual Aquifer Balances, 2100–2010 (MCM)
Aguascalientes	4	4	−232	4	4	0	−269	−37	4	4	0	−337	−105
Baja California	14	6	−88	14	14	2	−559	−471	9	14	0	−507	−419
Baja California Sur	8	5	−119	5	5	0	−84	35	5	6	0	−231	−112
Campeche	1	0	2099	0	0	0	2300	202	0	0	0	1325	−774
Chiapas	13	0	8397	0	0	0	7844	−553	0	0	0	4826	−3571
Chihuahua	18	7	−64	7	6	0	−4	59	7	8	2	−327	−264
Coahuila	11	7	−247	9	9	1	−686	−439	8	9	1	−559	−312
Colima	10	1	215	1	1	0	254	39	1	2	0	81	−134
Distrito Federal	0												
Durango	7	4	42	5	4	0	15	−27	6	6	0	−73	−115
Guanajuato	11	9	−1190	9	9	1	−1485	−295	9	9	2	−1738	−548
Guerrero	6	0	292	0	0	0	255	−38	0	0	0	261	−31
Hidalgo	10	1	962	2	2	0	791	−171	2	2	0	740	−222
Jalisco	15	3	716	3	2	0	849	132	5	5	0	284	−432
México	6	5	−604	5	5	1	−793	−189	5	5	1	−846	−242
Michoacán	9	2	814	2	2	0	764	−50	2	2	0	616	−197
Morelos	4	1	250	3	3	0	73	−177	3	3	0	91	−159
Nayarit	4	0	271	0	0	0	331	59	1	1	0	143	−129
Nuevo León	10	3	119	6	7	0	−125	−244	4	5	0	−93	−213
Oaxaca	5	0	364	0	0	0	309	−54	0	0	0	214	−150
Puebla	5	1	164	2	3	0	−134	−298	3	3	0	−207	−371
Querétaro	7	4	−139	5	6	0	−212	−73	6	6	0	−231	−92
Quintana Roo	2	0	1269	0	0	0	1491	222	0	0	0	934	−335
San Luis Potosí	7	4	−154	7	7	0	−204	−49	7	7	0	−269	−115
Sinaloa	14	0	2056	0	0	0	2591	535	0	0	0	1466	−590
Sonora	27	12	380	10	6	0	1076	696	12	15	0	456	76
Tabasco	8	0	9075	0	0	0	8323	−752	0	0	0	5647	−3428
Tamaulipas	7	0	325	2	0	0	185	−139	2	2	0	155	−169
Tlaxcala	3	0	214	0	0	0	126	−88	0	0	0	100	−114
Veracruz	10	0	2449	0	0	0	2063	−386	0	1	0	1690	−759
Yucatán	1	0	20,500	0	0	0	22,514	2014	0	0	0	13,454	−7046
Zacatecas	23	13	−91	13	13	0	−160	−69	15	15	0	−342	−251
Subtotal northern and central	234	92	3600	114	108	5	2340	−1260	116	129	6	−1630	−5230
National Total	280	92	48,044	114	108	5	47,439	−606	116	130	6	26,722	−21,323

[a] Note that 1000 million cubic meters (MCM) = 1 km^3.

[b] Names of northern and central states are in bold; names of southern states are in italics.

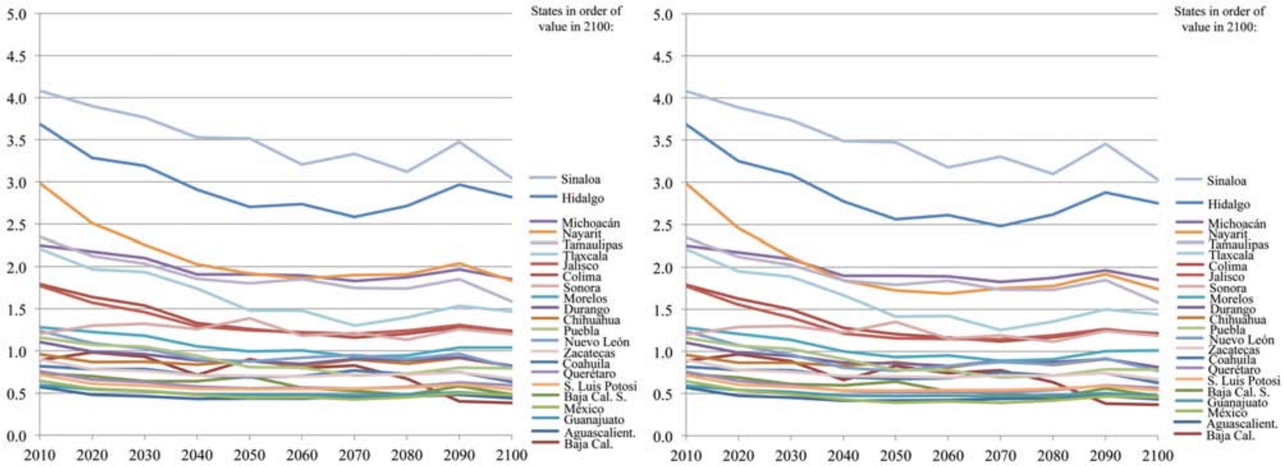

Figure 5. Dimensionless balances of the ratio of recharge to extraction for northern and central states from simulated aquifer water balances under (left) carbon emissions scenario A2 effects on recharge and agricultural groundwater demand with nonagricultural water demand under medium-variant population projection (A2-AGW-MV) and (right) constant-fertility (A2-AGW-CF) for 2010–2100.

success. Official bans on new wells remain in effect for all aquifers listed as overexploited. Unofficial accounts, however, suggest that unregistered wells continue to be drilled, often using the clause that allows repositioning of existing wells. The purely regulatory approach to control groundwater overdraft pursued in Mexico has, in itself, not been successful and must be combined with other tools. Efforts have emerged to organize water users in comités técnicos de aguas subterráneas (COTAS, or groundwater technical committees) around the central problem of groundwater overdraft at the aquifer level [*Wester et al.*, 2009]. These nascent bodies play a role not just in self-regulating but also in coordinating policy mechanisms including the water-energy-climate nexus approach outlined here.

5. The Water-Energy Nexus as a Policy Tool

[34] Farmers' production decisions, and thereby the water demand exerted by the crops planted, are strongly influenced by costs [*Griffin and Perry*, 1985] and returns, particularly when electricity represents a significant marginal cost. Because irrigation generally represents a relatively small fraction of the total input costs while it conveys a significant degree of risk mitigation for other factors of production (seed varieties, fertilizers, etc.), the tendency is to irrigate in excess of the crop's water requirement. This is changing as groundwater levels fall. One benign, even beneficial, outcome of overirrigation is that return flows can replenish rivers, wetlands, other surface water sources, and notably groundwater. A particularly damaging outcome, on the other hand, is waterlogging and salinization of soils as evidenced in numerous large surface irrigation systems around the world. Attempts to reduce groundwater extractions must address farmers' preference for overirrigation as a risk mitigation strategy [*Barrios et al.*, 2009].

[35] Following an economic rationale for decision making, farmers will adopt conservationist behavior when the cost of water increases to a level close to its marginal value. When costs and returns are not more closely matched, the elasticity of demand remains low and incremental price increases have little or no bearing on demand. This is the case with groundwater in many regions, where studies have shown that irrigation depths for the same crop irrigated from surface or groundwater sources were essentially the same [*Kloezen and Garcés-Restrepo*, 1998], despite the fact that groundwater cost approximately three times more than surface water. The limits to the expansion of surface water irrigated area were of course driven by water scarcity resulting in drawn down or depleted surface reservoirs. Groundwater, on the other hand, represents a much larger reservoir and unbounded demand results in increased area under groundwater irrigation and, by extension, the risk of aquifer depletion.

[36] A specific behavioral response by groundwater pumpers is set up by the large differential between fixed and recurring costs for a well. In order to recover the high capital investment, the tendency is to maximize the volume pumped. One very real though often overlooked outcome of efficiency improvements for groundwater irrigation is that the total area irrigated per well increases as a result of farmers' efforts to recover their investments. Efficiency improvement that is accompanied by downsizing of pump capacity (in other words to irrigate the same area at lower recurring pumping costs) and cropping shift to lower water demand are the only real ways to reduce groundwater overdraft through the efficiency approach.

[37] Utilizing energy pricing and supply as a tool to reduce groundwater pumping requires moving into the elastic range of demand behavior through sustained increases in power tariffs, as considered in the A2-AGW-MV-E2 scenario above. Power supply warrants some further discussion here. In order of least to most difficult or acceptable socially, politically, and technically in the Mexican context, the following nonpricing, direct control options exist: (1) restrictions on new connections, (2) caps on capacity or amperage, and (3) reductions in hours of power supply.

[38] New electrical connections for agricultural wells are granted even though the well may be in defiance of exiting

Table 2. Simulated Aquifer Water Balances Summed by State Under Carbon Emissions Scenario A2 Effects on Recharge and Agricultural Groundwater Demand With Nonagricultural Water Demand Under Medium-Variant (A2-AGW-MV) and Constant-Fertility (A2-AGW-CF) Population Projections for 2010–2100[a]

				A2-AGW-MV					A2-AGW-CF				
States[b]	Number of Aquifers Assessed	Number of Aquifers With Negative Balances, 2010	Sum of Aquifer Balances, 2010 (MCM)	Number of Aquifers With Negative Balances, 2060	Number of Aquifers With Negative Balances, 2100	Number of Aquifers With Depletion Risk, 2100	Volume (Sum) Aquifer Balances, 2100 (MCM)	Change (Volume) Annual Aquifer Balances, 2100–2010 (MCM)	Number of Aquifers With Negative Balances, 2060	Number of Aquifers With Negative Balances, 2100	Number of Aquifers With Depletion Risk, 2100	Volume (Sum) Aquifer Balances, 2100 (MCM)	Change (Volume) Annual Aquifer Balances, 2100–2010 (MCM)
Aguascalientes	4	4	−232	4	4	0	−351	−119	4	4	0	−360	−128
Baja California	14	6	−88	11	14	2	−566	−478	11	14	3	−600	−512
Baja California Sur	8	5	−119	6	7	0	−253	−134	6	7	0	−268	−150
Campeche	1	0	2099	0	0	0	1325	−774	0	0	0	1325	−774
Chiapas	13	0	8397	0	0	0	4822	−3575	0	0	0	4818	−3579
Chihuahua	18	7	−64	7	8	2	−331	−268	7	8	2	−338	−275
Coahuila	11	7	−247	8	9	1	−566	−319	8	9	1	−579	−332
Colima	10	1	215	2	2	0	71	−143	2	2	0	66	−149
Distrito Federal	0												
Durango	7	4	42	6	6	0	−80	−122	6	6	0	−85	−127
Guanajuato	11	9	−1190	9	9	2	−1757	−567	9	9	2	−1780	−590
Guerrero	6	0	292	0	0	0	260	−32	0	0	0	259	−33
Hidalgo	10	1	962	2	2	0	723	−239	2	2	0	713	−249
Jalisco	15	3	716	5	5	2	242	−475	5	5	2	213	−503
México	6	5	−604	6	6	1	−1009	−405	6	6	2	−1106	−502
Michoacán	9	2	814	2	2	0	619	−194	2	2	0	618	−195
Morelos	4	1	250	3	3	0	39	−210	3	3	0	11	−239
Nayarit	4	0	271	1	1	0	128	−143	1	1	0	120	−151
Nuevo León	10	3	119	5	5	0	−117	−236	6	6	0	−139	−258
Oaxaca	5	0	364	0	0	0	211	−153	0	0	0	208	−156
Puebla	5	1	164	3	3	0	−235	−399	3	3	0	−252	−416
Querétaro	7	4	−139	6	6	0	−271	−132	6	6	1	−296	−157
Quintana Roo	2	0	1269	0	0	0	931	−338	0	0	0	929	−340
San Luis Potosí	7	4	−154	7	7	0	−276	−122	7	7	0	−283	−129
Sinaloa	14	0	2056	0	0	0	1462	−594	0	0	0	1458	−598
Sonora	27	12	380	13	15	0	421	41	15	15	0	397	17
Tabasco	8	0	9075	0	0	0	5639	−3436	0	0	0	5633	−3442
Tamaulipas	7	0	325	2	2	0	157	−168	2	2	0	156	−169
Tlaxcala	3	0	214	0	0	0	93	−121	0	0	0	89	−125
Veracruz	10	0	2449	1	1	0	1677	−772	1	1	0	1669	−780
Yucatán	1	0	20,500	0	0	0	13,417	−7083	0	0	0	13,390	−7110
Zacatecas	23	13	−91	15	15	0	−341	−250	15	15	0	−343	−252
Subtototal northern and central	234	92	3600	123	131	10	−2198	−5798	126	132	13	−2588	−6188
National total	280	92	48,044	124	132	10	26,083	−21,961	127	133	13	25,643	−22,401

[a] Note that 1000 million cubic meters (MCM) = 1 km^3.

[b] Names of northern and central states are in bold; names of southern states are in italics.

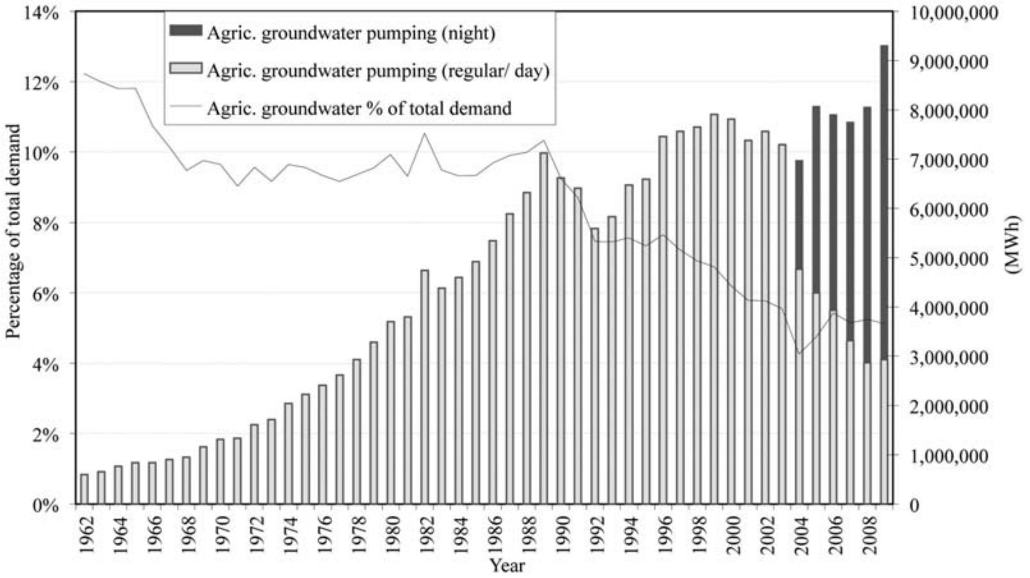

Figure 6. Agricultural energy consumption in Mexico and share of total national demand for 1962–2009. Source is Comisión Federal de Electricidad (CFE, http://www.cfe.gob.mx).

bans on new wells and hence illegal. Nevertheless, there is at present no effective parallel ban on new electrical connections; this appears to be another shortcoming of the regulatory approach to groundwater management.

[39] Amperage caps through limits to transformer capacity have been experimented with in Mexico. However, pumps must be sized to meet peak irrigation demand for the land authorized to be watered under the concession title, with the result that idle capacity may be used during nonpeak periods to irrigate additional land including through water trading or selling. Additionally, transformer installation is the responsibility of the well owner (transformers are sold by pump distributors), so voluntary capacity upgrades are now possible. Similar to the finding that failure to limit electrical connections is a lost opportunity, allowing well owners to size their own transformers appears to be a lacuna in the regulatory framework. Finally, reducing the hours of service is an energy supply control being used in other countries with groundwater overdraft and agricultural power subsidy challenges [*Scott and Sharma*, 2009].

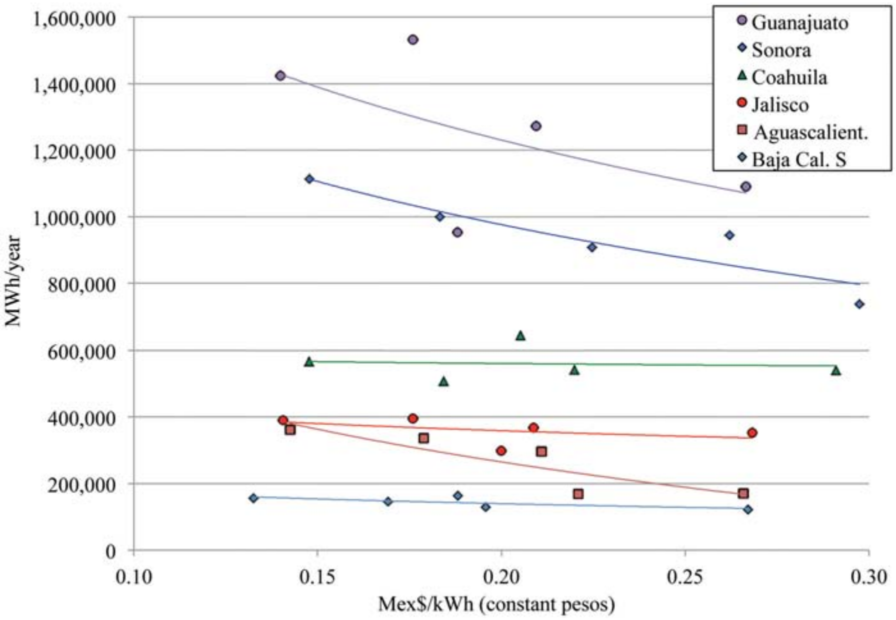

Figure 7. Price elasticities of electrical energy demand for groundwater pumping derived by regressing electricity use versus price. Selected states with high electricity use for groundwater pumping are depicted.

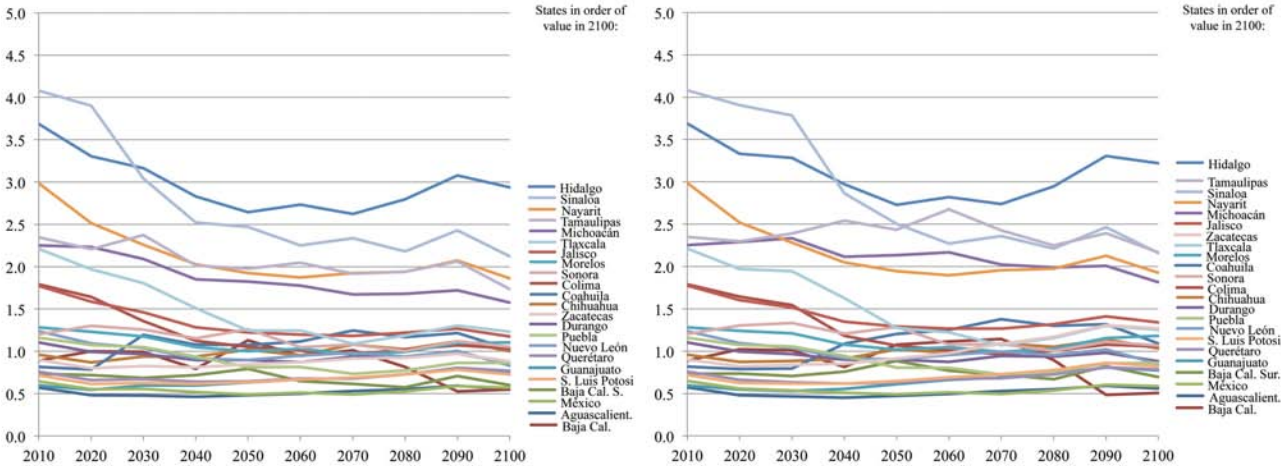

Figure 8. Dimensionless balances of the ratio of recharge to extraction for northern and central states from simulated aquifer water balances under (left) carbon emissions scenario A2 effects on recharge and agricultural groundwater demand, nonagricultural water demand under medium-variant population projection, and increases in agricultural power tariffs at 1% annually (A2-AGW-MV-E1) and (right) 2% annually (A2-AGW-MV-E2) for 2010–2100.

However, the groundwater overdraft implications of limiting hours of power supply are significant. Exercising this option in Mexico, however, would be very difficult socially and politically. Urban areas already command a disproportionate share of public services and further cutbacks, for instance, in rural power supply, could cause unrest and heighten political challenges [*Barkin and Klooster*, 2006].

6. Institutional Reform in the Water Sector

[40] The REPDA codifies water rights as mandated by the Law of the Nation's Waters (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]. It has been noted that for some aquifers, the sum total of volumetric concession titles may exceed sustainable yield [*Moreno Vázquez*, 2006], indicating an institutional tolerance for aquifer depletion. This must be considered in light of the scenarios presented in section 4, especially the power tariff policy included in the A2-AGW-MV-E2 simulation.

[41] Innovation in water management and policy in Mexico is scrutinized globally because of its 2 decades of efforts to navigate between free market and state-centric policy models [*Wilder et al.*, 2010; *Wester*, 2008; *Meinzen-Dick*, 2007; *Hearne*, 2004]. CONAGUA administers the titling and concessioning of all water rights, both to surface and groundwater sources, which are written into REPDA. 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. Concessions are granted for a specified annual volume over the period of the concession (typically 10 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. Three principal uses of groundwater are recognized: public/urban, industrial, and agricultural. Public/urban and industrial users pay for water rights. This represents an increasingly important source of revenue [*CONAGUA*, 2010b].

[42] Agriculture, which represents the largest share of groundwater extraction, does not have to pay CONAGUA for use of water. However, a process of "regularizing" agricultural rights for groundwater, even those that defied all the officials bans described above, has largely been completed, in which individual well owners (or groups of users) formalized their concessions with a title. In addition to specifying the annual volume concessioned on the basis of 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), the transfer (sale) of rights, etc. All agricultural concession titles now specify that the user must install a volumetric flowmeter and report pumped volumes to CONAGUA. This clause is not applied uniformly and users express disregard or unwillingness to install the meters. Users and CONAGUA officials alike admit that pumped volumes may exceed concessioned volumes.

[43] By way of providing context on groundwater irrigation in Mexico, it can be observed that agricultural pumps are metered and billed monthly (medium tension) or bimonthly (low tension). Groundwater extraction in Chihuahua, Guanajuato, Sonora, and other regions with deep water tables is entirely pumped using submersible or turbine pumps driven by electrical motors. Motor capacity is in the range of 75–300 horsepower, with 15–30 cm diameter discharge pipes on the pumps, yielding 20 to 400 L s^{-1}. Many wells discharge into unlined earthen channels that convey water to furrow-irrigated fields [*Barrios et al.*, 2009]. Government cost-sharing programs have resulted in growing adoption of piped conveyance and slotted-pipe delivery equipment (still largely for furrow irrigation). Drip irrigation is increasingly being adopted. Investment costs in

Table 3. Simulated Aquifer Water Balances Summed by State Under Carbon Emissions Scenario A2 Effects on Recharge and Agricultural Groundwater Demand, Nonagricultural Water Demand Under medium-Variant Population Projection, and Increases in Agricultural Power Tariffs at 1% annually (A2-AGW-MV-E1) or 2% Annually (A2-AGW-MV-E2) for 2010–2100[a]

				A2-AGW-MV-E1					A2-AGW-MV-E2				
States[b]	Number of Aquifers Assessed	Number of Aquifers With Negative Balances, 2010	Sum of Aquifer Balances, 2010 (MCM)	Number of Aquifers With Negative Balances, 2060	Number of Aquifers With Negative Balances, 2100	Number of Aquifers With Depletion Risk, 2100	Volume (Sum) Aquifer Balances, 2100 (MCM)	Change (Volume) Annual Aquifer Balances, 2100–2010 (MCM)	Number of Aquifers With Negative Balances, 2060	Number of Aquifers With Negative Balances, 2100	Number of Aquifers With Depletion Risk, 2100	Volume (Sum) Aquifer Balances, 2100 (MCM)	Change (Volume) Annual Aquifer Balances, 2100–2010 (MCM)
Aguascalientes	4	4	−232	4	4	0	−221	11	4	4	0	−218	14
Baja California	14	6	−88	9	14	1	−286	−198	3	14	1	−340	−252
Baja California Sur	8	5	−119	6	7	0	−159	−40	5	6	0	−104	15
Campeche	1	0	2099	0	0	0	1325	−774	0	0	0	1325	−774
Chiapas	13	0	8397	0	0	0	4864	−3534	0	0	0	4933	−3464
Chihuahua	18	7	−64	8	9	0	1	64	6	9	0	46	109
Coahuila	11	7	−247	8	9	0	23	270	7	9	0	80	327
Colima	10	1	215	5	5	0	12	−203	5	3	0	20	−195
Distrito Federal	0												
Durango	7	4	42	6	6	0	−55	−96	6	6	0	−49	−91
Guanajuato	11	9	−1190	9	9	0	−515	675	9	9	0	−464	726
Guerrero	6	0	292	0	0	0	260	−32	0	0	0	260	−32
Hidalgo	10	1	962	2	2	0	739	−223	2	1	0	772	−190
Jalisco	15	3	716	4	4	2	190	−526	4	4	2	326	−390
México	6	5	−604	6	5	1	−695	−91	5	5	1	−647	−43
Michoacán	9	2	814	2	2	0	492	−322	1	1	0	604	−209
Morelos	4	1	250	3	3	0	95	−155	3	2	0	155	−95
Nayarit	4	0	271	1	1	0	131	−141	1	1	0	136	−136
Nuevo León	10	3	119	4	7	0	−95	−214	4	6	0	−84	−203
Oaxaca	5	0	364	0	0	0	212	−152	0	0	0	213	−151
Puebla	5	1	164	3	3	0	−144	−308	3	3	0	−144	−308
Querétaro	7	4	−139	6	6	0	−115	24	6	4	0	−108	31
Quintana Roo	2	0	1269	0	0	0	945	−324	0	0	0	980	−289
San Luis Potosí	7	4	−154	7	7	0	−127	27	6	4	0	−74	80
Sinaloa	14	0	2056	0	1	0	1151	−905	0	1	0	1168	−888
Sonora	27	12	380	13	14	0	126	−254	12	14	0	157	−223
Tabasco	8	0	9075	0	0	0	5649	−3426	0	0	0	5678	−3397
Tamaulipas	7	0	325	0	1	0	179	−145	0	1	0	228	−96
Tlaxcala	3	0	214	1	1	0	55	−160	1	0	0	58	−156
Veracruz	10	0	2449	1	1	0	1702	−747	0	1	0	1723	−726
Yucatán	1	0	20,500	0	0	0	13,530	−6970	0	0	0	13,754	−6746
Zacatecas	23	13	−91	13	13	0	−93	−2	12	3	0	146	237
Subtotal northern and central	234	92	3600	120	133	4	688	−2912	105	110	4	1664	−1935
National total	280	92	48,044	121	134	4	29,174	−18,870	105	111	4	30,530	−17,515

[a] Note that 1000 million cubic meters (MCM) = 1 km^3.

[b] Names of northern and central states are in bold; names of southern states are in italics.

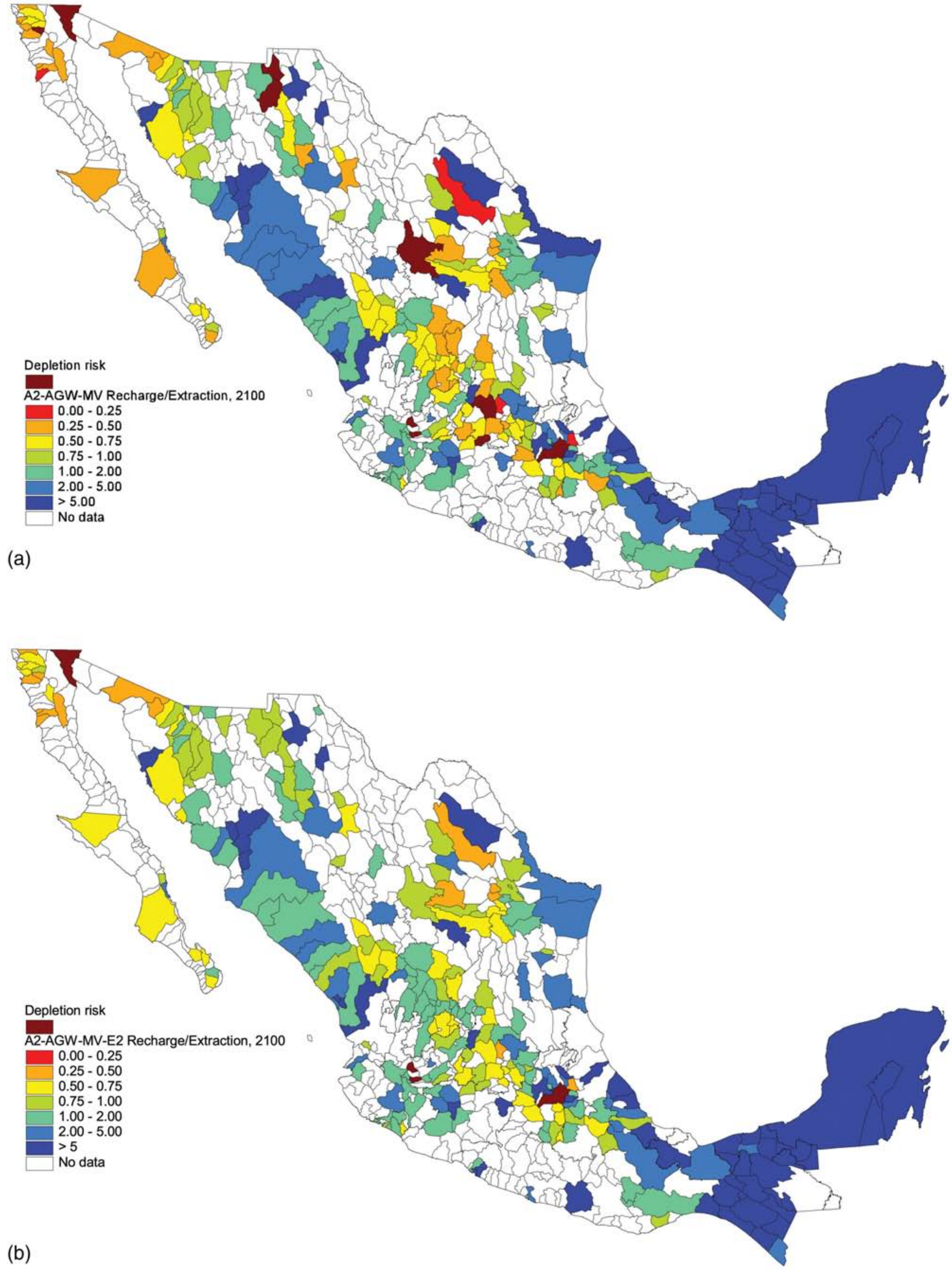
Depletion risk
A2-AGW-MV Recharge/Extraction, 2100
0.00 - 0.25
0.25 - 0.50
0.50 - 0.75
0.75 - 1.00
1.00 - 2.00
2.00 - 5.00
> 5.00
No data
(a)
Depletion risk
A2-AGW-MV-E2 Recharge/Extraction, 2100
0.00 - 0.25
0.25 - 0.50
0.50 - 0.75
0.75 - 1.00
1.00 - 2.00
2.00 - 5.00
> 5
No data
(b)

Figure 9

drip technology are currently in the range of Mex\$20,000–40,000 (US\$1700–3500) per hectare, exclusive of the well and pump.

[44] Prior to the 2003 introduction of nighttime tariffs, the CFE and the federal agricultural department (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA), whose mandate also covers livestock, rural development, fisheries and food security) issued a joint policy initiative examining various means to defray the rising costs of power supply to agriculture. In April 2002, CFE estimated that the average cost per unit of energy for agricultural use in Mexico was Mex\$0.3133 (US\$0.033) per kWh, representing a total subsidy of Mex\$5.62 billion (US\$592 million) at the national level in 2000. An equation was proposed in which SAGARPA would provide the subsidies to users who consumed less than 15,000 kWh annually, while CFE would subsidize those consuming more than this level [*SAGARPA*, 2002]. Incentives were proposed to further stimulate "irrigation technification," i.e., the adoption of drip and sprinkler technology.

[45] The tariff rationalization was adopted in December 2002, when the Chamber of Deputies unanimously passed the Rural Energy Law to regulate market mechanisms and incentives for petroleum-based energy sources and electricity use in agriculture. The law mandated a Rural Energy Program with an annual budget and implementation plan that had to be included in the federal budget. The intent of the law appeared to be to level the playing field with Mexico's principal competitors, U.S. and Canadian agricultural producers, who received similar energy subsidies.

[46] The initial regulations for the law appeared in the DOF on 7 January 2003. A new single rate tariff of Mex\$0.30 (US\$0.0316) per kWh called 9-CU was introduced for agricultural pumping under both low and medium tension. Normatively 9-CU was linked to groundwater draft; it required proof of a valid concession title from CONAGUA. Additionally, an annual energy limit (AEL) in kWh yr^{-1} was set for each well as follows:

$$\mathrm{AEL} = 438 + KVC/e \qquad (9)$$

where 438 is the lighting requirement for the well shed, $K = 0.0026$ (a units conversion constant), V is the annual concessioned volume (m^3), C is the dynamic lift equal to the depth of the well in meters as authorized in the concession title, and $e = 0.52$ is the minimum electromechanical efficiency of the pump-motor set. Consumption lower than the AEL would be billed at the single tariff of Mex\$0.30 kWh^{-1}. Electrical energy consumption that exceeded the AEL was to be billed at the regular agricultural 9 and 9M tariffs.

[47] A series of regulations published in the DOF modified the policy and application of the tariff regime. On 7 July 2003, 9-CU tariff for 2004 was set at Mex\$0.32 kWh^{-1}. A month later on 8 August 2003, the regulations were revised and a nighttime power tariff 9-N was introduced for the first time, with the preamble that "users of the 9-CU tariff should be offered the possibility of a tariff [level] that permits them the benefit of lower charges for energy in the degree to which they manage their demand and consume energy on a nighttime schedule" (author's translation of *DOF* [2003]). The 9-N tariff, applicable from midnight to 8:00 AM, was set at half of the 9-CU tariff, i.e., Mex\$0.15, 0.16, 0.17, and 0.18 per kWh for 2003, 2004, 2005, and 2006, respectively). Subsequently on 21 December 2007, the Mex\$0.01 kWh^{-1} annual increase in the 9-N tariff and Mex\$0.02 kWh^{-1} annual increases in the 9-CU and 9-M tariffs were regularized. In inflation adjusted terms, the planned increases have been 1.2% annually, in between the A2-AGW-MV-E1 and E2 scenarios presented above. As an indicator of the cascading effect of reducing power tariffs in the important agricultural sector, in June 2005, the power tariff for aquaculture was similarly reduced to half of its normal tariff. While the AEL and differential tariff provisions of the Rural Energy Law remain on the books, i.e., the law was not repealed, the 2003 and subsequent introduction of the 9-N nighttime tariff regime entirely superseded its implementation.

[48] In practice, because the main lift from the groundwater table is generally pumped at night, storage ponds at the surface are used so that irrigation distribution can be done through repumping during the day when farm labor is on hand. The general security situation in much of rural Mexico makes full-scale nighttime operations difficult. As a result, pressurizing delivery systems requires additional equipment and pumping costs, charged at the daytime power rate. Through influence and lobbying, in early 2006 farmers secured a Mex\$0.10 kWh^{-1} subsidy on daytime tariffs, paid by SAGARPA up to a total national limit of Mex\$686 million (approximately US\$62 million).

[49] What may be concluded from these overviews on electrical power pricing and institutional reforms in Mexico's water sector is that the stakes for groundwater use in agriculture are high. Lobbying and political influence exercised by farmers have been shown to effectively slow the rate of increase in power tariffs. This suggests that the 2% annual power tariff increases in real terms simulated in A2-AGW-MV-E2 above will face political challenges. Thus, from an integrated perspective on climate, agriculture, population, energy, and institutions the prognosis for groundwater balances and aquifer depletion in Mexico remains in the balance. An important policy assertion of this paper is that the energy-water-nexus opportunity presented by the 2002 Rural Energy Law must be recovered; specifically, agricultural power including nighttime tariffs will need to be raised to the level of residential domestic tariffs. Institutionally, such policy will need to be reinforced with regulatory approaches that are enforced (drilling bans concession titles, well metering, and reinstating the annual energy

Figure 9. Spatial distribution of aquifer water balances (ratio of recharge to extraction) and aquifers at risk of depletion in Mexico in 2100 under A2 emissions scenario effects on recharge and agricultural groundwater demand with nonagricultural water demand under medium-variant population projection. (a) The A2-AGW-MV scenario and (b) the effect of 2% annual increases in agricultural power tariffs (A2-AGW-MV-E2).

limit) as well as farmer-irrigator associations to pursue self-regulation.

7. Conclusions

[50] The water-energy-climate nexus described in this paper offers a new conceptual approach to understanding multiple drivers that contribute to aquifer depletion, a challenge experienced globally. Insights from the case of Mexico, especially the multiple scenario groundwater simulation results presented above, offer explanatory value for responses to the intensification of groundwater use in other regions including India and China.

[51] Agricultural use of groundwater in the context of rising temperatures coupled with variable and generally decreasing precipitation, as projected by the CMIP3 model ensemble suite for Mexico, will result in continued negative water balances for numerous aquifers particularly in the northern and central regions of the country. Population growth, although now projected to occur at rates lower than expected earlier, will drive increases in nonagricultural water demand and generate competition for groundwater currently used in agriculture. However, the incremental impact of medium-variant population growth in Mexico between 2010 and 2100 represents just 1.3 km^3 of additional groundwater demand, compared to 21.3 km^3 of additional agricultural groundwater demand simulated under A2 emissions.

[52] Groundwater management is a key challenge that requires regulatory and participatory approaches coupled with changes in demand behavior of pumpers. Where groundwater use is largely agricultural, cropping changes and water demand may be influenced by commodity prices; however, energy pricing and supply can be determinants of pumping behavior. Tariffs must be high enough to be in the elastic range of demand response, although power supply options can face social and political challenges as presented and discussed above. A sustained 2% annual increase in real power tariffs between 2010 and 2100 would reduce additional groundwater demand by an estimated 4.9 km^3, but still not bring national level balances into equilibrium.

[53] In Mexico, regulatory approaches to groundwater management have been in place, and have been largely unsuccessful, for over 50 years. The past decade's concessioning and licensing drive is an important administrative and regulatory accomplishment; water users and regulators (both government agencies and farmers' self-regulatory bodies) have the information required to address aquifer depletion challenges. Future policy formulation and program implementation that seek to arrest aquifer depletion must further develop the interlinkages described in this paper on the water-energy-climate nexus. Mexico's 2002 Rural Energy Law, superseded in 2003 by nighttime tariffs and subsequent subsidies for daytime pumping, represented an important but lost opportunity to utilize water-energy nexus interlinkages to address aquifer depletion. The analyses in this paper demonstrate that even sustained agricultural power tariff increases of 2% annually, which would place 2100 agricultural tariffs in the range of current domestic high-consumption or public service power tariffs, would be inadequate to address growth in groundwater demand for agricultural and other purposes. As a result, aquifer depletion must also be addressed through (1) the elimination of reduced nighttime tariffs, (2) enforcement of the Rural Energy Law that pegs groundwater extraction to power use, and (3) strict limits on new power connections for groundwater wells.

[54] The lessons of generic value that Mexico's case offers for other countries and regions experiencing groundwater use intensification and risk of aquifer depletion are three. First, climate change and variability may heighten agricultural groundwater demand as a result of variable surface flows. Additionally, for those water-scarce regions where precipitation is projected to decline over the long term (coupled with increased temperatures that all regions are expected to experience), adaptation to climate change that solely relies on increased recourse to groundwater, i.e., without effective conjunctive management of groundwater and surface water through the simultaneous management of demand and groundwater recharge via stormflow capture, is neither sound nor sustainable. Second, the strategic value of groundwater for nonagricultural demands, especially urban supplies, will likely outcompete agriculture for scarce water. The water demands for thermoelectric power generation were not explored here for lack of disaggregated data. Nevertheless, expanding electrical power generation resulting from increasing electricity demand for a range of climate adaptation activities (cooling, agricultural groundwater pumping as described here, urban water supply to cope with variable and warming climate, etc.) will undoubtedly exert pressure on water resources. Power generation water demands should be considered to have strategic value, like urban supplies, that will compete for agricultural groundwater. Third and finally, the energy component of the nexus offers both risks and opportunities. As a primary driver of agricultural groundwater demand, rural electrification has ushered in a range of welfare benefits despite the insidious contribution to negative groundwater balances and aquifer depletion. Yet the opportunities provided by power pricing, demonstrated here in technical and economic terms, will need to be seized socially and politically through forward thinking policy, for example, the implementation of power supply limits as proposed in Mexico's Rural Energy Law. Groundwater demand does not need to be self-limiting, i.e., depleted aquifers with seriously deteriorated water quality are not necessarily the only brakes on demand. Instead, with growing social and environmental impacts of expanding groundwater depletion, managing demand using the water-energy-climate nexus may become an imperative and a tool sooner than expected.

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