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Groundwater Depletion Under Irrigated Agriculture: Evidence and Governance

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Abstract

Groundwater carried the green revolution. It is now being spent faster than it is replaced across most of the world's intensively irrigated plains. This review synthesises 37 peer-reviewed studies on the measurement, drivers, consequences and governance of agricultural groundwater depletion, with north-west India treated as the principal case. Satellite gravimetry made the problem visible: Rodell and colleagues reported a loss of about 109 cubic kilometres from the aquifers of north-west India over roughly six years and Tiwari and colleagues put the northern Indian rate near 54 cubic kilometres a year. Global estimates remain far apart, from 283 down to 113 cubic kilometres a year depending on method and at least one reanalysis argues that satellite-based Indian figures were too high. We make three arguments. Depletion is a governance failure with an energy price at its centre, not a hydrological accident. Efficiency measures alone do not conserve the resource, because saved water is usually reinvested in more irrigated area. And the consequences now reach beyond the farm, into river baseflow, national emissions and the food trade of other countries. Measurement disagreement is itself a governance problem, since a resource nobody can measure consistently is hard to allocate.

Keywords:- Groundwater Depletion, Irrigation, Grace, Energy-Water Nexus, India, Aquifer Governance, Environmental Flows

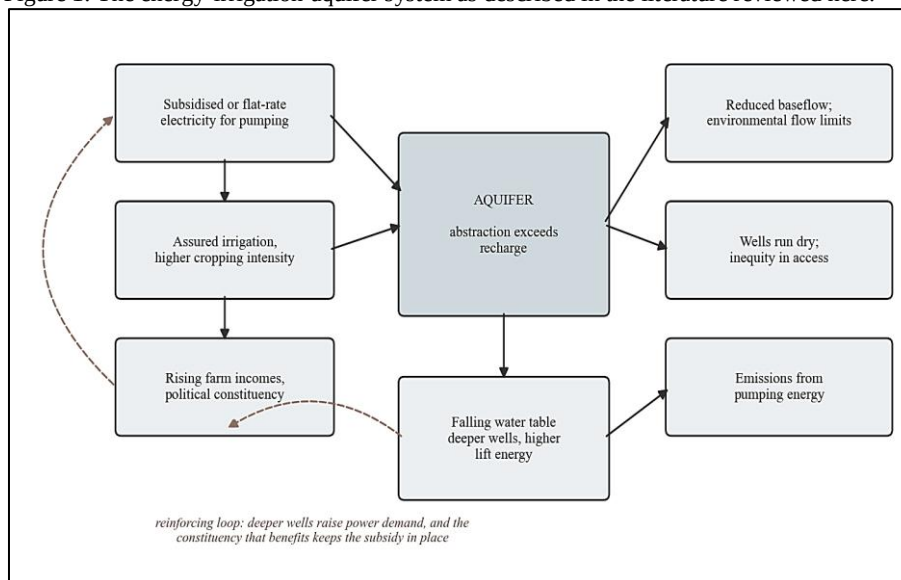
I. INTRODUCTION

The tube well changed Indian agriculture more than any single crop variety did. It gave farmers water on demand, independent of the canal roster and largely independent of the monsoon, and cropping intensity rose accordingly. Siebert and colleagues compiled the first global inventory of groundwater use for irrigation and found it supplying a substantial share of the world's irrigated area (Siebert et al., 2010). Wada and colleagues then estimated how much of the global gross irrigation demand was being met from non-renewable storage (Wada et al., 2012). The answer was uncomfortable.

Konikow and Kendy had already framed depletion as a global rather than local problem (Konikow & Kendy, 2005), building on Foster and Chilton's account of aquifer degradation as a slow, largely invisible process (Foster & Chilton, 2003). What changed after 2002 was observability. The GRACE satellites measured changes in the Earth's gravity field precisely enough to detect the mass of water leaving an aquifer system, and the first results from northern India were startling enough to move the issue into general policy discussion (Rodell et al., 2009; Tiwari et al., 2009).

This review asks four questions. How much groundwater is being lost, and how confident can we be in the number. What drives the loss. What are the consequences beyond falling water tables. And which governance responses have any evidence behind them. India recurs throughout, both because the depletion signal there is among the strongest measured anywhere and because its policy history offers unusually clear natural experiments.

Figure 1: The energy-irrigation-aquifer system as described in the literature reviewed here.



The diagram is schematic and contains no data; it follows the energy-irrigation nexus argument of Shah (2009) and the depletion consequences discussed in Sections 4 and 5.

II. HOW MUCH IS BEING LOST, AND HOW WELL DO WE KNOW IT

2.1. The satellite record

Rodell and colleagues used GRACE to isolate the groundwater component of terrestrial water storage over Rajasthan, Punjab and Haryana. Between 2002 and 2008 they reported a loss of roughly 109 cubic kilometres, in a period whose rainfall was close to normal (Rodell et al., 2009). Rainfall was not the cause. That detail is what made the result an irrigation story rather than a drought story. Tiwari and colleagues, working over a wider northern Indian domain and a somewhat different processing chain, reported a comparable signal expressed as an annual rate rather than a cumulative volume (Tiwari et al., 2009).

Global assessments followed. Wada and colleagues estimated worldwide depletion of about 283 cubic kilometres a year around 2000 using a hydrological model driven by abstraction estimates (Wada et al., 2010), while Döll and colleagues combined modelling with well observations and GRACE and arrived at a figure closer to 113 cubic kilometres a year for the following decade (Döll et al., 2014). Both are careful pieces of work. The gap between them is a statement about method, not about the aquifers. Rodell and colleagues later extended the GRACE record to global freshwater availability as a whole and found the pattern of change dominated by direct human intervention rather than by climate variability in the aquifer regions (Rodell et al., 2018). Figure 2 sets the published estimates alongside one another.

Figure 2: Published groundwater depletion estimates.

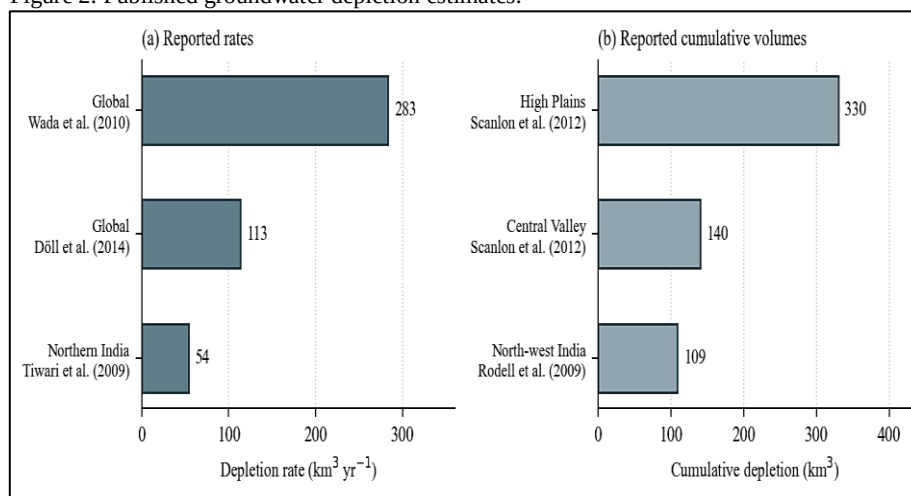


Figure 2 Published groundwater depletion estimates. Panel (a) shows reported rates and panel (b) reported cumulative volumes. The two panels are kept separate because the quantities and reference periods differ. The Central Valley figure is the 80 km^3 lost since the 1960s reported by Scanlon et al. (2012). Values are reproduced from the cited studies without conversion.

2.2. Where the estimates disagree

GRACE measures total water storage change. Separating the groundwater part means subtracting soil moisture, snow and surface water, and that subtraction is done with a land surface model. Models differ. Long and colleagues re-examined the north-west India case and argued that biases in the modelled soil moisture component had inflated the inferred groundwater

loss (Long et al., 2016). Bhanja and colleagues took the complementary route, validating GRACE-derived storage anomalies against in-situ well hydrographs across India; agreement was good in some regions and poor in others (Bhanja et al., 2016).

Regional detail complicates the national picture further. Asoka and colleagues separated the contributions of monsoon rainfall variability and pumping, and found opposite signs in the two halves of the country: storage falling in the north despite adequate rainfall, and rising in parts of the south where rainfall had increased (Asoka et al., 2017). MacDonald and colleagues, mapping the Indo-Gangetic Basin from in-situ observations, made a related point that is often lost in depletion headlines. Across large parts of that basin the binding constraint on usable groundwater is quality, salinity and arsenic in particular, rather than quantity (MacDonald et al., 2016).

Some of the news is better than the headlines suggest. Bhanja and colleagues documented storage recovery in parts of India following changes in water policy, which at least shows the trend is not everywhere one-directional (Bhanja et al., 2017).

Table 1. Published estimates of groundwater depletion and the methods behind them

Study	Domain and period	Reported estimate	Method
Rodell et al. (2009)	Rajasthan, Punjab, Haryana; 2002-2008	About 109 km ³ lost	GRACE minus modelled soil moisture
Tiwari et al. (2009)	Northern India; 2002-2008	About 54 km ³ per year	GRACE gravity observations
Wada et al. (2010)	Global; around 2000	About 283 km ³ per year	Global hydrological model with abstraction estimates
Döll et al. (2014)	Global; 2000-2009	About 113 km ³ per year	Model combined with well observations and GRACE
Scanlon et al. (2012)	US High Plains and Central Valley; cumulative	330 km ³ of fossil groundwater in the High Plains; 80 km ³ in the Central Valley since the 1960s	Recharge mapping and a Central Valley hydrologic model
Long et al. (2016)	North-west India; reanalysis	Argues earlier GRACE-based depletion was overestimated	Sensitivity analysis of the soil-moisture correction
Asoka et al. (2017)	India, north and south; 2002-2013	Storage falling in the north, rising in parts of the south	GRACE with attribution to rainfall and pumping

III. WHAT DRIVES THE LOSS

3.1. The energy price of water

Groundwater in India is not priced. Electricity for pumping it is, but for decades in most states it has been supplied flat-rate or free to agriculture, which sets the marginal cost of the next cubic metre at close to zero. Shah set out the consequences of this arrangement and the political economy that sustains it (Shah, 2009). The loop runs the wrong way. Falling water tables raise the energy needed per unit of water, which raises the subsidy bill, which strengthens the constituency defending the subsidy.

Sekhri provided causal evidence on the welfare side, showing that access to groundwater reduces rural poverty and that its loss raises conflict, which is precisely why withdrawal of the subsidy is politically difficult (Sekhri, 2014). Chindarkar and Grafton review where Indian groundwater policy and groundwater science have failed to meet (Chindarkar & Grafton, 2019).

3.2. Climate and the efficiency trap

Zaveri and colleagues modelled Indian agriculture under climate change and found that warming and shifting rainfall raise groundwater demand rather than lower it, since groundwater is the buffer farmers reach for when the monsoon disappoints (Zaveri et al., 2016).

The efficiency response is the one most often proposed and the one with the weakest evidence. Fishman and colleagues examined whether improved agricultural water use efficiency would save India's groundwater and concluded that it largely would not, because water saved per hectare is reinvested in additional irrigated area or thirstier crops (Fishman et al., 2015). This is the rebound problem in its classic form. Rosa and colleagues make the wider point that economic water scarcity, the inability to afford infrastructure rather than the absence of water, governs outcomes across much of the global South (Rosa et al., 2020).

IV. CONSEQUENCES BEYOND THE WATER TABLE

4.1. Wells, rivers and food

Jasechko and Perrone compiled construction records for millions of wells and found that a substantial minority sit only a few metres below the present water table, which puts them at risk of running dry with modest further decline (Jasechko & Perrone, 2021). Perrone and Jasechko had already documented the standard response, drilling deeper, and described it as a stopgap that raises costs and excludes smaller farmers (Perrone & Jasechko, 2019).

Rivers pay too. Groundwater sustains baseflow in the dry season, and de Graaf and colleagues estimated that by 2050 environmental flow limits will be reached in roughly 42 to 79 per cent of the watersheds where pumping occurs, generally before any dramatic loss of storage becomes visible (de Graaf et al., 2019). Gleeson and colleagues place this within a broader account of how far human activity has modified the water cycle (Gleeson et al., 2020), and Gleeson and colleagues' earlier groundwater footprint analysis showed that abstraction from many aquifers exceeds their recharge area many times over (Gleeson et al., 2012).

The trade dimension is less obvious and possibly more consequential. Dalin and colleagues traced non-renewable groundwater embedded in internationally traded food and found a rising share, with a small number of exporting countries, including India, accounting for most of it (Dalin et al., 2017). Depletion in one country is, in part, consumption in another.

4.2. Emissions, cropping and welfare

Pumping water uphill takes energy, and in India most of that energy is coal-fired. Mishra and colleagues estimated the carbon dioxide emissions associated with groundwater pumping across the country and found them to be a meaningful component of the national total (Mishra et al., 2018). Lift and energy scale together. Deeper tables mean more energy per unit of water, so the emissions grow as the resource shrinks.

Jain and colleagues asked what happens to cropping if groundwater irrigation is lost, and projected substantial reductions in winter cropping intensity across India, with the largest losses concentrated in the regions currently most dependent on the resource (Jain et al., 2021). Set beside Sekhri's welfare estimates (Sekhri, 2014), this describes a system that is difficult to unwind quickly without imposing real costs on people who are not the principal beneficiaries of the subsidy.

None of this is unique to India. Scanlon and colleagues documented comparable depletion in the United States High Plains and Central Valley (Scanlon et al., 2012), and Richey and colleagues found a majority of the world's large aquifer systems being drawn down faster than they recharge (Richey et al., 2015). Mekonnen and Hoekstra estimate that four billion people already face severe water scarcity for at least one month a year (Mekonnen & Hoekstra, 2016).

Table 2. Consequences of agricultural groundwater depletion reported in the reviewed literature, with the mechanism each author identifies.

Consequence	Mechanism	Representative source
Wells running dry	Modest further decline exceeds the depth of shallow wells	Jasechko and Perrone (2021)
Rising abstraction cost and exclusion	Deeper drilling prices smaller farmers out	Perrone and Jasechko (2019)
Loss of river baseflow	Reduced groundwater discharge to streams in the dry season	de Graaf et al. (2019); Gleeson et al. (2012)
Higher energy use and emissions	Greater lift per unit of water pumped	Mishra et al. (2018)
Reduced cropping intensity	Loss of the dry-season irrigation buffer	Jain et al. (2021)
Depletion embedded in food exports	Groundwater-irrigated produce traded internationally	Dalin et al. (2017)
Water-quality limits on usable storage	Salinity and arsenic restrict abstraction independently of quantity	MacDonald et al. (2016)

V. GOVERNANCE RESPONSES AND WHAT THE EVIDENCE SUPPORTS

Aeschbach-Hertig and Gleeson argued that the response has to be regional, matched to aquifer boundaries rather than administrative ones, and that the choice of instrument matters less than whether abstraction is capped in some enforceable way (Aeschbach-Hertig & Gleeson, 2012). Bierkens and Wada, reviewing the field, reach a similar conclusion and note how thin the evaluation literature is: many instruments have been proposed, few have been assessed against measured aquifer response (Bierkens & Wada, 2019).

Three lessons come through with reasonable consistency. The first is about price. Pricing the energy rather than the water is the more tractable lever, because meters on individual pumps are harder to install and enforce than tariffs on electricity (Shah, 2009). Efficiency programmes need a cap on irrigated area attached to them, or the saving is spent rather than banked (Fishman et al., 2015). And monitoring has to be built before allocation rules are written, since the disagreement between published estimates makes any quantitative entitlement contestable (Long et al., 2016; Bhanja et al., 2016).

Recovery is possible. Bhanja and colleagues found groundwater storage rising in parts of India after policy change (Bhanja et al., 2017), and Wada and Bierkens' projections show that the global trajectory is sensitive to demand-side assumptions rather than fixed (Wada & Bierkens, 2014). Giordano's earlier survey of the global groundwater problem made the point that the resource's invisibility, more than its physics, is what makes it hard to govern (Giordano, 2009), and Famiglietti's commentary put the same argument to a wider audience (Famiglietti, 2014).

One response deserves a caution. Where depletion coincides with salinity, desalination is sometimes proposed as the substitute supply. Jones and colleagues describe the current global state of desalination and, importantly, the volume and disposal problem posed by the brine it generates (Jones et al., 2019). Substituting one environmental externality for another is not a solution.

VI. LIMITATIONS

This is a narrative review. We did not reconcile the published depletion estimates, and we would caution against anyone doing so casually, since the domains, periods and corrections differ in ways that are not always fully documented. The Indian focus is deliberate but it limits generalisation: the energy subsidy structure that drives so much of the Indian story has no close analogue in the United States or the North China Plain, where depletion is nonetheless severe (Scanlon et al., 2012; Richey et al., 2015). Evidence on governance instruments is the weakest part of the base, as Bierkens and Wada note (Bierkens & Wada, 2019), and much of what is written about policy is proposal rather than evaluation.

VII. CONCLUSION

Aquifers under the world's irrigated plains are being drawn down, and north-west India is among the clearest cases anywhere. How fast remains genuinely uncertain, because the satellite record needs a model to separate groundwater from soil

moisture, and the models disagree. That uncertainty does not change the direction of travel, and it should not be used as a reason to wait. The driver is an energy price that makes the marginal cubic metre free at the point of use, and the standard remedy, irrigation efficiency, does not conserve water unless irrigated area is capped alongside it. The costs have already spread past the farm gate: rivers losing dry-season flow, wells too shallow to survive another metre of decline, emissions from lifting water further, and depletion exported in the food trade. Measurement first, then allocation, then price. That order matters, because the second and third are unenforceable without the first.

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