“Well-fare” Economics of Groundwater in South Asia

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Groundwater exploitation has been instrumental in raising agricultural productivity and reducing rural poverty in South Asia, a region that accounts for nearly half of the global groundwater used for irrigation. Over the past three decades there has been an explosion of private investment in borewells and mechanized pumps, which has allowed access to groundwater to be widely shared. But this profusion of drilling and pumping has also led to serious groundwater depletion. This essay explores South Asia’s groundwater dilemma through the lens of welfare economics, drawing on evidence from India and Pakistan gleaned from a variety of sources ranging from agricultural censuses to specialized surveys. Policies to arrest groundwater depletion are also discussed. JEL codes: Q15, Q25

Groundwater is being exploited at a breakneck pace across the Asian sub-continent. As borewells have sprung up by the millions in recent decades, groundwater, which is especially vital for dry-season cultivation, has become the paramount irrigation source in India and, in Pakistan’s vast Indus basin, a critical buffer against the vagaries of canal irrigation. Although much has been written about this transformation and its contribution to agricultural intensification (Briscoe and Malik 2006; Shah 2010), our understanding of South Asia’s groundwater economy remains inchoate and dispersed across multiple disciplines.

To structure what we know, and still need to know, this essay asks five interrelated questions:

- What is the link between poverty and access to groundwater?
- What is the private return to well-drilling and how does it differ from the social return?
- Is groundwater overexploited?
- What is the allocative role of groundwater markets?
- What policies can restrain groundwater exploitation?

The World Bank Research Observer

doi:10.1093/wbro/lkw008 32:1–20

In addressing these questions, I will highlight relevant work from several diverse bodies of literature and rummage through the welfare economist's toolkit, informing my analysis with data from India (some new), as well as from Pakistan's Punjab, the province with the lion's share of that country's accessible groundwater.

Globally, South Asia is far and away the largest user of groundwater for irrigation, with an estimated 262 km^3 of abstraction annually (Siebert et al. 2010), followed distantly by North America (principally the United States) with 100 km^3, the Middle East with 71 km^3, East Asia (principally China) with 58 km^3, and Northern Africa with 16 km^3. While these figures alone justify my regional focus, at least some of the lessons drawn from the South Asian experience apply to the other groundwater hotspots of the developing world.

South Asia's Borewell Revolution

In sheer numbers, the explosion of groundwater-lifting devices used South Asia since the 1970s has been virtually unprecedented in the annals of private-sector development. There are now at least 20 million mechanized wells of one kind or another across India and Pakistan.[1] Official census figures since the mid 1990s, pieced together in table 1, corroborate this central narrative and provide some interesting sub-plots as well.

Before borewell drilling rigs roamed the Indian countryside, most groundwater was drawn from large-diameter open dugwells. Typically, these brick-lined dugwells were equipped with surface (centrifugal) pumps powered by either electricity or diesel. Surface pumps create a vacuum and use atmospheric pressure to push water up to ground-level, which means that, in practice, they can generate about 8 meters of suction lift. Despite this limitation, surface pumps are the norm in Pakistan, even where water tables fall below 8 meters. The reason for this is that a surface pump can be deep-set in a dugwell and run (using a belt drive) from a motor at the surface. For example, a pump set down a 7 meter dugwell drawing water from an 8 meter borehole can be effective at water table depths of 15 meters, which is quite adequate for most of Punjab.[2]

For much of India, however, deep water tables render surface pumps infeasible. Here, the only option is an integrated centrifugal pump and electric motor that can be lowered into the borehole below groundwater level. Although these submersible pumps are more expensive than their surface-mounted cousins, they can extract water at depths of up to 200 meters. As water tables have fallen in India and the principal technologies to go after this deep groundwater—mechanized well-boring and submersible electric pumps—have become cheaper and more

Table 1. Census Counts of Irrigation Wells in Pakistan and India

Country	Province/State	Census	Year	Tubewells		Dugwells[c]
				Number (millions)	Electrified (fraction)	Number (millions)
Pakistan	Punjab[a]	*Ag. Machinery*	1994	0.41	0.15	—
			2004	0.82	0.07	0.01
India	All	*Minor Irrigation*	1994	5.53	0.39	6.08
			2007	9.83	0.45	9.20
	Andhra Pradesh		1994	0.32	0.93	1.22
			2007	1.18	0.97	1.01
	Punjab		1994	0.94	0.34	0.02
			2007	1.17	0.87	0.00
	Uttar Pradesh		1994	1.99	0.16	0.14
			2007	4.13	0.10	0.13
	All	*Agricultural*	1995	6.05	0.49	6.71
			2010	10.5	0.61	10.1
	Andhra Pradesh		1995	0.52	0.96	0.86
			2010	1.56	0.99	0.87
	Punjab		1995	1.49	0.55	0.03
			2010	1.44	0.81	0.02
	Uttar Pradesh		1995	1.12	0.29	0.43
			2010	0.34[b]	0.15	0.12

Note: [a]indicates that about 90% of Pakistan's tubewells are located in Punjab province; [b]This figure seems too low by an order of magnitude. The 2005 Agricultural Census shows 1.73 million tubewells in UP (of which 12% are electrified) whereas the UP irrigation dept. website gives a figure of 2.86 million tubewells (undated). Both of these numbers are still much lower than the above Minor Irrigation Census figure for 2007; [c]Only wells with motorized pumps. No data for 1994.

widely available, farmers have shifted out of dugwells and into borewells (or tubewells, which I will use synonymously).

What sets Pakistan—which is to say Punjab Province, with 90% of the country's tubewells—apart from much of India is the dense network of canals that comprise the vast Indus basin irrigation system. This colonial-era legacy has radically altered the natural aquifer recharge pattern in the areas circumscribed by Punjab's five rivers, leading to uniformly higher water tables therein. According to the most recent Agricultural Census, nearly half of Punjab's cultivated area is irrigated under so-called conjunctive use, that is, combining surface water and groundwater from tubewells; 18% by tubewells alone, and only 15% solely by canals.[3] In practice, this means that groundwater is most commonly used in Pakistan to buffer shortfalls in canal irrigation (see Jacoby et al. 2004 for evidence from a single watercourse in southern Punjab).

Census data reported in table 1 record a doubling in the number of tubewells in Punjab over a single decade. By 2004, a mere 7% of mechanized wells were run on electricity. The preponderance of diesel pumps in Pakistan stands in stark contrast to the situation in India, where, in recent years, electric power has become progressively (and artificially) cheaper, if not free, in most states.[4] Additionally, as already discussed, only a minute fraction of pumps in Pakistan are submersible; thus, electricity is not a necessity. Given that the marginal cost of pumping is equal to the diesel cost in Pakistan, whereas it is essentially zero in most of India, it is not surprising that the role of groundwater in agriculture has evolved very differently in the two countries. During the dry season, Indian farmers are typically running their pumps continuously for as long as power is available each day. This power constraint determines how much land they can cultivate in the season, which crops they can grow, and how much groundwater they can sell.

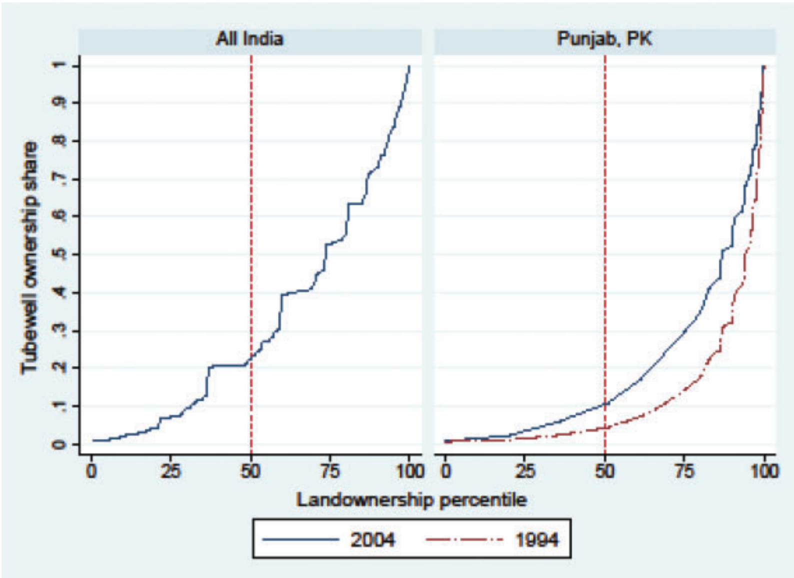
Whereas Pakistan has a single census providing a count of tubewells, India has two. Unfortunately, since data from the Agricultural and Minor Irrigation censuses are not entirely concordant, there is considerable uncertainty about the number of tubewells in India today. The latest figure of 10.5 million, derived from India's 2010 Agricultural Census, is marred by what appears to be a massive undercount of tubewells in Uttar Pradesh (see table 1). But the last Minor Irrigation Census shows that there were still under 10 million tubewells in India as of 2007. So the gap between these two sources may be as high as two or three *million* wells![5]

Nevertheless, the two Indian censuses show common trends, with the number of tubewells increasing at a faster rate than the number of dugwells, especially in some key states, and the proportion of electrified pumps rising, reflecting the recent dominance of the submersible technology.[6] Contrasting two major agricultural states of India, Punjab in the north and Andhra Pradesh in the south, we see that, while the number of borewells has tripled in AP over the 15 years of census data, the count in Punjab has remained stable. This latter stability, however, masks a nearly 60% *decline* in the number of diesel-powered borewells combined with a 43% increase in the number of electric-powered borewells. Evidently, falling water tables in northwest India have effectuated a massive shift out of surface pumps. In AP, diesel pumps represent just a tiny (and declining) share of the market.

Groundwater and Poverty

Has improved access to groundwater, as documented in table 1, reduced poverty in South Asia? As it stands, this is not a well-posed question. Even if areas of intense groundwater exploitation were less poor, correlation does not imply causation. The link between poverty and access to groundwater is a two-way street: On the one hand, access to groundwater allows for more intensive cultivation, which is a boon to farmers and to agricultural workers more broadly. On the other hand, insofar as borewell investments are financed out of agricultural surpluses, wealthier farmers are

Figure 1. Concentration of tubewell ownership.
Note: Cumulative proportion of households owning tubewells at each percentile of landownership distribution for India (2004 IHDS-I) and Punjab, Pakistan (1994 and 2004 Agricultural Machinery Census).

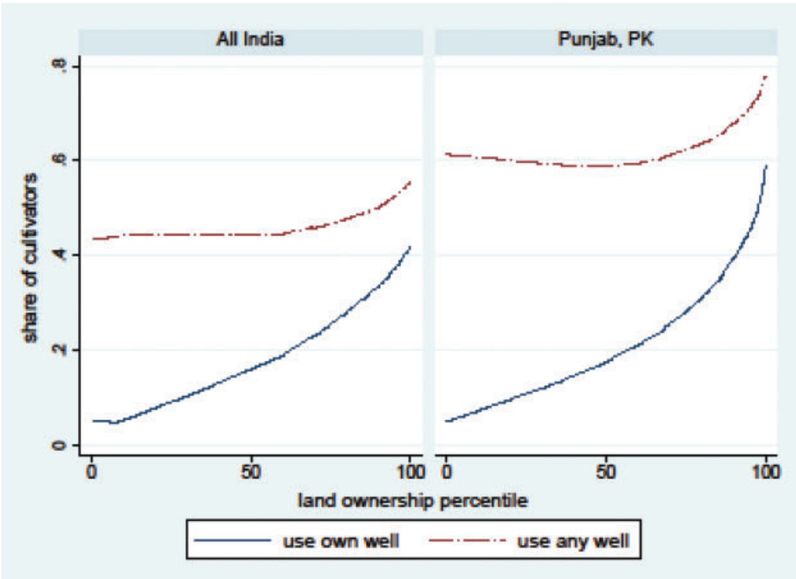


more likely to have access to groundwater; at least, they are more likely to own a well. So access to groundwater reduces poverty, but poverty reduces access as well.

Consider now the concentration of borewell ownership in India and Pakistan with respect to the distribution of landholdings as shown in figure 1. Unlike an income or a consumption-based measure of living standards, landholdings is plausibly exogenous with respect to well investments (land transactions are extremely rare). At any rate, borewell ownership is much more concentrated in Pakistan than in India; the bottom 50% of landholders own one-fifth of India's borewells, but only one-tenth of Pakistan's. Despite the inequality in well ownership in Pakistan circa 2004, the situation is better than in 1994 when the bottom half of landholders owned only around 5% of borewells (figure 1). Thus, in Pakistan at least, much of the recent tubewell development has been among poor farmers. Nevertheless, the upshot of figure 1 seems to be that poverty limits access to groundwater in South Asia.

Before jumping to this conclusion, however, we need to distinguish tubewell *ownership* from access to groundwater, or tubewell *use*. That is, we should ask to what extent groundwater markets fill the tubewell ownership gap in South Asia: figure 2 suggests quite a bit. Based on Agricultural Census data (Pakistan) and

Figure 2. Distribution of tubewell ownership vs. use.
Note: Proportion of cultivating households owning and using tubewells at each percentile of landownership distribution for India (2010 IHDS-II) and Punjab, Pakistan (2010 Agricultural Census).



nationally representative household survey data (India) circa 2010, we see that for the bottom three-quarters of agricultural households (in terms of land ownership) the share of cultivators using groundwater is roughly constant, rising with landholdings only in the top quartile.[7] Across the region, *access* to groundwater does not increase with wealth nearly as much as does ownership of the means to extract it. This fact gives rise to a key question: are the resource rents from groundwater exploitation as equitably distributed as groundwater access? The answer hinges on the industrial organization of groundwater markets (i.e., how competitive they are).

Returning to our main question—has groundwater access been poverty-reducing—we see now that it is nontrivial for two reasons: because of simultaneity between poverty and groundwater access, and because groundwater can be accessed through markets as much as through well ownership. So, how would one go about estimating the counterfactual distribution of rural wealth (or income) in the absence of groundwater access? Broadly speaking, there are two empirical approaches. An *ex ante* approach would first estimate the private *net* return to well drilling for a household in terms of an income flow and then subtract this return off of the income of a well-owning household to get the counterfactual income distribution. There is a problem with this exercise, but not one of feasibility; indeed, later on I will report plausible estimates of the return to well-drilling in an entirely different context. The problem, or rather the implicit assumption, with this approach is that it attributes all of the resource rents to the well owner; none are presumed to accrue to groundwater buyers. As alluded to above, this is tantamount to assuming a particular industrial organization of groundwater markets.

Sekhri (2014) overcomes this problem by taking the second empirical approach. She performs what is, in effect, an *ex post* impact assessment of groundwater access using an ingenious regression discontinuity design. But, before reviewing Sekhri's analysis, note that, because her outcome variable is the poverty rate at the *village* level, she does not need to assume anything about how resource rents are divided between groundwater buyers and sellers within a village; she can be agnostic about groundwater markets. Indeed, her approach captures all village-level spillovers from groundwater, including those operating through the labor market, such as when intensification increases the demand for agricultural labor.

Sekhri's strategy exploits the limited suction capacity of surface pumps (already discussed). In Uttar Pradesh, where she carries out her study, surface and submersible pumps coexist (note the state's relatively low [for India] rate of electrified tubewells in table 1), with the former, cheaper, technology predominating to a much greater extent in villages where the water table lies above 8 meters.[8] Across this same water table discontinuity of 8 meters, she compares the village-level poverty rate and finds it to be 11% higher just above the threshold, thus concluding that this increase in poverty is *caused* by the higher cost of accessing groundwater.

I began this section by asking whether and to what extent South Asia's borewell revolution has been poverty-reducing. Sekhri provides part of the answer: marginally lowering the cost of groundwater access does reduce poverty. If I take the liberty of generalizing Sekhri's findings away from the 8-meter discontinuity and beyond UP, I can argue that the secular decline in the cost of well-boring and the price of pump-sets must have made a significant dent in South Asian poverty, although precisely calibrating the size of the dent is beyond the scope of this paper. Looking toward the future, however, falling water tables create a countervailing force presumably working against poverty reduction, namely, the need to drill deeper and install ever more powerful and expensive pumps to lift groundwater.

Returns to Well-drilling

In this section, I illustrate some economics of well-drilling by working through an empirical example using data from a sample of around 1,500 agricultural households collected in 2010 in two drought-prone districts of Andhra Pradesh.[9] As in much of India, dry season cultivation in these districts is only possible with groundwater, which entails a large upfront outlay for a borewell. Yet striking

Table 2. Hedonic Estimates of the Return to a Borewell

VARIABLES	(1) log(value/acre)	(2) log(value/acre)
Functional borewells/acre[a]	0.459	0.472
	(0.066)	(0.071)
Log plot area	0.048	0.048
	(0.018)	(0.019)
Soil depth	0.028	0.008
	(0.021)	(0.022)
Black soil dummy	0.101	0.058
	(0.036)	(0.037)
No. of plots	2,495	2,100
No. of households	955	820

Note: Regressions include household fixed effects. Cluster-robust standard errors appear in parentheses. Column (1) includes all multi-plot households having plots with and without borewells. Column (2) excludes non-borewell plots on which at least one drilling attempt has been made.

[a]Accounts for fractional ownership (shares) of borewells.

water is by no means a foregone conclusion. In the hard-rock aquifers of the Deccan Plateau, groundwater is not contained in vast sub-surface lakes, but rather lies within narrow fissures caused by weathering. Uncertainty in groundwater exploration has important implications for the private returns to well-drilling.

Before considering these implications in full, in table 2 I report hedonic estimates of the *gross* return to a well, which is to ask: By how much does having a functional borewell augment the value of a plot? The increment to plot value represents the gross and not the net return precisely because, once the investment has been sunk, what matters is only the expected present value of the increased production potential, not the drilling cost.[10] Since farmers often have multiple plots, typically one with a borewell and one without, I can compare plot values within the same household so as to control for systematic mis-reporting of land values by a given individual as well as for any other farm-level unobservable. Results (column 1) indicate that one functional borewell per acre increases the value of a plot by 46%.

Note that my regression effectively compares "treatment" plots, those with functioning borewells, to "control" plots, those that presently do not have one. However, control plots may still have an option value inasmuch as *future* drilling may eventually yield a viable borewell. If so, 46% may *underestimate* the gross return to a functional borewell relative to not having one (i.e., forever). The final regression in table 2 thus removes control plots upon which a past *attempt* to drill a well has been made. The idea is that the remaining controls, plots upon which no drilling attempts have been made, are in fact plots for which the prospect of striking groundwater is perceived as hopeless (perhaps because no farmer has been successful on a neighboring plot; see figure 4). The result, however, is only a very small increase in the estimated gross return, to 47%, which, given the median value of a plot, amounts to 82,000 rupees in present value terms.

With this estimate in hand, consider now the net return to well-drilling. According to the survey data, the median installation cost for wells sunk within the last decade, including the boring of the well, the casing, and the electrical connection, is 23,000 rupees, about half of which consists of the boring. However, this total does not fully account for exploration costs; a farmer bears the cost of drilling whether the borewell attempt is successful or not. Conditional on a household having made a borewell attempt (about 60% of households in the sample have done so), the mean number of unsuccessful attempts is just under two. Hence, the *expected* cost of unsuccessful attempts amounts to 22,000 rupees, nearly the cost of installing a successful borewell. In sum, the *net* private benefit of investing in a borewell is 37,000 (= 82,000 – 23,000 – 22,000) rupees, which, amortized at an interest rate of 5%, amounts to 3% of median annual household consumption expenditures.

Let us now ask how these calculations would change if the electricity to power the pump was priced at cost rather than given away for free as is presently done in Andhra Pradesh and elsewhere in India. Assuming that the pump uses 4.7 kwh per hour of operation, that it operates 900 hours per year, and that the cost of electricity is 0.75 rupees/kwh (off-peak agricultural power tariff in W. Bengal), the capitalized power subsidy is 57,000 rupees, which when deducted from the above figure of 37,000 leads to a net benefit of −20,000. Therefore, the net *social* benefit of a borewell is substantially *negative*![11]

What we have here is a classic case of rent-seeking. To capture the massive power subsidy, farmers have been drilling wells that would not otherwise be economically viable. In the conventional welfare analysis of a subsidy, there is a social cost (deadweight loss) associated with over-use. In other words, the cost of the *additional* power consumption induced by free provision exceeds its value to farmers. Rent-seeking, however, entails the willingness to incur borewell acquisition costs up to the total net value of irrigation consumed, which is to say to *fully* dissipate surplus at the margin. By inflating total surplus, free electricity incentivizes farmers to attempt borewells in less viable areas (where success rates are lower and exploration costs are consequently higher) or to drill deeper than they otherwise would. Whichever mechanism is favored, borewell acquisition costs can rise by as much as the full increase in total surplus induced by the subsidy. Augmenting the conventional deadweight loss of a subsidy, therefore, is a potentially much larger social cost from rent-seeking.

While this analysis shows that government policy can drive a huge wedge between the private and social returns to well-drilling, there is another reason why private and social returns may diverge: the externalities associated with groundwater as a common pool resource. This is the topic of the next section.

Overexploitation of Groundwater

Is groundwater in South Asia overexploited? First we must define "overexploited," which is not synonymous with "depleted." After all, a declining stock of a natural resource may be socially desirable. Why? Imagine an aquifer owned by a single private firm. The firm's problem is to maximize the present value of the revenue stream (i.e., from selling the water to irrigators) subject to the law of motion for the water level in the aquifer. The change in water level depends on recharge—the rate at which the aquifer is replenished by rainfall or surface water sources—and on the rate of groundwater extraction, which depends, in turn, upon pumping costs. As long as the steady-state water level is below the initial water level, it will be optimal *for society* to deplete the aquifer until the rate of extraction equals the rate of recharge.[12] Moreover, if the cost of extraction is declining due to technical progress (e.g., better pumps), the optimal steady-state water-level itself may be declining over time. In short, either the transition to a steady-state or a shifting steady-state would be *consistent* with socially-optimal resource depletion.

There are, however, important externalities associated with groundwater exploitation that may lead to socially sub-optimal depletion. Let me first dispense with environmental externalities. In South Asia, pumping groundwater may impose external costs through seawater intrusion in coastal zones or through secondary salinity, a serious problem in Pakistan's Punjab. However, also important in the conjunctive use environment of the Punjab is the vertical drainage afforded by groundwater pumping, which, by alleviating waterlogging, confers a countervailing external benefit. Lastly, land subsidence does not appear to be a significant by-product of groundwater exploitation in South Asia. Thus, while some of these environmental externalities may be locally relevant, my reading of the evidence is that the borewell revolution has not precipitated widespread ecological damage in the region.[13]

The key problem associated with groundwater exploitation arises when many well owners pump from an aquifer under the rule of capture; groundwater thus becomes a common-pool resource. The so-called pumping-cost externality arises because each well owner only takes into account the (infinitesimal) impact of their extraction on their *own* future pumping costs, not on the future pumping costs of possibly many others. It can be shown theoretically (e.g., Rubio and Casino 2001) that, as a consequence of this free-for-all, the steady-state water level in the aquifer, and thus welfare, will be lower when there are many well owners than when there is a single owner, as in the scenario discussed above. The question is: How important is the welfare loss quantitatively?

In a seminal article, Gisser and Sanchez (1980) find that this loss is negligible. That is, when calibrated to an aquifer in the western US, the pumping cost externality is vanishingly small. Of course, the hydrological-economic model that underlies this conclusion makes a number of restrictive assumptions (see Koundouri 2004 for a sensitivity analysis focusing largely on functional form issues). I will mention two here that appear particularly questionable in the South Asian context. However, to make the discussion concrete, let me first document recent symptoms of groundwater depletion in Andhra Pradesh.

Demise of the Dugwell

Since they are relatively shallow, dugwells are obviously particularly vulnerable to a falling water table. As already mentioned, Minor Irrigation Census data indicate a substantial decline in the number of mechanized dugwells in Andhra Pradesh since the mid 1990s. Village-level data, collected as part of a 2012 groundwater markets survey (GWMS) covering six districts of Andhra Pradesh, reveal that in 62 (out of 144) villages that had at least one functioning dugwell in 2007, the mean number of functioning dugwells declined by nearly three-quarters (from 16.1 to 4.2) between 2007 and 2012.[14]

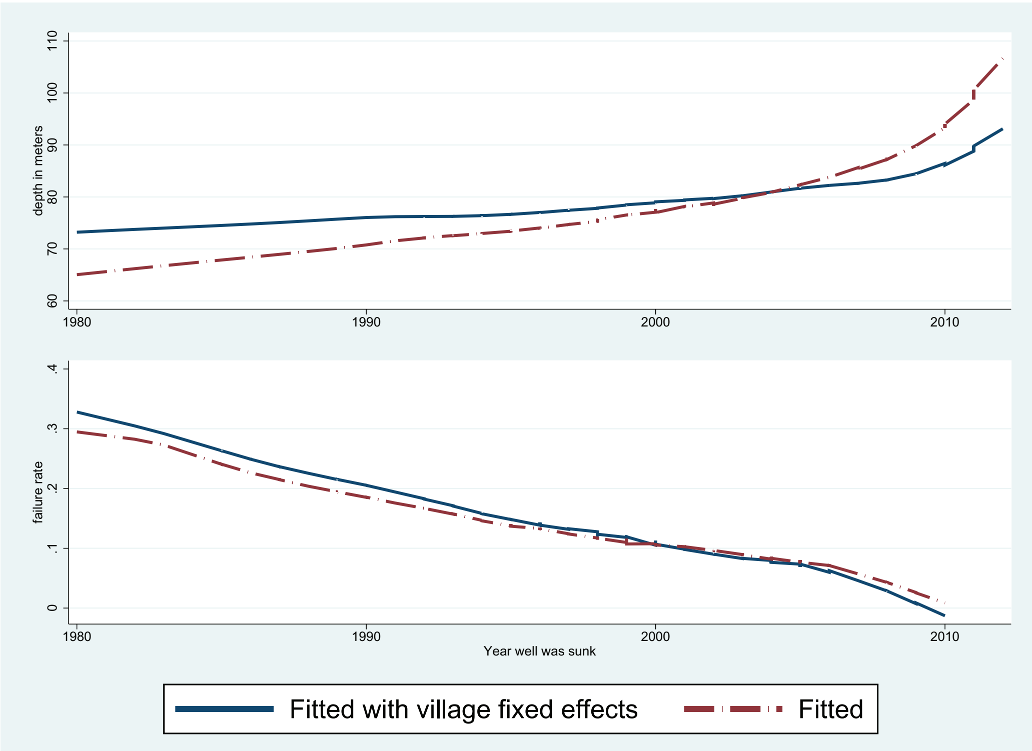
Drilling Deeper

The 2012 GWMS collects information on about 2,400 borewells, including bore depth and year of installation. In interpreting the relationship between these two variables, note that groundwater development may occur first in areas with a high water table precisely because drilling there is cheaper. In other words, finding that early wells are shallower may be a selection effect rather than a *consequence* of groundwater depletion. To deal with this issue, I fit the depth-age relationship with village fixed effects. As seen in figure 3 (top), *within* a village, more-recently-sunk borewells are deeper (without fixed effects the slope of the relationship is indeed overestimated due to the selection effect). This trend appears to have greatly accelerated in recent years. GWMS data also show that for every 10-meter increase in well depth, drilling costs increase by 6.6% and pump costs increase by 9.0% (due to greater horse-power requirements).

Borewell Failure

Since failed borewells are not enumerated in the 2012 GWMS, I look at data from the 2010 weather insurance survey, which covers all borewells. Figure 3 (bottom) shows

Figure 3. Borewell trends in Andhra Pradesh based on micro-data.
Note: Nonparametric regressions of borewell depth and failure dummy on year of well being sunk with and without conditioning on village fixed effects.

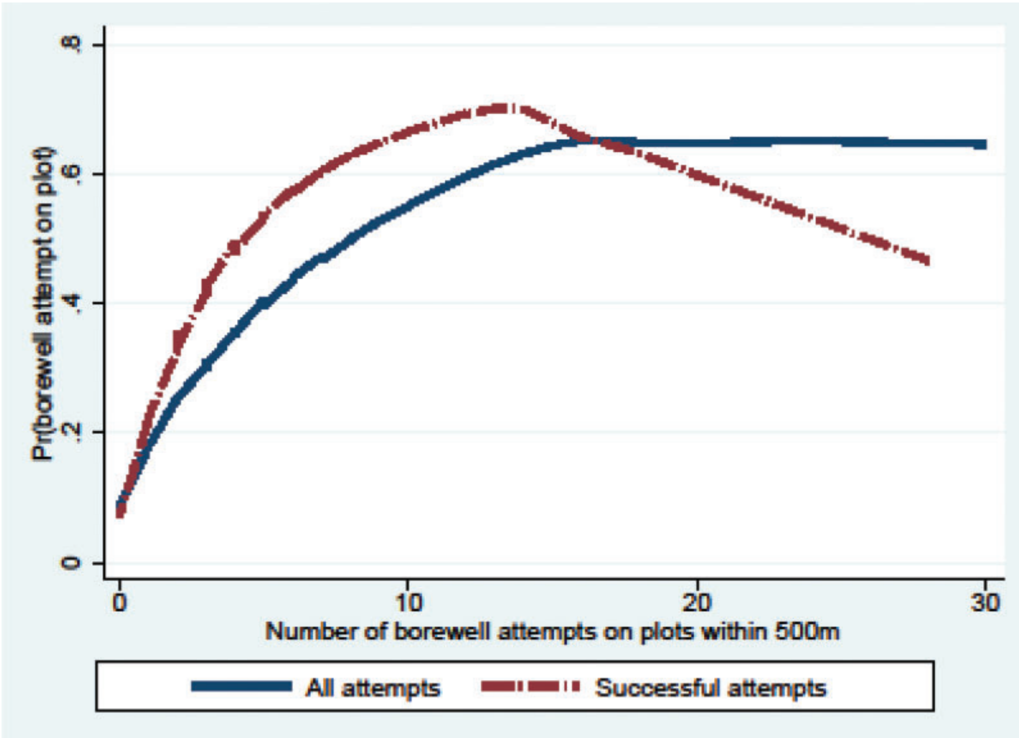


that older, presumably shallower wells are more likely to fail, indicating falling water tables; borewells sunk in 1990 are twice as likely to have run dry than those sunk in 2000. Once again, there is a hint of recent acceleration in the failure rate.

So the data suggest that the aquifers of Andhra Pradesh are drying up. And yet readings from a network of observation wells across the state (AP Groundwater Dept. 2012) show a modest statewide *rise* (of about 1 meter) in water tables over the last 15 years. How to reconcile these findings?[15] The key point to recognize is that, in a hard rock zone with its above-mentioned fissures, groundwater is a highly local resource; a cluster of several wells has little influence beyond a radius of a couple kilometers.

Borewell clustering is pervasive. The 2010 data show that, within 500 meters of a plot with a borewell, there are, on average, 4.6 *other* borewells, whereas this figure

Figure 4. Borewell clustering in Andhra Pradesh.
Note: Nonparametric regression of a plot-level dummy for attempted borewells on the number of borewell attempts within 500 meters (both total and successful attempts).



drops to 2.1 for plots without a borewell. Moreover, conditional on village fixed effects, the likelihood of a well-drilling attempt on a given plot is strongly positively related to the number of borewell attempts on neighboring land and, especially, to the number of *successful* attempts (see figure 4). One interpretation of this finding is that farmers learn from their neighbors about promising drilling opportunities. Alternatively, all farmers in a village may know where to drill but only are able to exploit this information once they have accumulated the requisite capital. Either interpretation of farmer behavior would lead to borewell clustering over time.

Borewell clustering leads to well interference. In Andhra Pradesh (AP), pumps are run continuously throughout the dry season for the hours during which electricity is available. When a pair of nearby submersible pumps run in tandem, the combined drawdown of the local water table is greater, and the combined discharge of the pumps correspondingly much less, than that of each pump running in isolation. This interference effect is accentuated by the low transmissivity (velocity of horizontal groundwater flow) through hard rock aquifers. A cluster of borewells, in short, creates a localized depression of the water table, which is increasing in borewell density. Since it is highly unlikely that the AP Groundwater Department locates its observation wells in such clusters, it is unsurprising that they have failed to detect any water table decline even as the number of borewells has soared in the state.

I now return to the pumping cost externality. As a theoretical matter, clustering can overturn the Gisser-Sanchez result that the welfare gains from centralized aquifer management are trivial. Brozović, Sunding, and Zilberman (2010) conclude the following: "...if wells are clustered together in a relatively small area within an aquifer with much larger surface area, then a spatially explicit model will predict much larger welfare gains from optimal management than a single-cell [Gisser-Sanchez type] model."

Intuitively, the external costs imposed by any single well pumping are concentrated within the cluster rather than diluted across the entire extent of the aquifer.

Well interference also implies that the marginal well may contribute quite little to overall groundwater extraction capacity in a given locality. But this marginal well is still costly to install, if not more costly than the very first well in the cluster. Thus, the mushrooming of borewell agglomerations across southern India may be more a symptom of surplus dissipation than of healthy groundwater development. The Gisser-Sanchez model, designed around the dispersed well structure of the American west, takes no account of the welfare losses from rent-seeking.[16]

Back to our question: If overexploitation connotes large welfare losses vis-à-vis centralized aquifer management, then groundwater in parts of India is arguably overexploited. But, as I have also argued in this section, determining groundwater overexploitation is not as straightforward as checking a water table trend.

Groundwater Markets

Groundwater markets are a pervasive feature of the agricultural landscape of South Asia; that much is clear from figure 2. However, these markets are inherently fragmented and localized. With the possible exception of Gujarat, where Dubash (2002) documents extensive underground pipeline networks connecting well owners and water buyers, groundwater transfers are typically limited to neighboring plots through unlined field channels with high seepage losses.[17] Given that borewells also tend to be scattered, albeit clustered to some degree, groundwater markets do not, prima facie, conform to the ideal of perfect competition. Under perfect competition, of course, the market price of groundwater would equal the marginal cost of extracting it and all the resource rents would accrue to the users rather than to the owners of the extraction devices insofar as these are different people.[18] Unfortunately, the industrial organization literature provides innumerable alternatives to perfect competition, each with different implications for the division of resource rents.[19]

Jacoby, Murgai, and Rehman (2004) consider one such alternative: single-price monopoly. Detailed data on groundwater prices and use in one watercourse of Pakistan's southern Punjab reveals two main findings: (1) tubewell owners charge lower prices to their *own* share-tenants than to all other buyers, including share-tenants of others landowners; (2) tubewell owners and their share-tenants use significantly more groundwater per acre than other farmers. Jacoby et al. interpret these results as implying that tubewell owners are charging their own share-tenants a price equal to marginal cost and all other water-buyers a substantial markup over marginal cost. The question they then go on to address, which is pertinent to our present discussion, is how a move to universal marginal cost pricing would alter the distribution of wealth in the watercourse. As it turns out, not very much. Despite this benign result, Jacoby, Murgai, and Rehman (2004) should give us pause: access to groundwater through markets need not imply an equitable distribution of resource rents.

A deeper question, however, is why single-price monopoly, with its attendant deadweight loss, arises in the first place. In other words, why can farmers not contract around the inefficiency? Specifically, the seller could adopt a two-part tariff, pricing groundwater at marginal cost and extracting buyer surplus through a lump-sum fee. One clue as to why such contracts do not occur (at least in southern Punjab) is that, since groundwater serves to buffer against surface water shortfalls, demand uncertainty tends to be high. As emphasized in the incomplete contracts _literature, uncertainty gives rise to hold-up problems that can render such ex-ante arrangements impracticable. Recent work in Andhra Pradesh using the aforementioned GWMS data (Giné and Jacoby 2016), suggests that uncertainty, in this case *supply* uncertainty, may indeed constrain contractual form in groundwater markets. Two principal selling arrangements are observed in the data: seasonal contracts under which irrigation is promised for the duration of the cropping cycle and spot contracts under which water is sold one irrigation at a time. Giné and Jacoby show theoretically that the seasonal contract becomes less attractive relative to the spot contract as uncertainty increases, which is exactly what they find in the data.

I close this section by considering how groundwater markets interact with well-drilling. Borewells are *strategic substitutes*; once every farmer has one, little scope remains for groundwater sales. Yet a farmer who eschews drilling can purchase water from a neighbor who has a well, thus obtaining irrigation without incurring the large fixed cost.[20] As noted, however, groundwater markets may not equally distribute the resource rents. Insofar as the well owner has monopoly power, he will earn the greater surplus. The choice to drill by a pair of neighboring farmers can thus be considered a coordination game like the one illustrated in panel (a) of

Figure 5. Well-drilling games.
Note: Shaded cells represent Nash equilibria in coordination game among neighboring farmers, each of whom could potentially drill a borewell.

(a) *Coordination failure*

	Drill	Not drill
Drill	12, 12	20, 10
Not drill	10, 20	0, 0

(b) *Coordination success*

	Drill	Not drill
Drill	12, 12	15, 15
Not drill	15, 15	0, 0

figure 5. While the social optimum in this case is for either one of the farmers to drill a well and for the other farmer to buy water, the Nash equilibrium (shaded) is for *both* farmers to drill. The reason for the inefficiency is precisely the inequitable allocation of rents. To bring this point home, the example in panel (b) of figure 5 assumes the same total surplus divided equally between buyer and seller. One institution that lends itself to equal division and is widespread across the Indian subcontinent is well co-ownership. At any rate, in this case, the (two) Nash equilibria do correspond to the social optimum; there is no wasteful drilling of wells. How important is this type of coordination failure empirically? In other words, are there too many wells because groundwater market institutions do not share the rents sufficiently equitably? This is an open question, and for good reason: it requires dealing with the thorny simultaneity between the local structure of groundwater markets and the intensity of well drilling.

Policy

To return to a recurring theme, there are two margins that policy-makers must pay attention to: well-drilling and groundwater pumping. We have seen that restricting either or both margins may be economically justified in some contexts, but not in all. For example, in command areas with reliable surface water, which exist in parts of Pakistan's Punjab, continued groundwater development may be worthwhile, especially where drainage is poor. Likewise, in groundwater-abundant areas like northeastern India and West Bengal, there are probably too few rather than too many borewells. Moreover, insofar as credit constraints limit profitable investments in agriculture, there is even a case for subsidizing borewell installation costs in these places. But, in regions undergoing massive depletion (northwest India) or where well clustering is rampant even with stable water tables (e.g., Andhra Pradesh), there is a case for action, at the very least for reforming those policies with perverse incentives vis-à-vis groundwater.

In India, the main culprit in this respect is state subsidies to agricultural powers.[21] These subsidies arose as a political response to farmers in non-command areas who saw themselves as not benefitting from free canal irrigation. But now free power has itself become something of a sacred cow. Indeed, power subsidies distort both the pumping (intensive) and the drilling (extensive) margins, although the former distortion is mitigated by the almost universal daily rationing of power to agriculture. Shah et al. (2004) argue against widespread electricity metering for borewells in India on both logistical and political grounds. Instead, these authors advocate raising the flat rate to cover power generation and transmission costs. To be sure, a flat rate on power that recovers total electricity costs from well owners has one considerable advantage: it eliminates the deadweight loss due to over-drilling (of future wells) without the expense of installing meters. However, it is not obvious that it will be acceptable to millions of existing well owners, since they will, after all, have to pay more.

A perhaps more politically feasible solution would be a subsidy buyout: irrespective of well ownership, farmers in non-command areas (but only those areas with groundwater potential) would be granted a fixed annual payment equivalent to the average yearly cost of electricity usage. In return, all new and existing electrical connections would be metered, with farmers getting a rebate (or, rather, a conservation bonus) for any power consumption below the average. In this way, the subsidy no longer becomes conditional on well ownership, hence no more drilling for a subsidy, and farmers who have already sunk wells would face a rational marginal pumping cost. Finally, this proposal may be easier for farmers to accept than either the flat rate or metering with conventional pricing because, unlike these schemes, it does not cost them anything. Of course, the downside of the buy-out is that it will cost Indian taxpayers more than the alternatives.[22]

The agricultural power problem interacts in an important way with a new player in the technological game, the solar pump. The prospect of relieving themselves of the massive fiscal burden of electricity subsidies has enticed states in India to contemplate subsidizing solar pump-sets. On the one hand, this policy could have the salubrious effect of mitigating rent-seeking; a solar pump obviates the need to drill multiple wells so as to capture more of the state electricity ration. On the other hand, free power *all day long* would undoubtedly increase pumping. Mass adoption of solar pumps could thus spell disaster for India's remaining groundwater resources, unless, of course, the power generated by the solar units is priced. This is exactly what the state of Karnataka is now doing (on an experimental basis)—paying farmers for solar power sent back to the grid. By reducing wasteful well-drilling *and* rationalizing the marginal cost of groundwater pumping, this policy is a potential win-win.

Finally, water-saving technologies like drip and sprinkler irrigation have sometimes been advocated as a way to avert groundwater "armageddon". India's huge national subsidy scheme, when combined with complementary programs offered by several states, defrays up to 90% of the cost of these micro-irrigation systems. To be sure, drip irrigation utilizes water much more efficiently than traditional flooding or furrow methods, but will it save groundwater? This again depends on context. Insofar as farmers can respond along the extensive margin, by planting more of their land in the dry season or by selling more of their groundwater to neighbors, who in turn expand their cultivation, there may be no effect on groundwater depletion. Moreover, in the longer run, higher water productivity may encourage even more drilling. So, while water-saving technologies certainly have the potential to raise farm *incomes*, they are no panacea for the region's groundwater problems.

Notes

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1. Bangladesh is a third South Asian groundwater dynamo with about a million mechanized wells, roughly the same number as in Pakistan.
2. According to the most recent piezometer readings from the Punjab Groundwater Department's roughly 2,300 observation wells, 15 meters is just about at the 90^{th} percentile of water table depth for the province.
3. Comparable figures on conjunctive use in India are harder to come by, but the practice is surely far less widespread. As of 2010, only 26% of the irrigated area nationwide was supplied by canals compared to 64% by wells of any kind (45% by tubewells and 19% by dugwells).
4. Pakistan also subsidizes electricity to farmers but supplies many fewer hours per day than most Indian states.
5. Some of these data discrepancies have also been brought to light by Rawat and Mukherji (2013).
6. Much of the increase in dugwells has been concentrated in Kerala, Tamil Nadu, and Maharashtra. By contrast, depending on which census one believes, dugwell numbers have either remained constant or declined by more than 20% in Andhra Pradesh (see table 1).
7. The India Human Development Survey-II (IHDS-II), 2011-12 is a nationally representative, multi-topic survey covering more than 27,000 rural households in around 1,500 villages (see Desai and Vanneman 2015).
8. As noted, no such discontinuity exists in Pakistan (recall the virtual absence of submersible pumps there). Evidently, farmers in India do not deep-set their surface pumps as is commonly done in the Punjab.

9. The survey was originally designed to study the uptake of index-based weather insurance, but the questionnaire was augmented by Xavier Giné and I to include information on borewells and groundwater.

10. In practice, I do not have data on actual land transaction prices. Instead, farmers were asked "If you were to sell this plot today, *including the associated water rights*, how much would you receive in`000 Rs/acre?" The implication of the italicized text is that shared borewell ownership would be discounted relative to full ownership.

11. I am ignoring any rents accruing to water buyers, which could add to the social but not to the private benefit of a borewell. However, the point is moot in this particular case since groundwater markets are virtually nonexistent in the two surveyed districts.

12. The existence of a steady-state requires that the marginal extraction cost of the last unit of water exceeds the maximum marginal valuation of water. Otherwise, it will be socially optimal to drain the aquifer entirely, assuming no significant environmental costs from doing so.

13. While the degradation of groundwater *quality* due to fertilizer and pesticide contamination is potentially serious, this is an externality attributable to farming practices rather than to groundwater pumping per se.

14. The GWMS survey was also collected in collaboration with Xavier Giné. In addition to the two water-scarce districts of the 2010 weather insurance survey, we included two coastal districts with plentiful groundwater and two interior districts with intermediate supplies of groundwater.

15. By contrast, in the deep alluvial aquifers of northwest India, there would be no need for such reconciliation. Based on NASA GRACE satellite data, water tables in Punjab, Haryana, and Rajasthan have fallen by one-third of a meter *per year* from 2002-08 (Rodell, Velicogna, and Famiglietti 2009).

16. Martin (2011) makes the theoretical point that when the number of farmers exploiting an aquifer is endogenous, resource rents are driven down to zero, obviously (much) lower than under optimal management.

17. A distinguishing feature of Gujarat is the extraordinarily deep water table. Since the cost of sinking a well is thus very large, we see widespread sharing of groundwater, including large well co-ownership groups and multiple buyers connected by pipeline to a single well.

18. To cover the fixed costs under these circumstances, a borewell owner would have to be a substantial user of his own groundwater.

19. For example, groundwater markets can be modeled as fragmented duopoly along the lines of Basu and Bell (1991), using the theory of spatial price differentiation (Chakravorty and Somanathan 2014), or even as a bilateral bargaining problem within a trading network as in Corominas-Bosch (2004).

20. For the sake of argument, assume that an additional borewell adds little to overall groundwater availability, certainly not enough to justify its fixed costs.

21. Another distortion is the system of minimum support prices for groundwater-intensive crops like wheat.

22. Another advantage of metering is that the price of electricity could, in principle, be used as an instrument to control groundwater overexploitation; i.e., by setting the price above the marginal cost of supplying power.

References

Basu, K., and C. Bell. 1991. "Fragmented Duopoly: Theory and Applications to Backward Agriculture." *Journal of Development Economics* 36 (2): 145–65.

Briscoe, J., and R. P. S. Malik. 2006. *India's Water Economy: Bracing for a Turbulent Future*. New Delhi: Oxford University Press.

Brozović, N., D. L. Sunding, and D. Zilberman. 2010. "On the Spatial Nature of the Groundwater Pumping Externality." *Resource and Energy Economics* 32 (2): 154–64.

Chakravorty, U. N., and E. Somanathan. 2014. "Drilling in the Drought: The Industrial Organization of Groundwater." Unpublished manuscript, Tufts University.

Corominas-Bosch, M. 2004. "Bargaining in a Network of Buyers and Sellers." *Journal of Economic Theory* 115 (1): 35–77.

Desai, S., and R., Vanneman. 2015. *India Human Development Survey-II (IHDS-II), 2011-12*. ICPSR36151-v2. Ann Arbor, MI: Inter-university Consortium for Political and Social Research [distributor], 2015-07-31. http://doi.org/10.3886/ICPSR36151.v2.

Dubash, N. K. 2002. *Tubewell Capitalism: Groundwater Development and Agrarian Change in Gujarat*. Oxford University Press.

Giné, X., and H. Jacoby. 2016. "Markets, Contracts and Uncertainty in a Groundwater Economy." Policy Research Working Paper 7694. World Bank, Policy Research Department, Washington DC.

Gisser, M., and D. A. Sanchez 1980. "Competition versus Optimal Control in Groundwater Pumping." *Water Resources Research* 16 (4): 638–42.

Jacoby, H. G., R. Murgai, and S. U. Rehman. 2004. "Monopoly Power and Distribution in Fragmented Markets: The Case of Groundwater." *The Review of Economic Studies* 71 (3): 783–808.

Koundouri, P. 2004. "Potential for Groundwater Management: Gisser-Sanchez Effect Reconsidered." *Water Resources Research* 40 (6), W06S16-1.

Martin, E. 2011. "Is the Gain from a Groundwater Management Policy Insignificant?" *Environmental Economics* 2 (4): 46–56.

Rawat, S., and A. Mukherji 2014. "Poor State of Irrigation Statistics in India: The Case of Pumps, Wells and Tubewells." *International Journal of Water Resources Development* 30 (2): 262–81.

Rodell, M., I. Velicogna, and J. S. Famiglietti. 2009. "Satellite-based Estimates of Groundwater Depletion in India." *Nature* 460 (7258): 999–1002.

Rubio, S. J., and B. Casino. 2001. "Competitive versus Efficient Extraction of a Common Property Resource: The Groundwater Case." *Journal of Economic Dynamics and Control* 25 (8): 1117–37.

Sekhri, S. 2014. "Wells, Water, and Welfare: The Impact of Access to Groundwater on Rural Poverty and Conflict." *American Economic Journal: Applied Economics* 6 (3): 76–102.

Shah, T. 2010. *Taming the Anarchy: Groundwater Governance in South Asia.* Resources for the Future Press, Washington DC.

Shah, T., C. Scott, A. Kishore, and A. Sharma. 2004. *Energy-irrigation Nexus in South Asia: Improving Groundwater Conservation and Power Sector Viability*, Research Report No. 70, International Water Management Institute, Colombo, Sri Lanka.

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F. T. Portmann. 2010. "Groundwater Use for Irrigation–A Global Inventory." *Hydrology and Earth System Sciences* 14 (10): 1863–80.