Electricity for groundwater use: constraints and opportunities for adaptive response to climate change

Christopher A Scott

School of Geography and Development, and Udall Center for Studies in Public Policy, University of Arizona, 803 East First Street, Tucson, AZ 85719, USA
E-mail: cascott@email.arizona.edu

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Abstract

Globally, groundwater use is intensifying to meet demands for irrigation, urban supply, industrialization, and, in some instances, electrical power generation. In response to hydroclimatic variability, surface water is being substituted with groundwater, which must be viewed as a strategic resource for climate adaptation. In this sense, the supply of electricity for pumping is an adaptation policy tool. Additionally, planning for climate-change mitigation must consider CO₂ emissions resulting from pumping. This paper examines the influence of electricity supply and pricing on groundwater irrigation and resulting emissions, with specific reference to Mexico—a climate–water–energy ‘perfect storm’. Night-time power supply at tariffs below the already-subsidized rates for agricultural groundwater use has caused Mexican farmers to increase pumping, reversing important water and electricity conservation gains achieved. Indiscriminate groundwater pumping, including for virtual water exports of agricultural produce, threatens the long-term sustainability of aquifers, non-agricultural water uses, and stream–aquifer interactions that sustain riparian ecosystems. Emissions resulting from agricultural groundwater pumping in Mexico are estimated to be 3.6% of total national emissions and are equivalent to emissions from transporting the same agricultural produce to market. The paper concludes with an assessment of energy, water, and climate trends coupled with policy futures to address these challenges.

Keywords: climate change, adaptation, policy, groundwater, water–energy nexus, virtual water, Mexico

1. Introduction

The combined effects of climate change, surface-water diversions, and groundwater pumping for human use threaten water security in an increasing number of regions around the world (Vörösmarty et al 2010). Humans exert ever-growing impacts on the Earth system, especially on water resources (Sivapalan et al 2012). A principal concern is the future availability and reliability of water resources for energy development (Hightower and Pierce 2008, King et al 2008) and electrical power generation in particular (Grubert et al 2012, authors of articles in the present focus issue ‘Electricity, Water and Climate Connections’ in Environmental Research Letters). Conversely, energy demands for water extraction, conveyance, treatment, and reclamation will continue to grow in the future. The temporal trends and spatial distribution across world regions of the energy-for-water nexus have profound implications for urbanization, agriculture and food security, and ecosystem services. In addition to research...
on joint energy–water resource assessments and biophysical dimensions of the nexus, there is growing recognition of the policy challenges and opportunities that coupling these two resources present (Scott et al 2011), especially for climate-change adaptation and mitigation (Bazilian et al 2011).

This paper examines electricity, water and climate connections with specific reference to groundwater—a resource of growing strategic and economic importance globally that is vulnerable to climate change (Doll 2009, Treidel et al 2012) and overexploitation that can lead to depletion (Aeschbach-Hertig and Gleeson 2012). Climate change is a force-multiplier for groundwater (Shah 2009), i.e., it tends to increase demand while reducing recharge. Around the world, groundwater accounts for a growing share of water supply for agricultural irrigation, which is the highest volume use for human purposes (Siebert et al 2010). Because of the energy-intensive nature of groundwater pumping, this represents a unique form of the water–energy nexus in which water is required to generate many forms of electricity that is used to pump groundwater. A further ‘nexus loop’ comes into play when groundwater is used for thermoelectric cooling or concentrated solar generation—practices that are increasingly being adopted in water-scarce regions (King et al 2008, Siddiqi and Anadon 2011, CONAGUA 2013).

Such manifestations of the electricity–groundwater nexus raise important questions for adaptation to concurrent processes of global environmental change, including climate change, globalization of food systems, and water-dependent ecosystem services, among others (Scott et al 2013). The conceptual approach and empirical analysis presented in this paper build on and extend past work (Scott 2011, which explored the groundwater depletion impacts of climate and energy supply scenarios), in particular by furthering scientific and policy understanding of the interconnections among electricity supply, groundwater use, and adaptive responses to climate change. The case of Mexico is presented as an especially compelling and instructive example, given its fossil-fuel dependence for power generation, major dependence on groundwater for irrigation and other water demands, and geographical location and vulnerability to climate-change impacts. First, the hydroclimatic and human drivers of groundwater use are summarized. This is followed by an assessment of the current electricity–groundwater nexus and resource demand patterns, including the virtual export of water and electricity consumed in the production of agricultural commodities transported beyond national borders. Finally, a broader set of policy implications and adaptive response options are presented and assessed.

2. Climate change and hydrological variability drive groundwater demand

Climate change influences hydrological processes over the short- to long-term and directly impacts water resources across a range of spatial scales (Milly et al 2008, Lođiçiga 2009, Roy et al 2012). Despite emblematic extreme events like Hurricane Sandy in 2012, water scarcity and quality degradation will be among the chronic water-resources challenges of climate change in the future, especially in arid and semi-arid regions. Extended drought, heat waves, wildfires, and declining water levels in storage reservoirs are just some of the more visible symptoms. Added to these biophysical drivers and impacts on water resources, human water demands are increasing both in response to hydroclimatic change and variability and as a consequence of population growth, economic development, and ecosystem conservation imperatives.

2.1. Projected climate

Climate-model projections of temperature and precipitation are in broad agreement for numerous regions around the globe that already experience water scarcity. While specific impacts vary by location, the combination of increasing temperatures and more variable precipitation will negatively affect the physical availability of water (Bovolo et al 2009). Mid-latitude precipitation is projected to be variable and to decline over the 21st century under higher carbon-emission scenarios, further exacerbating water availability for human and ecosystem purposes (Burkett et al 2005).

Differnaugh and Giorgi (2012) assessed the CMIP5 ensemble’s RCP8.5 simulations (with greenhouse gas concentrations exceeding 1370 ppm CO$_2$–e by 2100, radiative forcing of $\sim$8.5 W m$^{-2}$, and median global warming of 4.9 °C above pre-industrial levels). They identified Central America and Western North America, among other regions, as climate-change hotspots. Temperature increases of 4–5 °C are projected, comparing 2080–2099 with the 1986–2005 reference period for both December–January–February (DJF) and June–July–August (JJA). Based on the same reference and future time periods, precipitation decreases of 10–30% for DJF and 0–20% for JJA were projected. Knutti and Sediľáček (2013) compared CMIP5 and IPCC AR4 projections, accounted for differences in emissions scenarios, and found the temperature and precipitation projections between the two model ensembles to be similar in magnitude, time of onset, and spatial distribution across Central America and Western North America. These findings reinforce the water-resource implications of studies based on the AR4 ensemble (Scott 2011, which this paper builds upon) plus the observational record (Matías and Mañá 2010, Brito-Castillo 2012) and indicate that under CMIP5 projections arid and semi-arid regions of central and northern Mexico will face heightened climatic drivers of water scarcity.

2.2. Variability and adaptive response

Hydrologically, rainfall–runoff response to precipitation variability and changes in seasonality results in more variable streamflow in northwestern Mexico (Gochis et al 2006), which in turn makes surface water a less reliable source of supply for irrigation and other human uses, even with surface storage reservoirs. As a result, increased pumping of groundwater has been documented (CONAGUA 2011). At the same time, groundwater recharge is likely to decrease
Based on the projected precipitation declines in winter when much of the recharge in arid regions occurs (Flint and Flint 2007). Thus, the combined effects of projected increased temperature, variable and declining precipitation, and reductions in winter precipitation (Gutierrez-Ruacho et al. 2010) will drive increased use of groundwater resources in central and northern Mexico.

Groundwater-use intensification raises important questions for adaptation. Over the short term, substitution of groundwater for surface water is an important supply strategy; however, increasing demands with variable or declining recharge over time can undermine this approach. The principal challenges are reliable availability of water over the long term, surface-water capture and streamflow depletion resulting from drawdown of shallow aquifer levels (Barlow and Leake 2012), energy supply and associated emissions for groundwater extraction (energy supply and pricing issues will be presented and discussed in section 3.1, below) especially in relation to the viability of irrigated agriculture, and the central importance of groundwater for agricultural productivity and rural livelihoods. In this context, the sustainable use of groundwater can represent an adaptive strategy if appropriate management systems are in place to constrain overuse and depletion while safeguarding human dependence (particularly food security) and ecosystem reliance on groundwater. Effective approaches to groundwater management more generally are beyond the scope of this paper but have been addressed elsewhere (Aeschbach-Hertig and Gleeson 2012, Shah 2009, among others).

### 3. Electricity–groundwater nexus

For millennia humans have extracted shallow groundwater from open wells and dewatered mines using a variety of lift devices and power sources. With innovations in steam technology and the advent of electrical pumps, by the late 19th century humans possessed both the technology and energy to exert appreciable impacts on groundwater (Wescoat 2013). With rural electrification in the early to mid-20th century, countries that today pump the greatest volumes of groundwater (India, China, United States, and Mexico to name a few) transformed their irrigation sectors. In water-scarce regions, however, electrical pumping of groundwater has raised a series of challenges for water-resource planning, riparian ecosystem dynamics, and the social and economic viability of groundwater-dependent farming. These are explored briefly in this paper considering Mexico’s past experience, present juncture, and future trajectory.

#### 3.1. Mexico—‘perfect storm’

Three central factors make central-northern Mexico especially sensitive to climate, water, and energy interactions. First, this region is experiencing water scarcity driven by climate change, hydrological variability, and human demands for water as indicated above. Second, groundwater irrigation has been a mainstay of agriculture and livestock production for at least the past three decades. Official January 2013 data put current agricultural and livestock use of groundwater nationally at 18.91 km³ year⁻¹ (of a total of 31.23 km³ of groundwater used for all purposes) compared to 49.44 km³ of surface water used for all purposes excluding hydroelectric generation, considered a non-consumptive use (CONAGUA 2013). The National Water Commission (Comisión Nacional del Agua, or CONAGUA) is actively seeking to reduce the total volume of groundwater it concessions for irrigation in overexploited aquifers and to grant new concessions in aquifers currently deemed to have ‘availability’ (disponibilidad). On paper, agricultural groundwater (AGW) concessions have decreased by 1.96 km³ over the 2009–2013 period; nevertheless, groundwater remains over a third of the total water (55.41 km³) allocated to agriculture and livestock and generates an even larger share of the economic returns from this sector. Third, Mexico’s electrical generation portfolio is dominated by fossil fuels (CFE 2013, Sheinbaum-Pardo et al 2012, Santoyo-Castelazo et al 2011), making the connections among electricity, water, and climate especially pronounced. The use of groundwater for electricity generation referred to in the introduction, above, is evidenced by four concession titles for this purpose in the states of Baja California Sur, Nuevo Leon, and the Distrito Federal.

Based on the data presented in table 1, agricultural groundwater pumping in Mexico in 2009 resulted in estimated emissions of 4.7 million metric tons of CO₂, equivalent to 3.6% of total national fossil-fuel emissions of 129.8 million metric tons in 2008 (Boden et al 2011). In locations with deep dynamic pumping lifts, up to 0.22 kg CO₂ was emitted per m³ of groundwater pumped.

The states with the highest volumes of groundwater pumped for irrigation are Chihuahua and Sonora in the northwest and Guanajuato in the center of the country (see figure 1). Subsequent analysis and discussion will focus on these as being especially illustrative of electricity, water and climate connections. New wells are declared banned in aquifers listed by CONAGUA as overexploited; this applies

### Table 1. CO₂ emissions by fuel type and generation portfolio in Mexico.

| Fuel                          | Lbs. CO₂ kWh⁻¹ | Metric tons CO₂ MWh⁻¹ | Generation mix in Mexico b (%) |
|-------------------------------|----------------|-----------------------|--------------------------------|
| Coal                          | 2.09           | 0.9485                | 6.7                            |
| Natural gas                   | 1.12           | 0.5091                | 47.3                           |
| Oil                           | 1.61           | 0.7318                | 27.0                           |
| Hydropower, geothermal, wind, solar | —              | —                     | 19.0                           |
| Composite across generation portfolio | 1.10         | 0.5017                | 100                            |

a Source: www.eia.gov/tools/faqs/faq.cfm?id=74&t=11.

b Source: compiled from CFE (2013).
Figure 1. Map of Mexico showing states that pump the greatest volumes of groundwater.

to 100 aquifers nationally (of 653 total assessed), 11 in Chihuahua (of its 61 total), 11 in Guanajuato (18 total), and 12 in Sonora (60 total).

Electrical power tariffs vary by type of connection, time of day, and region. A subsidized tariff (known as tarifa 09) is available ‘for pumping water for agricultural irrigation’ (CFE 2013). A special ‘night-time stimulus’ tariff for pumping water for agricultural irrigation (09-N, applicable for pumping between midnight and 8:00 AM) was introduced in 2003 but began in force in 2004. It should be noted that a negligible amount of surface water is pumped for irrigation; hence, 09 and 09-N provide excellent proxies for agricultural groundwater use (Muñoz et al 2006). The average daytime 09 tariff is US$ 0.048 kWh\(^{-1}\) while 09-N is US$ 0.039 kWh\(^{-1}\), compared to tariffs of US$ 0.227 kWh\(^{-1}\) for public service, US$ 0.234 kWh\(^{-1}\) for low-tension general use, and US$ 0.093 for medium-tension general connections. In other words, electricity for groundwater pumping is subsidized by a factor of two to four times compared to commercial rates, while night-time pumping is subsidized by an additional 20% below daytime rates.

The ‘stimulus’ effect of 09-N to induce the shift from day- to night-time pumping occurred across the country (figure 2(a)) and is evident for the three states of interest (figures 2(b)–(d), which also show trends in the fraction of electricity for agricultural groundwater pumping to total supply). Night-time irrigation often involves additional costs to construct farm ponds to store water pumped until farm labor is available for operations during the day. This may require subsequent pumping to pressurize irrigation equipment including drip and sprinkler systems. In some cases, solar-powered pumps are used for low-pressure applications like drip irrigation, but grid-power remains essential for deep pumping.

The switch to night-time supply in 2004 has resulted in increases in groundwater withdrawals at the national level, even when accounting for the effects of falling water levels that require more electricity to pump a given volume of water (Scott 2011). The continued increase in pumping is most pronounced in the state of Chihuahua, where irrigation that currently consumes over a quarter of all electricity in the state pumps almost 6 km\(^3\) of groundwater per year—an increase of 44% in just three years from 2010–2012. Here electricity for AGW pumping increased 9.6% year\(^{-1}\) over the eight years following 2004 compared to a 4.0% year\(^{-1}\) for the preceding eight years (even while total power supplied in the state for all purposes slowed its rate of growth after 2004). More seriously—but conversely, relatively straightforward to address from a policy perspective—Chihuahua continued to add new AGW users (new electrical connections) at a compounded rate of 3.3% year\(^{-1}\) after 2004; Sonora and Guanajuato added new AGW users at 2.0% and 0.9% year\(^{-1}\), respectively, after 2004. Additionally, to mitigate drought conditions in Chihuahua (INE 2013), which the governor categorized as ‘catastrophic’ (Milenio 2012), the federal and state governments responded to lobbying efforts by large farmers and wrote off a portion of farmers’ unpaid electricity bills estimated to total over US$ 200 million in this state alone (Jornada 2012). These trends have important implications for resource-use sustainability (see figure 3), and as will be discussed below, offer opportunities for adaptation to climate change.

Further assessment of the primary policy mechanism to manage groundwater in Mexico—the concession title—indicates that in 2009 AGW volumes pumped exceeded AGW volumes titled by an estimated 1.36 times as seen in figure 3. Indeed, questions have been raised whether the sum total of concession titles for a given aquifer are, in fact, determined
3.2. Virtual exports of groundwater and energy

Much of the AGW in the three states of interest (and others in Mexico’s central-northern region) is used to produce high-value vegetables and, to a lesser extent, fruit. In turn, a significant portion of the produce is exported, largely to the United States but also to markets in Europe and Asia. Virtual water, the volumes required to irrigate crops that are imported and exported across national borders, can represent an important offset for the local or regional use of water (Konar et al. 2012). Mexico’s annual net imports of virtual water are reported to be 12.5 km$^3$ in agricultural products and 10.6 km$^3$ in animal products (CONAGUA 2011). It should be noted that these virtual water imports are primarily from Mexico’s largest trading partner, the US, where production of the commodities in question is derived principally from ‘green water’ (rainfall) but also some ‘blue water’ (surface water and groundwater). Mexico’s virtual water exports are, in contrast, chiefly groundwater for vegetable and fruit production that contribute to aquifer depletion. Because groundwater, compared to rainfall, has high strategic value for future potable-water supply and other climate adaptation purposes, caution must be exercised in the rationale used to balance or cancel virtual water imports and exports.
Regional and global virtual water trade drives aquifer depletion in certain locations in Mexico that are also experiencing rapid urban growth and demand for groundwater. In this sense, groundwater use is currently caught in an inter-generational equity trap, i.e., the near-term gains of export-oriented agriculture trade off against the longer-term strategic value of groundwater for multiple societal demands including urban water supply.

Estimates of the virtual water required to produce Mexico’s vegetable and fruit exports to the US are based on US Department of Agriculture statistics on imports from Mexico. Recent increases in virtual groundwater and total virtual water exports are shown in figure 4, with approximately 1 km$^3$ of virtual groundwater exported from Mexico to the US in 2009. The electricity used to pump this volume of groundwater generated approximately 0.19 million metric tons of CO$_2$ emissions, which are on the same order of magnitude as the CO$_2$ emitted in transporting the produce by road an estimated average distance of 300 km to export markets in the US.

Groundwater pumped to irrigate produce that is not exported beyond Mexico’s borders but consumed within the country, e.g., in large urban markets like Mexico City, is very considerable. Additional groundwater is pumped to irrigate low-value produce (e.g., staple grains) that could be grown under rainfed conditions (although with lower yields and higher risk), using surface water (with inherent challenges of supply variability), or they could be imported. Indeed, all three alternatives occur in Mexico; however, inadequate policy support (particularly in crop insurance, risk offsets, and longer-term food security planning) will maintain pressure on groundwater (Wester 2008).

3.3. Policy tool for adaptation and mitigation

The potential to harness the electricity–groundwater nexus for sustainable aquifer management relies on policymakers and groundwater users identifying effective interventions in supply and pricing of electricity (Scott and Shah 2004, Shah 2009) and other support mechanisms that are both politically feasible and acceptable to all farmers in order to offset detrimental impacts to users including through cash transfers and incentives to change cropping patterns, reduce irrigated area, and adopt water-saving technologies.
4. Conclusions

Coupled natural-human processes are central to the global water crisis and its regional manifestations (Srinivasan et al 2012), which are connected to a set of energy challenges (Hightower and Pierce 2008) and climate futures (Scott 2011). The water-for-energy nexus explored in the present ERL special issue is a major opportunity for resource management and policy. While case examples such as Mexico presented in this paper offer specific insights on the interconnections among electricity, water, and climate, they can also be used to identify a broader set of resource-use patterns, policy implications, and adaptive response options.

The discussion above has shown that climatic processes resulting in variable surface-water availability tend to shift human demand to groundwater as a more reliable source of supply. Short-term use that contributes to depletion or quality degradation can undermine groundwater’s strategic value as a resource for adaptation to the increasingly extreme effects of drought resulting from climate change especially for agriculture, which will require additional water to maintain production per unit of land and value of output. Behind the rapid expansion of groundwater are successful electrification programs that have transformed the rural landscape economically, socially, and biophysically. Yet groundwater-dependent regions such as central-northern Mexico are rapidly approaching or passing sustainable levels of groundwater use. Once depleted or with significantly impaired water quality, aquifer degradation is essentially irreversible, although over long timescales and with significant changes in water use recovery may be possible.

Continued overexploitation and heavy reliance on fossil-fuel electricity for groundwater pumping are neither adaptive over the medium to long term nor are they sound approaches for emissions mitigation. By contrast, sustainable use of groundwater can represent an adaptive response to climate change if water and energy resources are managed jointly, including the judicious removal of subsidies for electricity used to pump groundwater. This would strengthen three central policy goals of: (1) maintaining or enhancing human well being by safeguarding groundwater for drinking water supply and livelihood support, (2) protecting the integrity of ecosystem services by ensuring streamflow for riparian habitats and human amenity values, and (3) curbing emissions.

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(Muñoz et al 2006). The nexus can also represent one of several tools to adaptively respond to global environmental change, chiefly through climate adaptation and mitigation actions. Coordinating policies for water (e.g., bringing titled water volumes in line with renewable supplies, maintaining strategic buffer reserves of water for future contingencies that will inevitably ensue from climate change, and investing in managed aquifer recharge) as well as for energy (e.g., phased removal of tariff subsidies as analyzed in detail by Scott 2011, with demand management and limits on energy consumption to limit emissions) presents real opportunities. In Mexico, state climate action programs do not currently use these policy levers (Landa et al 2012), although recognition is growing that the electricity–groundwater nexus is both a driver and a potential adaptive response to climate change.
