Policy Paper 43

Regulation and Policy Response to Groundwater Preservation in India

Prabhat Kishore
Devesh Roy
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New Delhi - 110 012

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Prabhat Kishore, Pratap S Birthal and S K Srivastava are scientist, director and senior scientist respectively at ICAR-National Institute of Agricultural Economics and Policy Research, New Delhi; and Devesh Roy is senior research fellow at International Food Policy Research Institute, Washington DC. The views expressed in this paper are those of the authors and do not necessarily reflect the official position of the institutes to which they are affiliated.

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Preface

Policy supported technology-led intensification of agriculture has led to significant increases in agricultural productivity and food supplies in India. However, of late its negative externalities to natural resources, especially groundwater in semi-arid north-western region comprising the states of Punjab, Haryana and Rajasthan have become visible. Recognizing this, Punjab and Haryana brought out almost an identical groundwater regulation in 2009 which aligned sowing of water-guzzling paddy crop towards onset of the monsoon to prevent falling groundwater level.

This paper reveals reveal that overextraction of groundwater continued even the regulation being in force. This perverse outcome could be due policy offsets such as highly subsidized electric power for irrigation, excessive procurement of paddy at minimum support price, stagnation in investment in major and medium irrigation schemes, and lack of incentives for crop diversification and adoption of water-saving technologies.

It suggests a holistic approach for groundwater management, encompassing policies, technologies, incentives, institutions, and regulations. I am sure that policymakers will take due cognizance of this while designing a framework for groundwater governance.

P S Birthal
Director, ICAR-NIAP

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Authors

Executive Summary

In India, agriculture accounts for about 78% of total water demand, and close to two-third of it is met from aquifers beneath the earth's surface. Nevertheless, in endeavour of increasing foodgrain production, groundwater has been overextracted, particularly in states of Punjab and Haryana, the sheet of the Green Revolution in India.

Overextraction of groundwater is attributed to extensification of paddy crop, the water requirement of which is one of the highest among field crops. Paddy was never an important crop in Punjab and Haryana five decades ago. However, it surfaced as the most important crop, displacing low-water footprint crops like millets, pulses and oilseeds. Between 1985-86 and 2019-20, paddy area increased 1.8 times in Punjab and 2.5 times in Haryana, leading to a significant fall in groundwater level. To arrest falling groundwater level, governments of Punjab and Haryana in 2009 brought out almost identical Acts, mandating delay in paddy sowing towards onset of the monsoon. Their non-compliance attracts penalty — destruction of nursery or transplanted crop at farmer's expenses or disconnection of electricity supply, or cash payment, or all of these.

This paper has addressed an important question: Whether these Acts could succeed in arresting falling groundwater level? And if not, then why?'

Findings reveal that despite Acts being in force, overextraction of groundwater continued, at an average 988 cubic meters per hectare, leading to a steep decline in its level — more than 0.5 meter a year. Rate of overextraction is three times more in Punjab than in Haryana. This perverse outcome could have been on account of policy engendered behavioural responses that not only offset effects of the Acts on groundwater use but also led to a significant increase in paddy area and tube-well density accompanied by replacement of centrifugal pumps with high-powered submersible pumps.

State-sponsored free or subsidized electric power has been one of the factors rendering the Acts ineffective. Punjab has been providing free electricity to agriculture since 1997, and Haryana has been charging extremely low tariff on electric power. Another policy offset had been huge procurement of paddy at pre-announced minimum support price (MSP), which provides as an insurance against price and market risks. Over 90% paddy output from Punjab and Haryana is purchased for public distribution system (PDS) and buffer stocking.

If the Acts could not prevent overextraction of groundwater, then what kind of policy and institutional reforms are needed to achieve their intended objective of preventing falling level of groundwater.

Rationalize and target electricity subsidy: Instead of providing power subsidy to all, it may be restricted to smallholders who are capital-constrained. Others may be charged for it based on volume of water extracted. Here too, a system of differentiated tariff may be thought of. Tariff rates may be decided based on volume of water extracted. Evidence suggest that differential tariff is more effective in reducing paddy acreage, and consequently groundwater draft (Chand *et al.*, 2022). Nevertheless, political economy of agricultural incentives is complex, and these once provided for are difficult to withdraw.

Re-purpose agricultural subsidies: Re-purposing existing agricultural incentives to the adoption of technologies and practices such as alternate wet and drying irrigation system, direct seeding of rice, sensor-based irrigation, micro-irrigation, which are compatible with principles of natural resource management is a politically feasible option. These practices besides saving water and electric power also reduce production cost and mitigate greenhouse gas emission. Groundwater regulations could have induced adoption of such measures but it did not happen due to farmers' risk aversion and lack of incentives. The recently notified 'Green Credit Scheme' by the Government of India offers monetary incentives for the adoption of sustainable agricultural practices; hence is an opportunity to re-purpose agricultural subsidies.

Crop planning: Diversification of crop portfolio in favour of low-water footprint crops is one of the most important options to restore health of groundwater resources. Choice of a crop, however, is dictated by its economics relative to other crops. In Punjab and Haryana, there is hardly any crop (except horticulture crops), which is as profitable as paddy. Maize, soybean, pigeon-pea, and groundnut are often-suggested alternatives, but their yields are too low to compensate farmers for revenue foregone from paddy. Moreover, substitute crops have their own production niches, and are unlikely to exhibit their full production potential in all types of agro-ecologies. This implies need for crop planning at lower geographical scales — district and block levels — based on their resource endowments and climatic conditions. However, resource-endowment based crop planning is a necessary but not a sufficient condition for crop diversification. It must be accompanied by a package of compensation for revenue foregone from paddy. Further, agricultural research should focus on breeding crops alternative to paddy for higher yield and tolerance to abiotic and biotic stresses.

Evolve value chains for perishable high-value crops: High-value crops, i.e., fruits and vegetables, generate much higher returns compared to paddy, and most of these, except a few plantation crops, can be cultivated in all types of agro-ecologies. However, their cultivation is labour-intensive, and Punjab and Haryana are acutely labour scarce. This suggests more research on mechanization of horticultural crops. Further, most high-value food crops are perishable and prone to high production and post-production loss. Post-harvest, these require immediate transportation to market centres or storage or processing into less perishable forms. Investment in cold storages, refrigerated vans and processing can encourage farmers to allocate more area to high-value crops.

Follow cap-to-trade approach: Water rights are embedded in land rights; hence landowners can extract limitless water beneath the surface. Farmers in Punjab and Haryana have heavily invested in irrigation. To restrict further exploitation of groundwater, it is important to follow a cap-to-trade approach to create shared space for community-based irrigation system for sharing and trading of groundwater (Chaudhuri *et al.*, 2023). Individual ownership of new tube-wells should be discouraged by restricting their access to institutional credit and electric power. And if not, their provision should be made conditional upon adoption of water-saving technologies and agronomic practices.

Engage grass-root institutions in participatory water management: Governments should increasingly involve grass-root institutions such as village panchayats and non-governmental organizations to sensitize farmers about negative externalities of excessive withdrawal of groundwater and their short-run and long-run consequences, and also for implementation, coordination and monitoring of land and water conservation programmes.

Rehabilitate canal irrigation: Canals comprise an important source of irrigation and also of groundwater recharge. However, in both states canal-irrigated area has remained almost static for some time due to poor maintenance of canal system. In fact, investment in canal irrigation in Punjab has declined, while in Haryana it has remained almost stagnant.

Rehabilitation of canals is essential to reduce irrigation pressure on groundwater.

***Reform agricultural price policy*:** Cereal-centric MSP-based procurement acts as an insurance against price and market risks. Several crops are covered under MSP, but except paddy and wheat, other crops are rarely procured. In Punjab and Haryana, about 90% paddy output is procured at MSP. Such a huge procurement is a disincentive to crop diversification (Negi *et al.*, 2020). Hence, it is important to limit procurement based on demand and supply situation in states. The rest of the paddy surplus can be covered under price deficiency scheme. Sekhar (2021) finds a mix of MSP and price deficiency scheme more effective in reducing fiscal burden.

***Regulate rice milling industry*:** Increasing procurement of paddy has been accompanied by a significant expansion of rice milling industry. Currently, there are around 4500 rice mills in Punjab and 1300 in Haryana. Henceforth, governments should restrict fresh licenses for establishment of new mills and also capacity expansion of existing mills.

Reform public distribution system: Alongside reforms in price policy, there is also a need for reforms in food distribution policy. Paddy and wheat may partially be substituted with millets and pulses in public distribution system (PDS). Another option could be cash transfer in lieu of grains, which offers consumers a wider choice of foods while reducing cost of holding food stocks. Such reforms provide signals to farmers to produce crops conforming to consumers' food preferences.

In essence, there are several policies, in and outside agriculture, which can potentially offset effect of a direct policy instrument as the Preservation of Subsoil Water Act. Management of groundwater, thus, requires a holistic approach encompassing technologies, institutions, regulations and policies that directly or indirectly impinge on groundwater use.

1 Introduction

Worldwide, groundwater plays a crucial role in agri-food production systems. Bulk of the drinking and irrigation water requirement is met from aquifers beneath the earth's surface. During the past five decades, there has been an unparalleled increase in groundwater use in agriculture, primarily to support spread of high-yielding seeds and fertilizers to produce enough food for all. No denying, groundwater has been a significant instrument in augmenting food supplies, serious concerns have now cropped up regarding its sustainability, especially in developing countries located in tropics and subtropics (Falamiglietti, 2014). According to Vanham *et al.* (2021), 32 to 46% of global population faces water stress at least for one month in a year, and 80% of it lives in Asia.

If rate of groundwater withdrawal exceeds its recharge, overexploitation occurs (Wada *et al.*, 2014). India, the most populous and largest user of groundwater (approximately 23% of global total), is one of the most water-stressed countries (Siebert *et al.*, 2013; World Bank, 2010; United Nations, 2023). There are several hotspots of overextraction of groundwater in the country, for example, north-western states of Punjab, Haryana and Rajasthan (Rodell *et al.*, 2009; United Nations, 2023). The NASA-National Aeronautics and Space Administration of the US has estimated that over past few decades, groundwater in these states has decreased by more than 88 million acre-feet, which is eight times the amount that the Lake Mead, the largest reservoir in the US, holds (Sharghi, 2023).

The Constitution of India classifies agriculture as a state subject; hence, any policy, institutional or regulatory matter related to agriculture falls in states' jurisdiction. A few states facing acute scarcity of water have pushed for some technological, institutional and policy measures to arrest declining groundwater level.

This paper evaluates the impact of a stringent regulation on groundwater use in agriculture. The governments of Punjab and Haryana in 2009 brought out almost an identical regulation — the 'Punjab Preservation of Subsoil Water Act 2009' (hereafter the PPSWA)' and the 'Haryana Preservation of Subsoil Water Act 2009' (hereafter the HPSWA) — to prevent excessive and indiscriminate use of groundwater in paddy, the water-guzzling crop.

Generally, paddy is transplanted during peak summers, i.e., in May, which makes it excessively groundwater-dependent. Due to lack of rainfall or canal water at this time, groundwater is extensively extracted for preparing fields until onset of the monsoon in first week of July (Rosencranz *et al*., 2021). Further, there is a significant evapotranspiration loss due to hot and dry weather at this time. These regulations mandated paddy sowing towards onset of the monsoon. The PPSWA prohibits raising paddy nursery before May 10 and its transplantation not before June 10. Corresponding dates in the HPSWA are May 15 and June 15. And their non-compliance attracts a penalty of Rs. 10,000 per hectare of cropped area, or disconnection of electricity supply, or destruction of nursery and transplanted crop at farmer's expense, or all of these.

Punjab and Haryana lie in water-rich Indo-Gangetic River basin and have been at forefront of the Green Revolution. Together, they share less than 7% of the country's total cropped area but are amongst the largest producers of paddy and wheat, contributing 14% and 27%, respectively to the total production. To produce more foodgrains, mainly paddy and wheat, for nation's food security, since the late 1960s farmers have been incentivized through input subsidies and output price support. This cereal-centric policy helped achieve intended objective of self-sufficiency in foodgrains yet led to distortion in cropping pattern and degradation of natural resources. For example, before advent of the Green Revolution in mid-1960s paddy was not an important crop in these states but its share in the gross cropped area (GCA) in Punjab increased to 40% in 2019-20 from 7% in 1970-71, and in Haryana to 24% from 4%.

The tremendous increase in production of staple food crops came at the cost to natural resources. Groundwater level in Punjab declined continuously to 18.06 m in 2018-19 from 12.10 m in 2009-10 and 9.25 m in 2000-01. In Haryana too, it declined to 17.31m in 2018-19 from 12.9 m in 2009-10 and 9.06 m in 2000-01. Current level of groundwater development is estimated at 164% in Punjab and at 136% in Haryana (GoI, 2023). On the other hand, rainfall is low — 534 mm in Punjab and 680 mm in Haryana as compared to national average of 1236 mm. Overexploitation of groundwater can have devastating effects on natural stream flow, groundwater-fed wetlands and related ecosystems (Gleeson *et al*., 2010), and consequently sustainability of agriculture. As groundwater level plummets, deeper wells are dug, and more powerful pumps are deployed to extract water.

Groundwater regulation has attracted attention in economic research but focusing on Punjab *per se*. Haryana also implemented an identical regulation at same time and is a good basis to understand the effects of design of the Act itself, in terms of it being an indirect instrument and possible responses offsetting its effect. Singh (2009) using time-series experimental data on paddy acreage, crop water requirement, groundwater use, and precipitation, contemplated that the PPSWA can potentially prevent falling groundwater level by 30 cm. However, limitation of such an *ex-ante* assessment is that it assumes full compliance of the Act and no offsets from behavioural responses such as changes in power sources and type of pumps, and acreage response of water-intensive crops that directly influence groundwater draft.

Sekhri (2012) showed a decline in groundwater level in intensively paddy cultivated districts of Punjab after implementation of the Act. On the other hand, Tripathi *et al*. (2016) have shown an improvement in it during post-Act period. Sharma *et al*. (2023) also have reported an improvement in it initially but a decline later on.

One of the main limitations to these studies is that their assessments have utilized variation in paddy acreage across districts, while the Act applies equally to all districts in a state. Hence, paddy acreage itself could be endogenous. Thus, identification dependent on paddy acreage (i.e., high paddy-growing districts as treatment) may be problematic, if acreage changes across districts with respect to baseline. Constrained by shorter cultivation cycle, farmers could respond by expanding paddy acreage based on their subjective beliefs. Similarly, perceptions could engender more applications of irrigation and consequently excess withdrawal of groundwater if farmers perceive more benefit from intensification of irrigation system.[1] These studies have conjectured, but not estimated, such possible behavioural responses.

Second major limitation is the time effect of regulation. Except Sharma *et al*. (2023), all others have drawn inference based on short period data (for 2-3 years) post-implementation of the Act. While several changes take place in long-run, which may interact with regulation and influence its outcome differently.

Third, several factors like prior groundwater level, extent of paddy procurement at minimum support price, change in type and power of pumps (e.g., submersibles in lieu of centrifugal pumps), and adjustment in irrigation hours *inter alia* can influence groundwater draft. These studies have not accounted for such behavioural responses. Further, these studies

1 At least seven districts, four in Punjab (i.e., Bhatinda, Mansa, Muktsar, and Rupnagar), and three in Haryana (i.e., Fatehabad, Jind and Sonipat) switched from control to treatment based on median cut-off.

have not estimated the causal impact of the Act on groundwater draft, which we argue is an appropriate outcome to look at as it incorporates responses of agents to policy change.

Fourth, several time-varying factors can influence draft and level of groundwater simultaneously across treated and untreated or control units. These studies have estimated the impact of the Act employing fixed effects and difference-in-difference methods that cannot account for such time-varying factors and behavioural responses. This means that it is not only spatial units but also time periods that need to be weighted differentially in creating counterfactual of the Act.

Employing the most recent impact evaluation technique 'synthetic difference-in-difference', this paper uniquely estimates the outcomes of the PPSWA and the HPSWA on groundwater draft and its level. And unlike other studies, it considers state(s) that enacted the Act as treated unit(s), and other states as untreated units.

Information on groundwater draft is available discontinuously[2] yet it represents a direct behavioural response to the Act. Our submission is that similarity of regulation in two states could have engendered behavioural responses in terms of crop choice and acreage, intensification of irrigation system (power and type of pumps, and irrigation hours), and both legit (i.e., planting water-intensive spring maize in Punjab, and sunflower in Haryana) and illegit (i.e., early sowing of paddy) non-compliances.[3] Such responses not only offset effects of a regulation but probably may worsen its outcomes by aggravating groundwater draft. In this study, we have extended post-Act period upto 2018-19, which allows a comparison of short and long run effects that are expected to be different.

Averaged over a long period, groundwater level worsened in both states despite the Act being in force. What factors are responsible for this paradox? This paper finds out factors that can explain this perverse outcome. Specifically, it addresses the following questions.

- Has the Preservation of Subsoil Water Act been effective in preventing overextraction of groundwater?

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2 We have interpolated groundwater draft for our analysis.

3 Producing one kilogram of rice requires 3800-4000 litres of water, which is 6-7 times more than required to produce an equivalent quantity of summer maize. On the other hand, water requirement of spring maize is as high as of paddy (Kukal, 2022) because of its requirement of frequent irrigation, at an interval of 5-7 days (Sharma *et al.*, 2014; Kaur and Arora, 2018).

- What are the ways in which effectiveness (or lack of it) of the Act is determined by behavioural responses?
- What are the impacts of the Act on groundwater extraction, encompassing behavioural responses to it?

As an indirect instrument to prevent overextraction of groundwater by regulating date of sowing/transplanting of crop rather groundwater draft itself (logistically difficult with a vast number of small farmers and non-separable groundwater and land rights – riparian rights) can lead to perverse responses, especially when supplementary policies like subsidized electric power and procurement of crop at minimum support price (MSP) have persisted as before. Legal framework in India does not define groundwater rights separate from land rights.[4] Thus, groundwater's legal status is based on a common law approach to land ownership doctrine, meaning that groundwater belongs to landowner as legally the term 'land' includes water below it (Rosencranz *et al*., 2021).

Rest of the paper is organized as follows. Chapter 2 presents sources of data used in this study. A brief description of method of quantifying impact of the Act on groundwater use is provided in Chapter 3. Chapter 4 discusses groundwater scenario in Punjab and Haryana, and summarizes key policies influencing groundwater use. Chapter 5 discusses factors that influence demand and supply of groundwater. Chapter 6 presents results, and discusses behavioural responses that can offset the potential impacts of the Acts. Chapter 7 discusses reasons that can lead to perverse outcomes of regulations. Conclusions and policy implications are provided in Chapter 8.

[4] The Indian Easement Act 1882 entitles a farmer to withdraw limitless water from beneath the land he/she owns.

2 Data Sources

This paper utilizes data compiled from several sources (Table 1). Data on groundwater depth has been obtained from the Central Ground Water Board (CGWB), Ministry of Jal Shakti, Government of India. Data on rainfall have been obtained from the Indian Metrological Department, Ministry of Earth Science, Government of India. Information on acreage under paddy and other crops has been compiled from the Directorate of Economics and Statistics, Ministry of Agriculture and Farmers' Welfare, Government of India.

Table 1. Data sources

Type of data	Source of data
Groundwater level	India Water Resource Information System, Ministry of Jal Shakti, Government of India- https://indiawris.gov.in/wris/#/groundWater
Groundwater draft	Groundwater Resource Assessment, CGWB, Ministry of Jal Shakti, Government of India- http://cgwb.gov.in/ground-water-resource-assessment-0
Rainfall	India Meteorological Department, Ministry of Earth Science, Government of India- https://mausam.imd.gov.in/
Electricity consumption	Central Electricity Authority, Ministry of Power, Government of India- https://cea.nic.in/annual-generation-report/?lang=en
Cropped area and irrigation	Land Use Statistics, Directorate of Economics and Statistics, Ministry of Agriculture and Farmers Welfare, Government of India- https://eands.dacnet.nic.in/
Tube-well numbers and electrification	Minor Irrigation Census, Ministry of Jal Shakti, Government of India- http://micensus.gov.in/ Economic and Statistical Organization, Department of Planning, Government of Punjab- https://www.esopb.gov.in/static/Publications.html Department of Economic and Statistical Affairs, Government of Haryana- https://esaharyana.gov.in/statistical-wing/
Paddy irrigation hours	Cost of Cultivation, Directorate of Economics and Statistics, Ministry of Agriculture and Farmers Welfare, Government of India- https://eands.dacnet.nic.in/Cost_of_Cultivation.htm

Data on electricity-operated tube-wells are taken from the Minor Irrigation Census (MIC) conducted by the Department of Water Resources, Ministry of Jal Shakti, Government of India; on electricity consumption in agriculture from the Central Electricity Authority (CEA), Ministry of Power, Government of India; and on irrigation hours from the Cost of Cultivation Scheme (CCS) implemented by the Commission on Agricultural Costs and Prices (CACP), Ministry of Agriculture and Farmers Welfare, Government of India. The dataset pertains to 2000-01 to 2018-19.

The CGWB monitors groundwater level four times a year — during pre-monsoon (April/May), monsoon (August), post-monsoon kharif (November) and post-monsoon rabi (January) — in 22,730 observation wells spread across all states of India. Determinants of groundwater draft comprise rainfall, electricity consumption, cropping intensity, irrigation dependence on groundwater, paddy acreage, irrigation hours, tube-well density, and water extraction capacity of pumps.

During 2000-01 to 2018-19, mean groundwater depth in Punjab and Haryana was 12.71 m and 13.97 m, respectively; significantly deeper than average for the donor pool states (Andhra Pradesh, Assam, Bihar, Chhattisgarh, Gujarat, Himachal Pradesh, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Odisha, Rajasthan, Tamil Nadu, Uttar Pradesh, Uttarakhand, and West Bengal). Groundwater level in both states has fallen significantly during past two decades. In Punjab it fell to 18.06 m in 2018-19 from 12.10 m in 2009-10 and 9.25 m in 2000-01. Similarly, in Haryana, it fell to 17.31 m in 2018-19 from 12.9 m in 2009-10 and 9.06 m in 2000-01.

Current level of groundwater development is estimated at 164% for Punjab and at 134% for Haryana. In both states, rainfall is scarce — 534 mm in Punjab and 687 mm in Haryana, which is about half of that for donor pool states. Electricity consumption in agriculture in Punjab and Haryana is 2195 kWh/ha and 2172 kWh/ha, respectively, which is almost three times of that for donor pool states. Over 90% tube-wells in these states are run on electric power. Significantly higher use of electric power is mainly because of heavy subsidy on it — Rs 17674 and Rs 14382 per hectare of net sown area in Punjab and Haryana, respectively. In Punjab and Haryana, near-zero cost of electricity use in agriculture has existed for long.

Paddy acreage is larger in Punjab and Haryana compared to the average for donor pool states. Also, irrigation hours per hectare of paddy-cropped area are 2.3 and 1.7 times more in Punjab and Haryana, respectively. Continuous increase in paddy acreage has accelerated groundwater extraction. Since most pumps have been electrified, electricity policy regime is an important determinant of groundwater extraction.

Both states enacted the Preservation of Subsoil Water Acts almost at same time, i.e., in 2009, and these are almost similar in their content. Other states that did not implement any such Act serve as a control for generating a counterfactual groundwater level or draft in the absence of the Acts.

3 Method for Estimating Impact of Regulation

To assess the impact of the Preservation of Subsoil Water Act on groundwater use we have employed 'synthetic difference-in-difference' (SDiD) method, which combines synthetic control matching (SCM) and difference-in-difference (DiD) techniques. The SCM constructs a synthetic Punjab (or Haryana) as a convex combination of donor pool states that closely resembles it in important determinants of groundwater draft or level. Like matching estimators, SDiD demonstrates affinity between an administrative unit exposed to an intervention and its counterfactual or synthetic situation.

The SCM, pioneered by Abadie and Gardeazabal (2003), is data-driven in choosing units for comparison. It provides insights into systematic selection of comparison units based on similarity of relevant parameters and constructs a counterfactual of treated unit by assigning appropriate weights to untreated units. Further, it allows incorporation of temporal effects of observed and unobserved predictors on outcome assuming that pre-intervention covariates have a linear relationship with post-treatment outcome (Kreif *et al*., 2016).

The advantage of a counterfactual is that pre-intervention characteristics of treated unit are more accurately approximated by a combination of characteristics of untreated units rather of a single untreated unit (Abadie *et al*., 2015). Outcome of each untreated unit is weighted to construct a counterfactual outcome for treated unit in the absence of an intervention (Kreif *et al*., 2016). If intervention is effective, then there is a divergence, positive or negative, between its synthetic and actual outcome in post-treatment period.

Suppose there are S+1 administrative units, of which one unit (Punjab or Haryana or combination thereof) receives a treatment, and others comprise a 'potential control' or 'donor pool'. Let, Y_{it}^{N} be the outcome for unit i at time t in the absence of an intervention, where i= 1, 2..., S+1 and time t=1, 2,…,T. T_0 is the timing of intervention such that $1 \leq T_0 < T$. Further, Y_{it}^{N} is the outcome that could have been realized by unit i at time t in period T_0+1 to T. Here, the assumption is that outcomes of untreated units are not affected by intervention in treated unit. Thus, effect of an intervention through SCM can be assessed as:

$$\delta_{it} = Y_{it}^{I} - Y_{it}^{N} \qquad (1)$$

Let, β_{it} be an indicator taking a value of 1 if unit *i* is exposed to an intervention at time *t*, or zero otherwise, i.e., $\beta_{it} = \begin{cases} 1 & if\ i = treated\ unit\ and\ t > T_0 \\ 0 & Otherwise \end{cases}$, then, observed outcome for unit *i* at time *t* is estimated as:

$$Y_{it} = Y_{it}^{N} - \alpha_{it}\beta_{it} \qquad (2)$$

Since, Y_{it}^{I} is observed, one needs to estimate Y_{it}^{I} for calculating α_{it}. Let, Y_{it}^{I} is given by a factor model such that:

$$Y_{it}^{N} = \alpha_t + \theta_t z_i + \tau_t \mu_i + \varepsilon_{it} \qquad (3)$$

Where, α_t is unknown with a constant factor loading across units, z_i is a *(r* ×1*)* vector of observed covariates (not affected by intervention), θ_t is a *(*1 × *r)* vector of unknown parameters, τ_t is a *(*1×*F)* vector of unobserved common factors, and μ_i is a *(F*×1*)* vector of unknown factor loadings. Error term, ε_{it}, is an unobserved transitory shock at an administrative level with zero mean.

The SCM subjects attributes of a predictor variable in pre-treatment period to a dual optimization process to minimize $\sum V_m(X_{1m} - X_{0m}W)^2$ by selecting optimal values of *W* and V_m. X_{1m} is the value of m^{th} attribute of treated unit; X_0m is a 1 x *j* vector of values of m^{th} predictor attributes of each control unit in S. *W* is a vector of weights for control units, and V_m is a vector of weights for attributes of control units such that these maximize probability to predict outcome (Abadie *et al*., 2010). Such an optimization process minimizes prediction error between actual and counterfactual outcome in pre-treatment period. Y_1 is observed outcome for treated unit. Y_0W is weighted average of outcomes of untreated units. If no important predictor variable has been omitted, then a reliable synthetic match is created such that Y_1-Y_0W is small in pre-intervention period (Abadie *et al*., 2010). If counterfactual outcome diverges significantly from actual outcome in post-treatment period, then it is attributed to the intervention.

In recent years, a flurry of papers on SCM has emerged that introduce a setting with only a single or few treated units, compensating for parallel trends by reweighting control units to match their pre-exposure trends. For holding up estimated results obtained through SCM, Arkhangelsky *et al*. (2021) presented a new method 'synthetic difference-in-difference', which we employ in this study.

The SDiD combines attractive features of SCM and DiD. Like SCM, it reweights and matches pre-intervention trends to weaken reliance on parallel trend assumption. The SDiD is invariant to additive unit-level shift as in case of DiD. It assigns greater weights to control units that are more like treated units, and also to time period which is comparable with treated period. In DiD, raw data rarely exhibit parallel time trends for treated and control units, which necessitate adjustments in covariates or selection of appropriate time periods. However, SDiD makes this process automatic (Arkhangelsky *et al*., 2021), and involves following maximization process:

$$\left(\hat{\tau}^{sdid},\ \hat{\mu},\ \hat{\alpha},\hat{\beta}\right) = arg.min\,\{\textstyle\sum_{i=1}^{N}\sum_{t=1}^{T}(Y_{it}-\mu-\alpha_i-\beta_t-W_{it}\tau)^2\hat{w}_i^{sdid}\hat{\lambda}_t^{sdid} \quad (4)$$

The SDiD puts greater weights on units and time periods that on average are like treated unit in terms of their past. Unit weights are so designed that average outcome for treated unit is approximately parallel to weighted average of control units, and time weights are so designed that average post-treatment outcome for each control unit differ by a constant from weighted average of pre-treatment outcome for same control units. The SDID reweighs and matches pre-exposure trend to weaken reliance on parallel trend, and like canonical DiD it is invariant to additive unit-level shift. Both DiD and SCM are special cases of nested models that we implement alongside SDiD for comparison of estimates.

Optimization for DiD has no time and unit weights:

$$\left(\hat{\tau}^{did},\ \hat{\mu},\ \hat{\alpha},\hat{\beta}\right) = arg.min\,\{\textstyle\sum_{i=1}^{N}\sum_{t=1}^{T}(Y_{it}-\mu-\alpha_i-\beta_t-W_{it}\tau)^2 \quad (5)$$

While, SCM has:

$$\left(\hat{\tau}^{sc},\ \hat{\mu},\ \hat{\alpha},\hat{\beta}\right) = arg.min\,\{\textstyle\sum_{i=1}^{N}\sum_{t=1}^{T}(Y_{it}-\mu-\beta_t-W_{it}\tau)^2\hat{w}_i^{sc} \quad (6)$$

The SDiD enables causal inference with large panels even if there is a short pre-treatment period. In our study, we have comparatively a large pre-treatment span of nine years for a panel of 19 states. A synthetic control group is constructed using same approach as in SCM. Average treatment effect (ATT) is, however, estimated using elements of DiD comparing change in outcome of treated unit and synthetic control group before and after treatment. Thus, SDiD improves DiD by accounting for pre-existing differences between treatment and control units. It estimates the treatment effects by comparing change in outcomes of treated unit and synthetic control group before and after treatment, and thus, combines DiD and SCM.

By construction, in contrast to SCM, the SDiD can be used for impact evaluation even if pre-treatment period is short. Estimates, however, are comparatively robust if there are more pre-treatment periods, which is an advantage for us (nine pre-treatment periods). Estimator is considered consistent and asymptotically normal, and is, thus, amenable to hypothesis testing if combination of control units and pre-treatment periods is sufficiently large relative to combination of treated units and post-treatment periods (Arkhangelsky *et al*., 2021), which again holds in our case, where impacts are evaluated for individual treatment units and combination thereof.

The flip side of SDiD is the requirement of a balanced panel and treatment timing to be identical for all treatment units.[5] Fortuitously, in our study, treatment timing is same, i.e., year 2009. In the process of pre-treatment matching, SDiD tries to determine average treatment effect for entire sample. This approach might render individual time-period estimates to be less precise but provides an unbiased evaluation (Arkhangelsky *et al*., 2021). Standard errors for treatment effects can be obtained with jacknife or bootstrap methods, and if a cohort has only one treated unit then with placebo method. Hence, we estimate separate models for Punjab and Haryana, and rely on placebo method for inference. Since in both states the Act is identical and its timing of implementation is same, we also combine their dataset (i.e., more than one treatment unit), which allows obtaining standard errors using bootstrap method.

In practice, pre-treatment variables have a minor role in SDiD, as lagged outcomes have a better predictive power, making treatment variables less critical. For estimating impact of a policy when observations are available in a panel or repeated cross-section of units and time periods (see, Roth *et al*., 2022), a number of empirical studies have employed DiD. This had been the case in evaluating impact of the PPSWA conditional on satisfying requirement of parallel trends.[6] Whether this assumption is reasonable in a particular context is an empirical issue. Synthetic control approach comprises one particular solution to the challenge due to difficult requirement of parallel trends as in case of DiD. The SDiD assigns weights to control units that make time trend parallel (not necessarily identical) to that for treated units in pre-intervention period, and then applies DiD to reweighted panel.

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5 Recent innovations in synthetic DiD allow staggered timing of treatment.

6 Recent methodologies have worked with less stringent assumptions including methods that allow bounded deviation from strict parallel treands settling on partial identification (Rambachan and Roth, 2023; Goodman-Bacon, 2021).

As an input, SDiD requires a balanced panel of N units observed over T time periods, which we adopt. The goal of SDiD is to consistently estimate causal effect of a policy intervention (i.e., average treatment effect on treated, i.e., ATT) even if parallel trend assumption may not hold completely. A key element of both Acts is that treated units remain exposed to treatment throughout. The SDiD would require at least two pre-treatment periods to determine control units.

As estimation procedure includes unit-fixed effects, SDiD seeks to match treated and untreated units on pre-treatment trends, and not necessarily on both pre-treatment trends and levels, which allows a constant difference between treated and untreated units (Clarke *et al*., 2023).

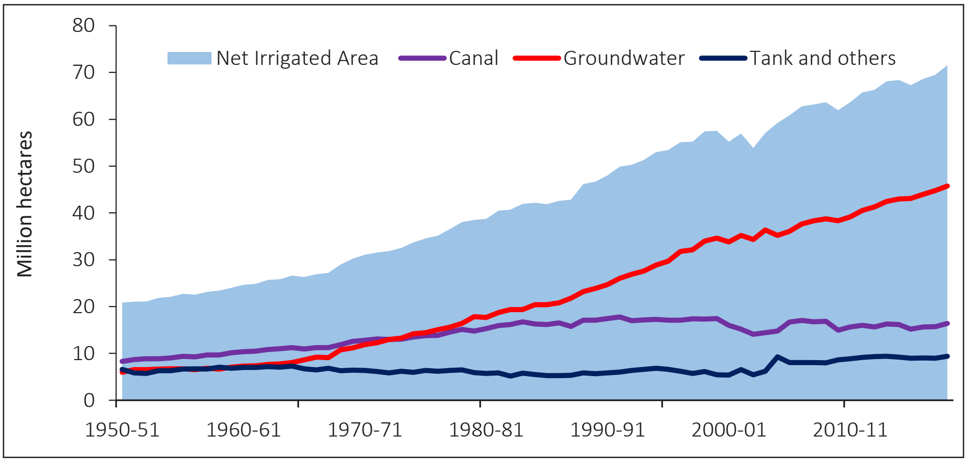
4 Groundwater Scenario and Policies

India as the biggest user of groundwater has an annual groundwater draft of 245 billion cubic meters (bcm), of which 89% is used in agriculture. Between 2000-01 and 2017-18, number of deep tube-wells surged almost seven times, from 0.53 million to 3.75 million. Approximately half of these are in Punjab, Rajasthan and Haryana, and are predominantly owned by individual farm families. About 40% deep tube-wells have a depth range of 70-90 m and another 26% of 90-110 m.

Paddy, wheat and sugarcane are cultivated in 62% of total cropped area and account for 80% of total irrigation water use (Sharma *et al.*, 2018). Preponderance of individual ownership of wells renders monitoring of groundwater extraction extremely difficult; hence, policy focus has mostly been on supply side interventions.

Figure 1 plots path of irrigation development in India. After an initial lead by surface irrigation, groundwater has dominated irrigation landscape. Its share in irrigated area almost doubled during the past seven decades, from 31% between 1950-51 to 1968-69 to over 60% between 1991-92 and 2018-19. Parallel, share of canal irrigation fell from 42% to 27%.

Figure 1. Irrigation development in India



Figures 2a-2c indicate high irrigation intensity and sub-state overexploitation of groundwater (mainly in high paddy areas) in northwest India where lie Punjab and Haryana. Compared across states, the highest number of overexploited groundwater blocks are in Punjab, and third highest in Haryana (Figure 2a to c). Deterioration in groundwater has been comparatively severe in paddy-growing districts (highlighted in red in Figure 2d).

Groundwater has been overextracted due to free or highly subsidized electric power, or no tariff levied on water itself, implying near-zero marginal cost of irrigation (Pahuja *et al.*, 2010; Shah *et al.*, 2012; Mitra *et al.*, 2023).

Figure 2a. Spatial variation in groundwater development in India

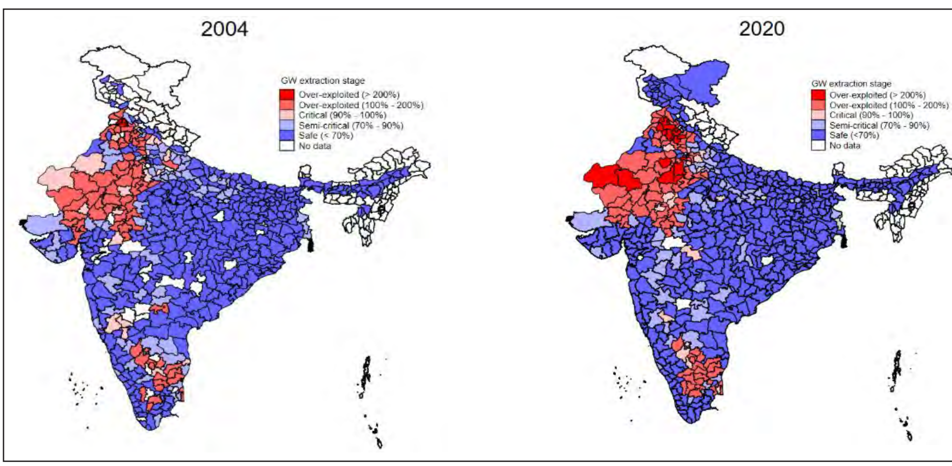


Figure 2b. Groundwater availability and usage, 2020

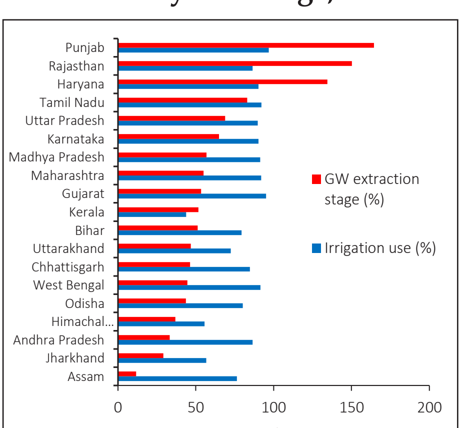


Figure 2c. Overexploited groundwater blocks, 2020

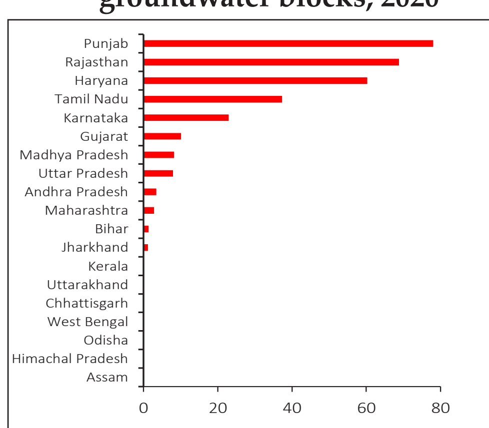
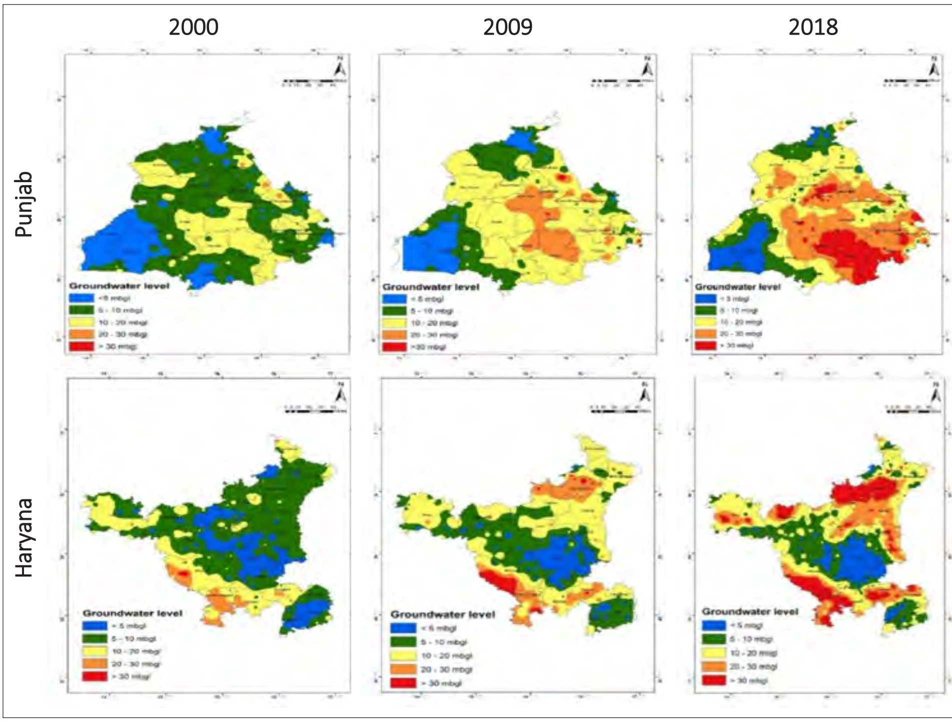


Figure 2d. Groundwater situation in Punjab and Haryana



Extraction of groundwater although increased throughout the country, its extraction is exceptionally high in Punjab and Haryana. Between 2004 and 2017, groundwater extraction increased by 14%, from 30.34 bcm to 34.56 bcm in Punjab; and in Haryana by 27%, from 9.1 bcm to 11.53 bcm. Its intensity is far more evident in these states — groundwater extraction is the highest at 8381 cubic m/ha in Punjab, followed by Haryana (3278 cubic m/ha) and Tamil Nadu (CGWB, 2004; 2009; 2017).

Table 2 provides important details on determinants of groundwater use in Punjab and Haryana *vis-à-vis* donor pool states. Punjab and Haryana stand out prominent in groundwater use, electricity consumption and tube-well density, and comparatively low in groundwater recharge.

Table 2. Status of groundwater, 2017

State	Share of irrigation in groundwater draft (%)	Share of rainfall in groundwater recharge	Electricity use (kWh/ ha of NSA)	Well density (no./000 ha of NSA)	Electric wells (%)	Over-exploited blocks (%)
	Treated units (with Subsoil Water Preservation Acts)					
Punjab	96.59	28.63	2735.8	357	96.78	79
Haryana	92.24	45.22	2698.04	232	94.05	61
	Donor pool states (without Subsoil Water Preservation Acts)					
Rajasthan	88.55	75.55	1310.6	76	70.68	63
Himachal Pradesh	51.28	0.88	116.1	19	93.15	50
Tamil Nadu	88.66	42.33	2853.8	439	93.83	40
Uttar Pradesh	89.20	56.24	1049.8	208	14.80	11
Karnataka	90.81	54.99	2136.8	129	99.47	26
Gujarat	94.55	71.30	1417.1	137	98.87	10
Uttarakhand	79.27	40.79	695.0	84	16.10	0
Madhya Pradesh	92.32	76.66	1334.0	142	94.05	7
Maharashtra	92.47	66.75	2058.6	081	97.69	3
Andhra Pradesh	87.93	60.97	3447.3	220	90.66	9
Kerala	45.69	79.55	171.5	46	98.34	1
Bihar	81.30	73.13	140.6	124	6.73	2
West Bengal	91.55	81.73	288.8	67	27.25	0
Chhattisgarh	84.68	74.16	1076.8	87	97.20	0
Odisha	80.37	71.86	139.5	51	23.34	0
Jharkhand	50.63	91.14	164.3	133	4.89	1
Assam	72.16	95.92	17.2	52	0.66	0

Water requirement of paddy is almost twice of that of wheat. Both crops rely heavily groundwater. Following the land consolidation programme during the 1950s and then the Green Revolution during 1960s, farmers started shifting to groundwater, a reliable source for irrigation. In Punjab and Haryana, tube-well irrigation became so widespread that Repetto (1994) was compelled to conclude that the 'Green Revolution is more a tube-well revolution than a wheat revolution'. Alongside, there has been rise of so-called tube-well capitalists with rich farmers investing more in tube-well irrigation.

Until the 1970s, state electricity utilities levied tariff on electric power for agriculture based on its metered consumption. However, with rapid increase in tube-wells, electricity meters were removed and a flat tariff was introduced with an idea of increasing flat tariff gradually (Rosencranz *et al*., 2021). It, however, turned out hard to implement because of complex political economy of agricultural incentives, which once provided for are difficult to withdraw. Governments have continued with subsidized or free unmetered electric power as a competitive populist measure to gain electoral support. Punjab has been providing free electricity for irrigation since 1997, which has led to proliferation of tube-wells and consequently dominance of water-intensive paddy-wheat cropping system.

Haryana also provides subsidized electric power for irrigation charging a flat rate (no volumetric pricing) based on power rating of pumping device — Rs 15 per horse power per month for motor capacity upto 15 BHP (about two-third tube-wells) and Rs 12 per horse power per month for motor capacity of more than 15 BHP (about one-third tube-wells) on unmetered connections. Extremely low unmetered flat tariff encouraged intensive use of electricity. On the other hand, canal irrigation deteriorated due to poor maintenance. As an important factor in groundwater extraction, power tariff is a key predictor in our analysis.

Overall, subsidy on electric power has encouraged cultivation of water-intensive crops using high-capacity pumping technology that aggravated groundwater draft. In Haryana, in the past decade, more than two-third observational wells experienced a significant decline in groundwater level (GoI, 2022). Groundwater extraction in Punjab is 64% higher over its sustainable limit, while its recharge rate is 26%. Groundwater in about 80% of the administrative blocks in Punjab and 60% in Haryana has been overexploited (GoI, 2023).

5 Factors in Groundwater Sustainability

Principally, there are four pathways through which erosion of groundwater resources can be checked. These are discussed below.

(i) Crop choices

The most direct path to check groundwater erosion is to cultivate crops as dictated by natural resource endowment. Agro-climatic conditions of Punjab and Haryana are characterized by alluvial soils and low yet high seasonal concentration of rainfall, significant variation in temperature. Despite unfavourable climatic conditions, paddy emerged as the most prominent crop replacing low-water footprint crops like millets, pulses and oilseeds. Table 3 and figures 3a and 3b present salient features of crop agriculture that influence groundwater draft. In both states, area under paddy and wheat increased consistently and significantly (Figure 3a). Simultaneously, cropping intensity also increased increasing farmers' dependence on groundwater.

Table 3. Key characteristics of agriculture in Punjab and Haryana

Particulars	1970-71	1980-81	1990-91	2000-01	2010-11	2020-21
Punjab						
Gross sown area ('000ha)	5658	6763	7502	7941	7883	7834
Gross irrigated area ('000ha)	4243	5781	7055	7664	7724	7787
Cropping intensity (%)	140	161	178	187	190	190
Irrigation intensity (%)	147	171	180	190	190	186
Groundwater irrigation (%)	55	57	57	76	73	72
Canal irrigation (%)	45	42	42	24	27	28
Haryana						
Gross sown area ('000ha)	4957	5462	5919	6115	6505	6566
Gross irrigated area ('000ha)	2230	3309	4237	5223	5543	6504
Cropping intensity (%)	139	152	166	173	165	182
Irrigation intensity (%)	146	155	163	177	192	182
Groundwater irrigation (%)	37	45	48	50	57	65
Canal irrigation (%)	62	54	51	50	43	35

Figure 3a. Crop acreage in Punjab and Haryana

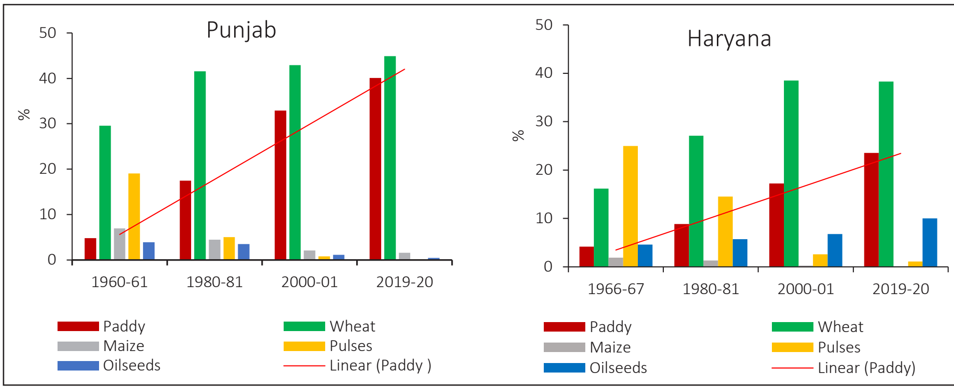
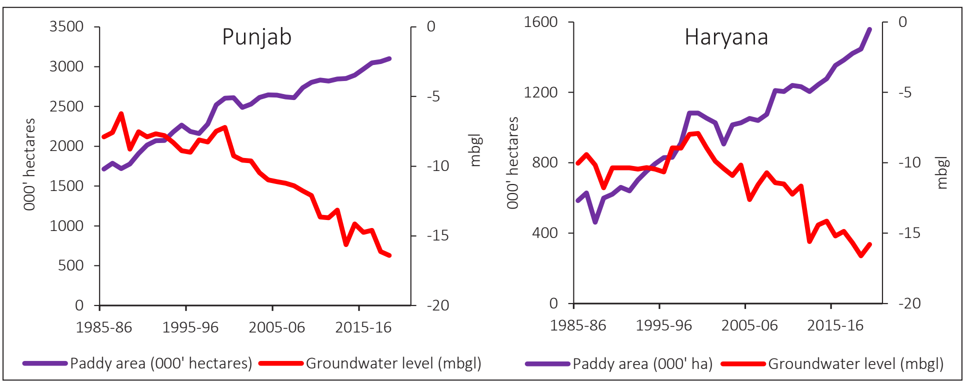


Figure 3b. Paddy acreage and groundwater level in Punjab and Haryana



Procurement of paddy and wheat at minimum support prices, which began in 1966, had been a significant incentive for farmers to allocate more area to these crops. Between 2000-01 and 2019-20, their procurement increased considerably (Table 4). In 2019-20, about 92% paddy and 73% wheat output in Punjab was procured by the Government of India. Corresponding figures for Haryana are 89% and 78%, respectively.

Thus, paddy and wheat do not confront significant price and market risks as compared to millets, maize, pulses, and oilseeds (Shah *et al.*, 2012; Vatta *et al.*, 2013). This aggravated deterioration in groundwater level (Figure 3b). A more comprehensive and effective policy could have been inclusion of non-cereal water-efficient crops in MSP-based procurement system.

Table 4. Procurement of rice and wheat for central pool

Year	Paddy			Wheat		
	Production (million tons)	Procurement (million tons)	Procurement as % of production	Production (million tons)	Procurement for (million tons)	Procurement as % of production
Punjab						
2000-01	9.15	6.96(33)	76.03	15.55	9.42(58)	60.59
2010-11	10.84	8.63(25)	79.67	16.47	10.21(45)	61.98
2015-16	11.82	9.35(27)	79.08	16.08	10.34(37)	64.34
2016-17	11.59	11.05(29)	95.39	16.44	10.65(46)	64.77
2017-18	13.38	11.84(31)	88.47	17.83	11.71(38)	65.65
2018-19	12.82	11.33(26)	88.40	18.26	12.69(35)	69.50
2019-20	11.78	10.88(21)	92.33	17.62	12.91(38)	73.30
Haryana						
2000-01	2.70	1.48(7)	54.95	9.67	4.50(28)	46.51
2010-11	3.47	1.69(5)	48.59	11.63	6.35(28)	54.57
2015-16	4.15	2.86(8)	69.02	11.35	6.78(24)	59.71
2016-17	4.45	3.58(9)	80.46	11.55	6.75(29)	58.48
2017-18	4.52	3.99(10)	88.25	10.77	7.43(24)	69.04
2018-19	4.52	3.94(9)	87.27	12.57	8.78(25)	69.86
2019-20	4.82	4.31(8)	89.28	11.88	9.32(27)	78.48

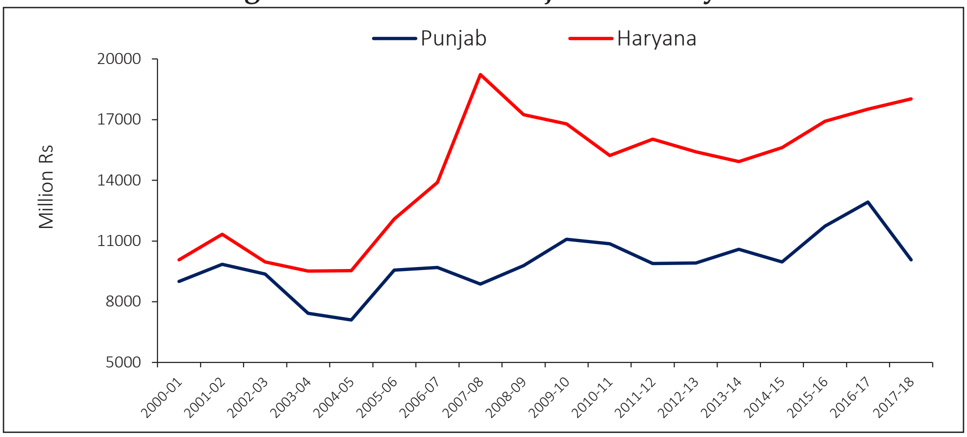
Note: Figures in parentheses are shares in all-India total procurement.

Extensive cultivation of paddy has been main factor in groundwater depletion. This view, however, obscures reality that it is not paddy *per se* but timing of its transplantation that decides rise or decline in groundwater level. This motivated government of Punjab and Haryana to enact the Preservation of Subsoil Water Acts to arrest deterioration of groundwater resources. Note, area sown with paddy upto mid-June is often too high. In Punjab, during 1996-2005 about one-fourth of area under paddy was sown by May-end and about 60% by mid-June. Maximum paddy area sown by May-end touched 36% in 1997 and 66% by mid-June in 1998. This trend remained almost unchanged until 2004. In 2007, about 48% paddy area was transplanted before June 15 (Singh, 2009). Early transplantation also results in high evapotranspiration loss.

(ii) Irrigation sources

Led by groundwater, irrigation intensity increased considerably. Monsoon rains comprise another important source for meeting crops' water requirement, and also an important means of groundwater recharge. However, precipitation is low and erratic. Punjab and Haryana, respectively, receive 534 mm and 687 mm rainfall. Canal irrigation, an important source of groundwater recharge, deteriorated. During the 1960s, groundwater comprised 41% of irrigated area in Punjab and 22% in Haryana, which increased to 71% and 64%, respectively in 2018-19. On the other hand, investment on canal irrigation in Punjab has declined since 2008-09, which incidentally coincides with timing of the Preservation of Subsoil Water Acts (Figure 4).

Figure 4. Trend in total public expenditure on major and medium irrigation schemes in Punjab and Haryana



(iii) System of groundwater extraction

Groundwater draft is a function of several demand and supply side factors such as choice of crops, their water requirements, output prices, alternate sources of irrigation, prior level of groundwater, and type of pump and its efficiency used for groundwater extraction.

Demand for groundwater increased because of state-sponsored supply of electricity to agriculture at zero or near-zero tariff. This led to proliferation of pumps of higher extraction capacity, in terms of power and type of pumps (Tables 5 and 6). Between 1970-71 and 2019-20 although share of agriculture in total electric power consumption declined, its absolute consumption increased 25 times in Punjab and 34 times in Haryana.

Moving away from free or subsidized supply of electricity to a system of volumetric pricing can be an important means of checking excessive groundwater draft, and reducing fiscal burden. Orienting date of sowing towards onset of monsoon to reduce groundwater draft in principle cannot be the best policy option, as we see its pitfalls subsequently.

Table 5. Electricity consumption in Punjab and Haryana

Year	Electricity (Million KWh)		Agriculture's share (%)	Electricity use in agriculture (Kwh/ha)
	Total consumption	Consumption in agriculture		
Punjab				
1970-71	1220	463	38	114
1980-81	4236	1850	44	441
1990-91	11907	5104	43	1210
2000-01	19185	5534	29	1302
2010-11	32232	10117	31	2433
2015-16	40768	11514	28	2783
2019-20	53098	11538	22	2796
Haryana				
1970-71	904	299	33	84
1980-81	2556	954	37	265
1990-91	6051	2712	45	759
2000-01	10144	4756	47	1349
2010-11	24012	8097	34	2302
2015-16	32172	9295	29	2641
2019-20	43095	10307	24	2887

Table 6 shows changes in energy sources for irrigation. There has been a secular increase in electrification of irrigation system. In Punjab, share of electric tube-wells increased from 47% in 1980-81 to over 90% in 2020-21 and in Haryana it remained almost unchanged at around two-third. Tube-well density (number of tube-wells per unit of land) increased considerably, from 143 to 357 in Punjab, and from 92 to 232 in Haryana. Following the Preservation of Subsoil Water Acts, electrification of tube-wells might have countervailed their effects on groundwater exploitation.

Table 6. Energy sources for irrigation and tube-well density

Year	Punjab		Haryana	
	Electric tube-wells (%)	Tube-well density (No. /000 ha)	Electric tube-wells (%)	Tube-well density (No. /000 ha)
1970-71	47.40	47	82.69	29
1980-81	46.67	143	67.07	92
1990-91	75.00	190	68.68	139
2000-01	73.44	252	56.69	167
2010-11	82.63	332	68.05	206
2020-21	90.58	357	67.03	232

Falling groundwater level compelled farmers to switch from shallow to deep wells and centrifugal to submersible pumps of higher draft capacity. Table 7 presents share of submersible pumps in Punjab and Haryana vis-a-vis donor pool states. It may be noted that the Acts mention neither power of pumps nor mechanisms of monitoring groundwater draft.

The policy of delayed transplanting has engendered responses such as deployment of more powerful pumps or submersibles or irrigation hours, which are aligned with incentives to expend more of a private good (i.e., groundwater), and legitimately there is nothing in the Acts to prevent such responses. These might have offset prospective saving in groundwater envisaged in the Acts.

Table 7. Share of submersible pumps and well depth

State	2006-07 (4th MIC)		2013-14 (5th MIC)		2017-19 (6th MIC)	
	Submersible pump (%)	Wells depth >10m (%)	Submersible pump (%)	Wells depth >10m (%)	Submersible pump (%)	Wells depth >10m (%)
Punjab	52.73	44.33	83.83	66.21	90.85	71.76
Haryana	67.47	44.83	87.47	54.05	83.62	57.36
Andhra Pradesh	62.56	25.99	74.59	26.69	80.06	40.95
Assam	0.62	1.90	0.89	1.98	16.46	2.68
Bihar	5.82	1.83	7.16	4.97	17.67	8.72
Chhattisgarh	24.93	20.46	87.10	22.51	93.13	19.58
Gujarat	59.20	45.04	94.77	53.30	95.76	53.23
Himachal Pradesh	51.09	32.93	67.18	29.67	70.16	23.53

State	2006-07 (4th MIC)		2013-14 (5th MIC)		2017-19 (6th MIC)	
	Submersible pump (%)	Wells depth >10m (%)	Submersible pump (%)	Wells depth >10m (%)	Submersible pump (%)	Wells depth >10m (%)
Jammu	52.55	17.86	11.44	16.67	67.22	15.66
Jharkhand	1.50	21.92	4.51	19.66	3.01	14.9
Karnataka	74.60	31.79	89.58	43.12	94.29	29.71
Kerala	6.55	18.38	17.37	35.43	24.93	22.58
Madhya Pradesh	62.75	48.28	63.52	45.47	73.42	48.54
Maharashtra	23.34	26.57	57.39	31.26	53.1	33.71
Odisha	2.74	5.86	10.33	12.34	29.42	3.31
Rajasthan	33.51	72.81	57.09	65.38	63.83	68.49
Tamil Nadu	21.97	14.62	48.91	31.04	54.55	19.11
Uttarakhand	14.35	38.3	14.05	20.80	42.41	43.9
Uttar Pradesh	4.06	23.91	9.63	43.64	15.26	28.92
West Bengal	15.63	17.29	25.65	29.35	36.53	21.16

(iv) Technology-driven solutions

The Preservation of Subsoil Water Acts could have induced farmers to adopt water-saving technologies and practices such as sensor-based irrigation, direct seeding of rice (DSR), alternate wetting and drying (AWD) system, and short-duration paddy varieties, among others (Aryal *et al*., 2015; Chahal *et al*., 2014; Sidhu and Vatta, 2012). It, however, did not happen because of near-zero marginal cost of water extraction (Shah, 2009; Shah *et al.,* 2012; Gautam, 2015).

Policymakers have been looking for technological and institutional solutions to preserve groundwater. One such option is to promote soil-moisture-sensor-based irrigation scheduling devices like tensiometer[7], which have been found to save water and electricity to the extent of 15% (Bhatt *et al*., 2016; Bhatt and Sharma, 2010; World Bank, 2010; Vatta *et al*., 2018).

Fishman *et al*. (2015) remind that ultimate impact of technologies and practices on groundwater use depends on farmers' behaviour and not solely on their technical potential for water conservation. Ample evidence

[7] A tensiometer measures amount of energy required by plants to pull soil water (water potential) at current moisture level, guiding farmers on timing of irrigation and water requirement.

exists where a technology aimed at reducing water consumption resulted in its greater consumption (Qureshi *et al*., 2010; Ward and Pulido-Velazquez, 2008). In Punjab and Haryana, adoption of water-saving technologies and practices has remained low. Despite the low cost, their dis-adoption has also been reported because of near-zero marginal cost of electricity use (Vatta *et al*., 2018).

6 Effectiveness of Groundwater Regulations

6.1 Impact on groundwater level

Table 8 and figures 5a to 5f show the estimated effects of the PSSWA and the HPSWA separately and the combined two (for obtaining standard errors with bootstrapping which requires more than one treatment unit). Estimates have been obtained with and without time-varying exogenous covariates.

Impact of regulation is estimated as 'average treatment effect on treated' (ATT). ATT is estimated for pre-monsoon, post-monsoon and average groundwater levels using estimated coefficients from DiD, SCM, and SDiD. Qualitatively, results from all the models are similar.[8] ATTs for pre-monsoon and post-monsoon are presented in Table 8a and 8b, respectively. As expected, impact is more significant on pre-monsoon groundwater level; hence further discussion is restricted to pre-monsoon groundwater level. Figures 5a-f also show estimated trends in pre-monsoon groundwater level before and after implementation of the Acts. The estimated trends for post-monsoon groundwater level are given in figure A1a-f in the appendix.

Without covariates, post-treatment ATTs show a significant decline in pre-monsoon groundwater level — 4 meters below ground level (mbgl) in Punjab. Conditioning upon covariates, decline is bigger (4.64 mbgl). In Haryana, without covariates, decline is 4.35 mbgl, and conditional upon covariates it is 4.8 mbgl. For state level estimates, placebo method is used to obtain standard errors. For SDiD, standard errors can be obtained through bootstrapping provided there is more than a single treatment unit.

Given similarity of the Acts, data for Punjab and Haryana are combined to estimate SDiD model. This provides average effect of a generic groundwater regulation. ATTs show a decline in groundwater level by 4.1 mbgl without covariates, and 4.7 mbgl conditional on covariates. In Figure 5a-f, states in donor pool with zero weight are denoted by x. Weights assigned by SDiD to donor pool states appear less sparse, i.e., SDiD did not assign larger weight to any particular state due to more balanced weighting compared to SCM, which assigns a larger weight to a particular state (e.g., Uttar Pradesh).

8 Results for average groundwater level are available on request.

Table 8a. ATTs for pre-monsoon groundwater level

Punjab			Haryana			Combined with bootstrap standard error		
DiD	SCM	SDiD	DiD	SCM	SDiD	DiD	SCM	SDiD
Without covariates								
-3.902***	-3.548*	-4.000***	-3.279***	-4.271**	-4.351***	-3.591***	-4.454**	-4.140***
(0.960)	(1.978)	(1.165)	(0.959)	(1.974)	(1.165)	(0.308)	(0.655)	(0.834)
With covariates								
-4.203***	-4.079*	-4.639***	-3.329***	-4.332*	-4.798***	-3.766***	-4.483***	-4.694***
(0.951)	(2.319)	(1.078)	(0.951)	(2.319)	(1.078)	(0.700)	(1.010)	(0.802)

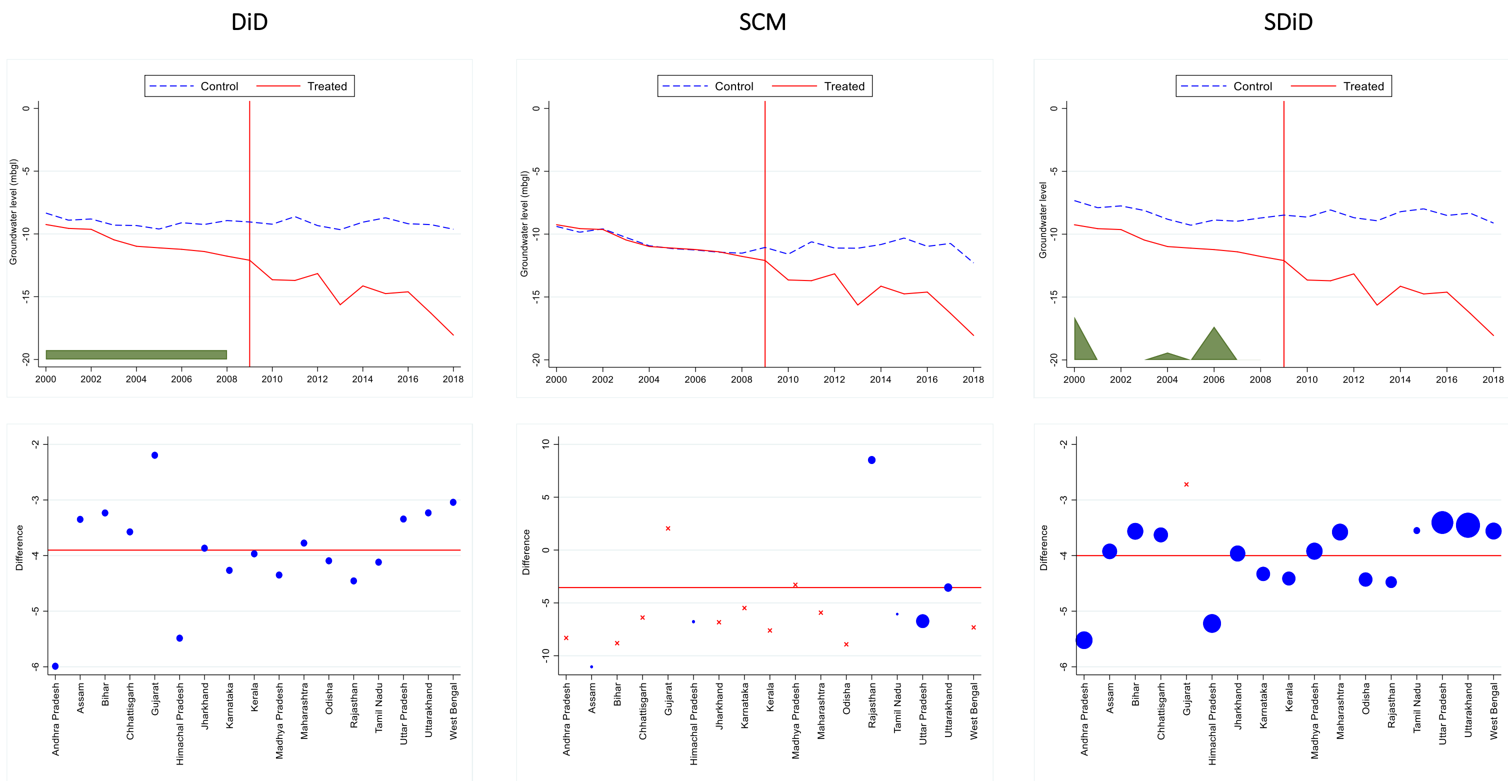
*Note: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1*

Table 8b. ATTs for post-monsoon groundwater level

Punjab			Haryana			Combined with bootstrap standard error		
DiD	SCM	SDiD	DiD	SCM	SDiD	DiD	SCM	SDiD
Without covariates								
-4.423***	-3.776*	-4.563***	-3.006**	-2.551	-2.957*	-3.715***	-3.113**	-3.775***
(1.376)	(2.054)	(1.574)	(1.376)	(2.052)	(1.574)	(0.618)	(1.513)	(0.696)
With covariates								
-4.092***	-3.181*	-3.924***	-2.571**	-1.934	-2.333*	-2.974***	-2.111*	-2.685**
(1.464)	(1.773)	(1.574)	(1.155)	(1.740)	(1.401)	(1.044)	(1.134)	(1.222)

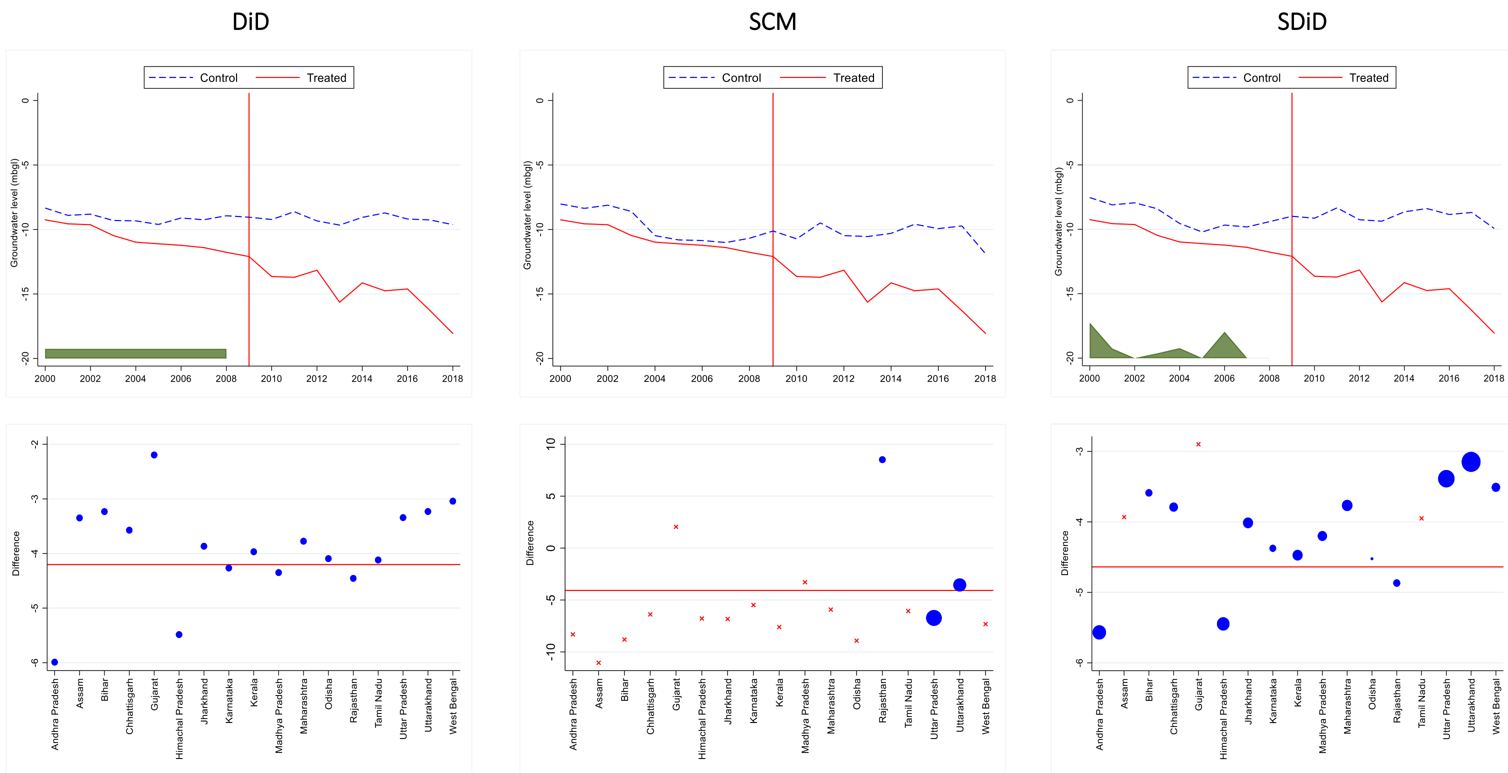
*Note: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1*

Figure 5a: Estimated impact of PPSWA on pre-monsoon groundwater level in Punjab (without covariates)



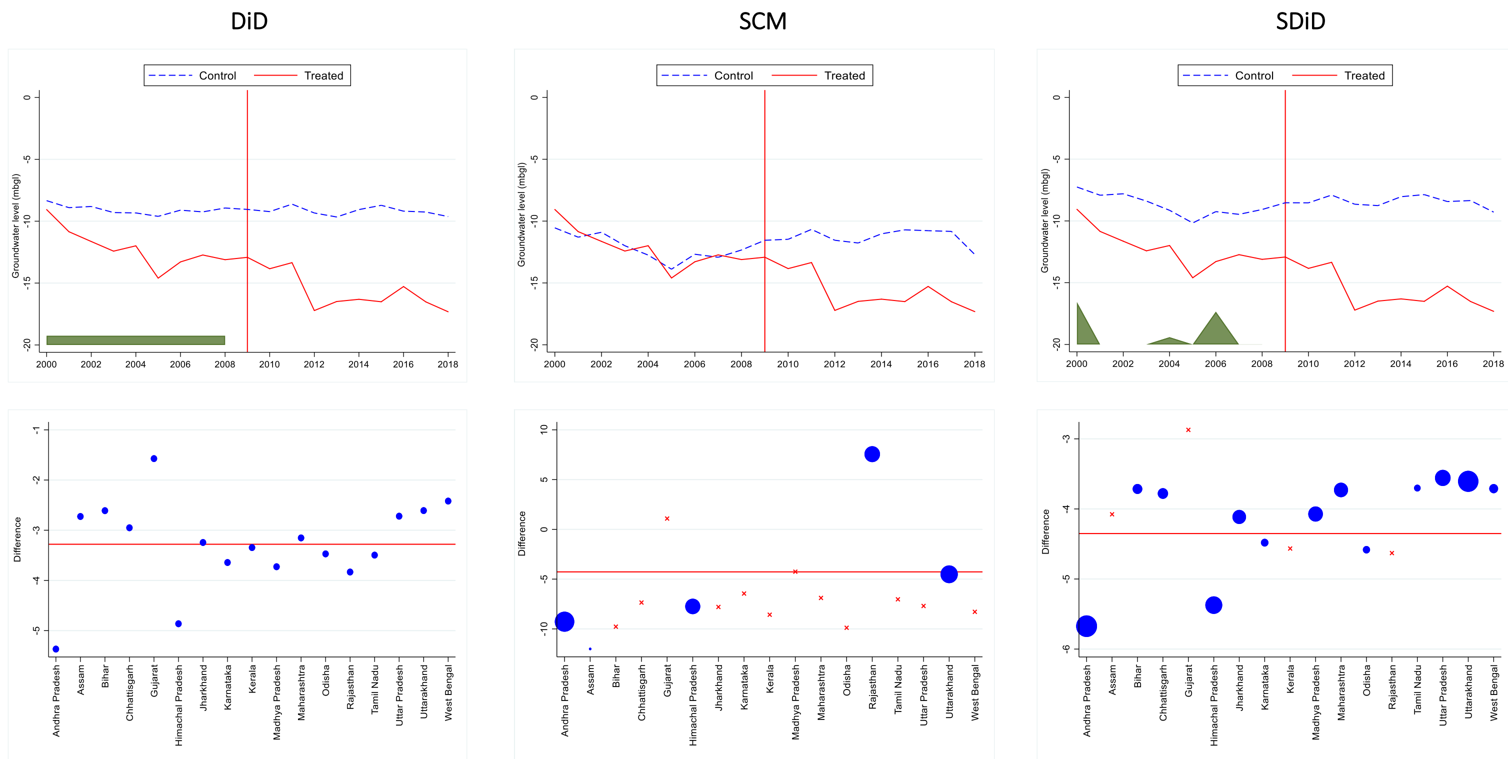
Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

Figure 5b. Estimated impact of PPSWA on pre-monsoon groundwater level in Punjab (with covariates)



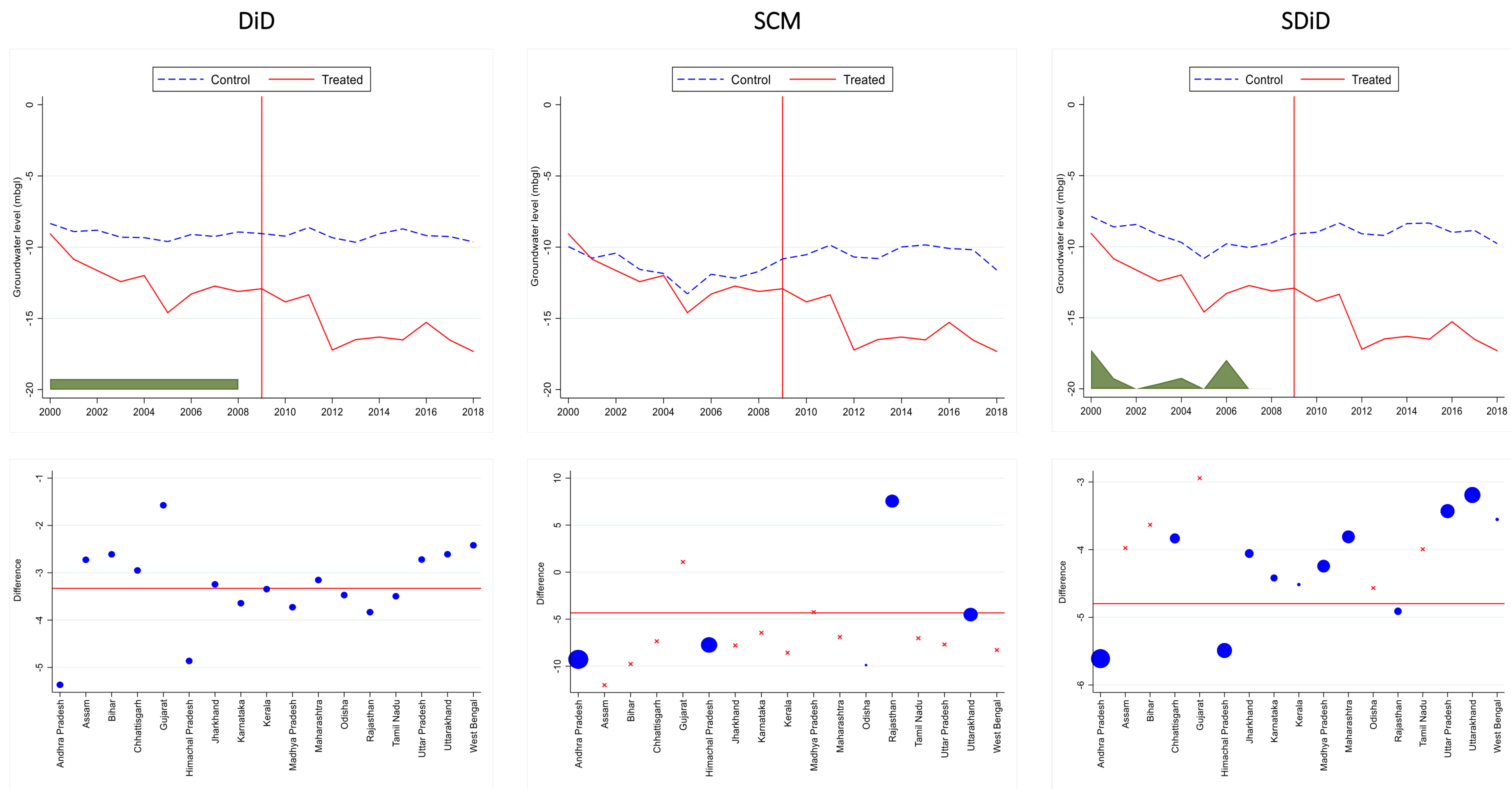
Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

Figure 5c. Estimated impact of HPSWA on pre-monsoon groundwater level in Haryana (without covariates)



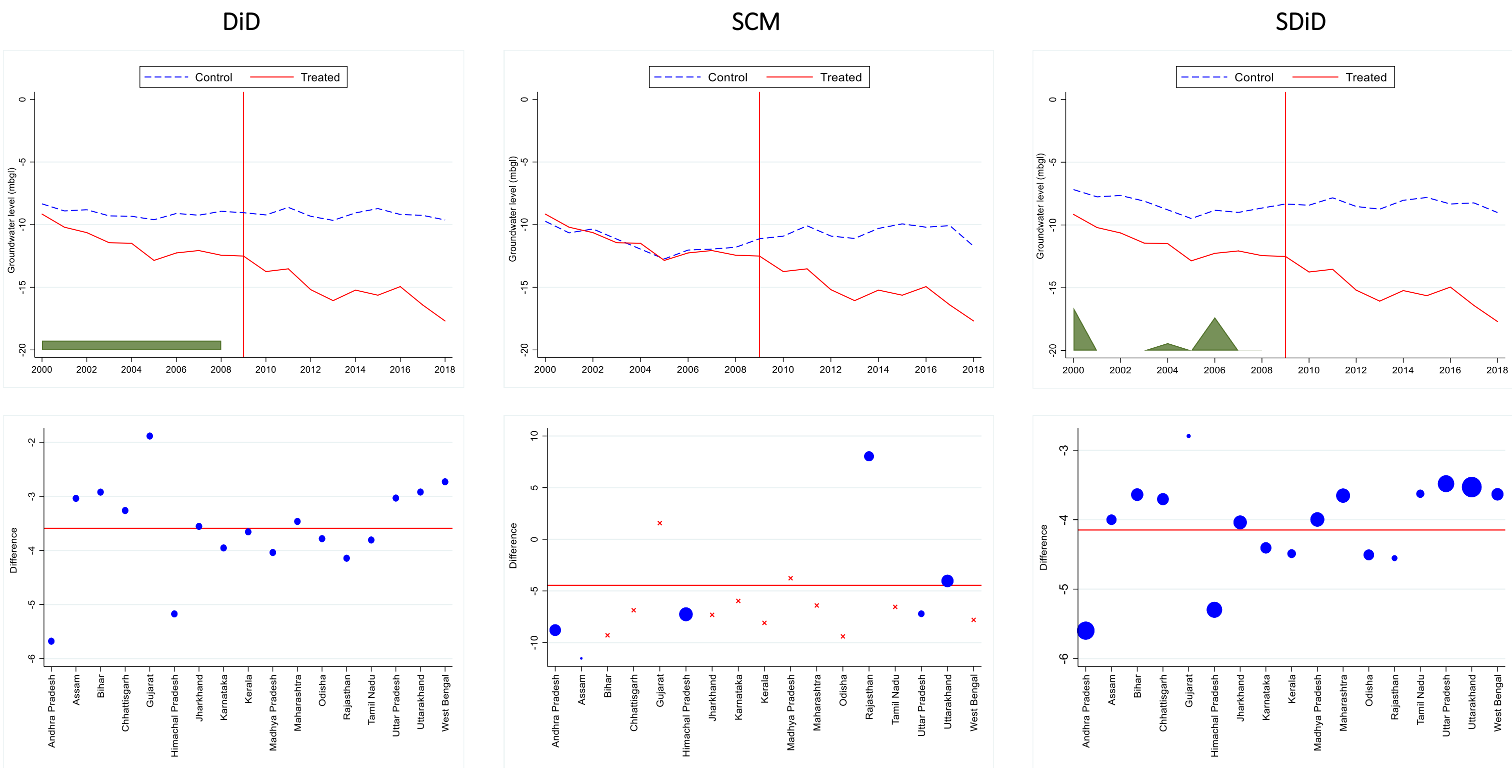
Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

Figure 5d. Estimated impact of HPSWA on pre-monsoon groundwater level in Haryana (with covariates)



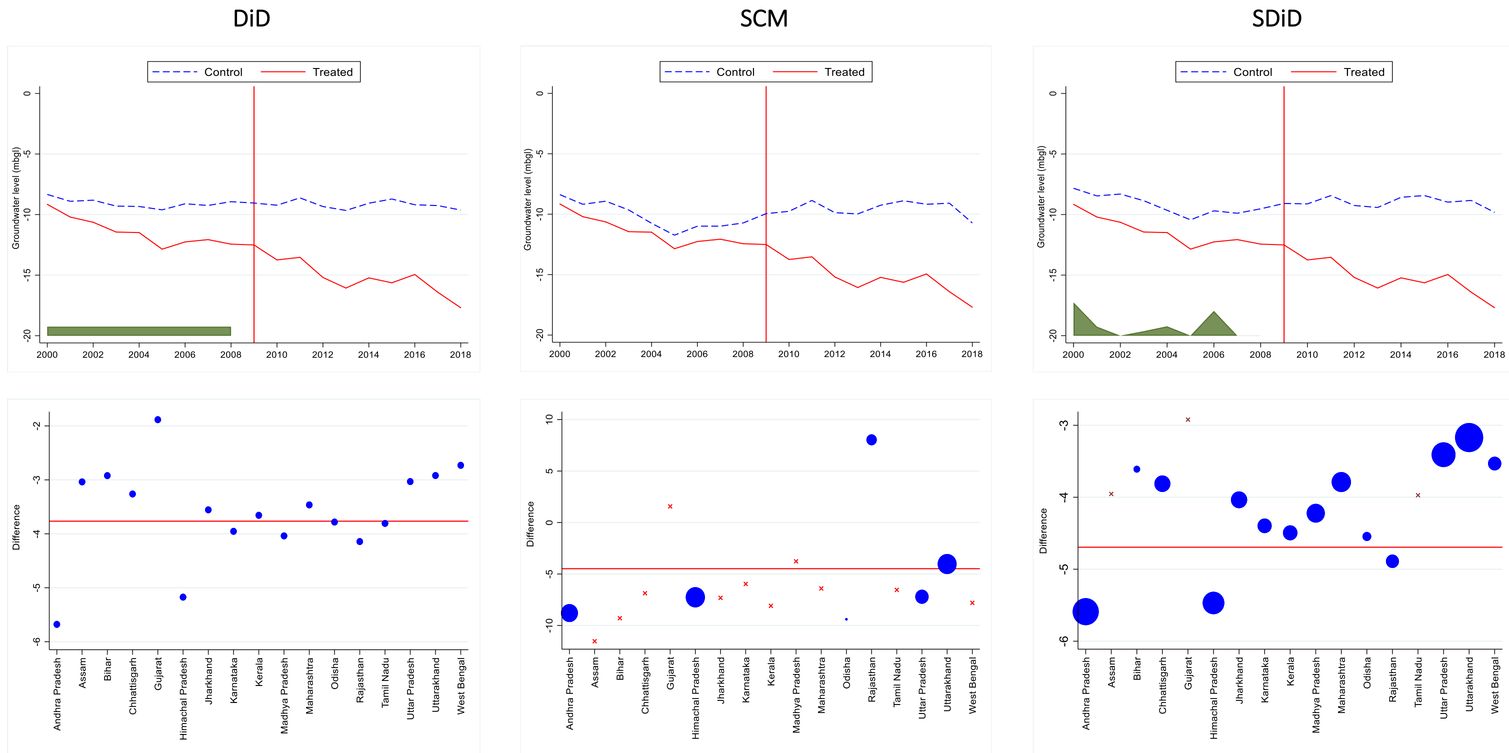
Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

Figure 5e. Estimated impact of Acts on pre-monsoon groundwater level in combined Punjab and Haryana (bootstrapped- without covariates)



Note: First row shows trend in groundwater level for treated units and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

Figure 5f. Estimated impact of Acts on pre-monsoon groundwater level in combined Punjab and Haryana (bootstrapped- with covariates)



Note: First row shows trend in groundwater level for treated units and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

How do our estimates compare with those reported by others (Table 9). Note, in their assessment, they have focused on the PPSWA. Using a panel of district level data for 1985 to 2011, Tripathi *et al.* (2016) have reported a positive change in groundwater level after implementation of the PPSWA. Our findings, however, contradict this. On the other hand, Sekhri (2012) and Sharma *et al.* (2023) have reported a decline in groundwater level in post-Act period. In these studies, change in groundwater level is high in paddy-growing districts. We estimated it for Haryana and/or Punjab relative to other states.

Table 9. Estimated impacts of PPSWA 2009 from other studies

Authors	Time period	Method	Estimated effect
Sekhri (2012)	2003-2011	DiD	Groundwater declined by 1.17m (August water level) and by 1.60m (annual water level).
Sharma *et al.*(2023)	1999-2018	DiD	Groundwater declined by 1.72m (pre-monsoon water level) and by 1.55m (post-monsoon water level).
Tripathi *et al.*(2016)	1985-2011	Panel regression	Coefficient of policy dummy is significant in groundwater level of pre-monsoon (-2.795***), post-monsoon (-2.310***) and annual (-2.115***) suggesting policy led to improvement in groundwater level.

*Note: *** p<0.01, ** p<0.05, * p<01.*

Our study differs in several aspects from above-mentioned studies. These have estimated impact of the regulation utilizing district-level variation in paddy acreage, i.e., high paddy acreage districts as treated units and low paddy acreage districts as untreated units. While a regulation equally applies to all districts in a state unless it specifies inclusions or exclusions. The PPSWA and HPSWA do not specify any inclusion or exclusion. We have evaluated their impact on groundwater use in treated states (Punjab and Haryana) in relation to other states which did not implement such Acts.

We have uniquely evaluated impact of the Acts on groundwater draft, which most adequately captures farmers' response to the Acts. Importantly, we have assessed their impacts employing the most recent 'synthetic difference-in-difference technique' with states implementing an Act as treated unit, and others as untreated units. Further, above-mentioned studies, except Sharma *et al.* (2023), have considered a shorter period of 2-3 years after the

Act, while several changes take place in long-run. We have extended post-Act period upto 2018-19. Beyond differences in units of comparison relative to treated units, our estimates of groundwater depletion are significantly larger than those reported in other studies.

6.2 Possible Offsets to the Groundwater Regulations

The findings show failure of the Acts in preventing overextraction of groundwater. Impact of this policy change is determined by responses that impinge on groundwater draft. As discussed earlier, choice of crops and their acreage (legit compliance and non-compliance if transplanting were done earlier on the sly), methods of groundwater extraction (power source and type of pump) and irrigation intensity (hours of irrigation) comprise main determinants of groundwater draft. Groundwater level in both states has secularly declined despite regulations being in force. True measure of impact of these regulations would be in terms of their impact on determinants of groundwater draft and subsequently on draft itself. Only in a naïve behavioural scenario, farmers would maintain irrigated area at level before enactment of the Acts.

There could have been several possible offsets to the policy of delayed paddy transplantation to restrict groundwater extraction. A few of these are discussed below.

Extensification of paddy: First offset relates to increase in paddy acreage, i.e., extensification. If acreage under paddy itself is impacted to increase in post-Act period, then overextraction of groundwater may continue even after delayed paddy transplantation. This endogenous increase in paddy acreage puts a question on estimation strategy using variation in paddy acreage across districts.

Treating paddy acreage not exogenous, we have implemented SDiD with covariates, including paddy acreage, to evaluate impact of Acts on paddy acreage itself. Table 10 and figure 6 presents results. Notwithstanding mandatory delayed sowing, paddy acreage increased in a causal way —about 14% in both states.

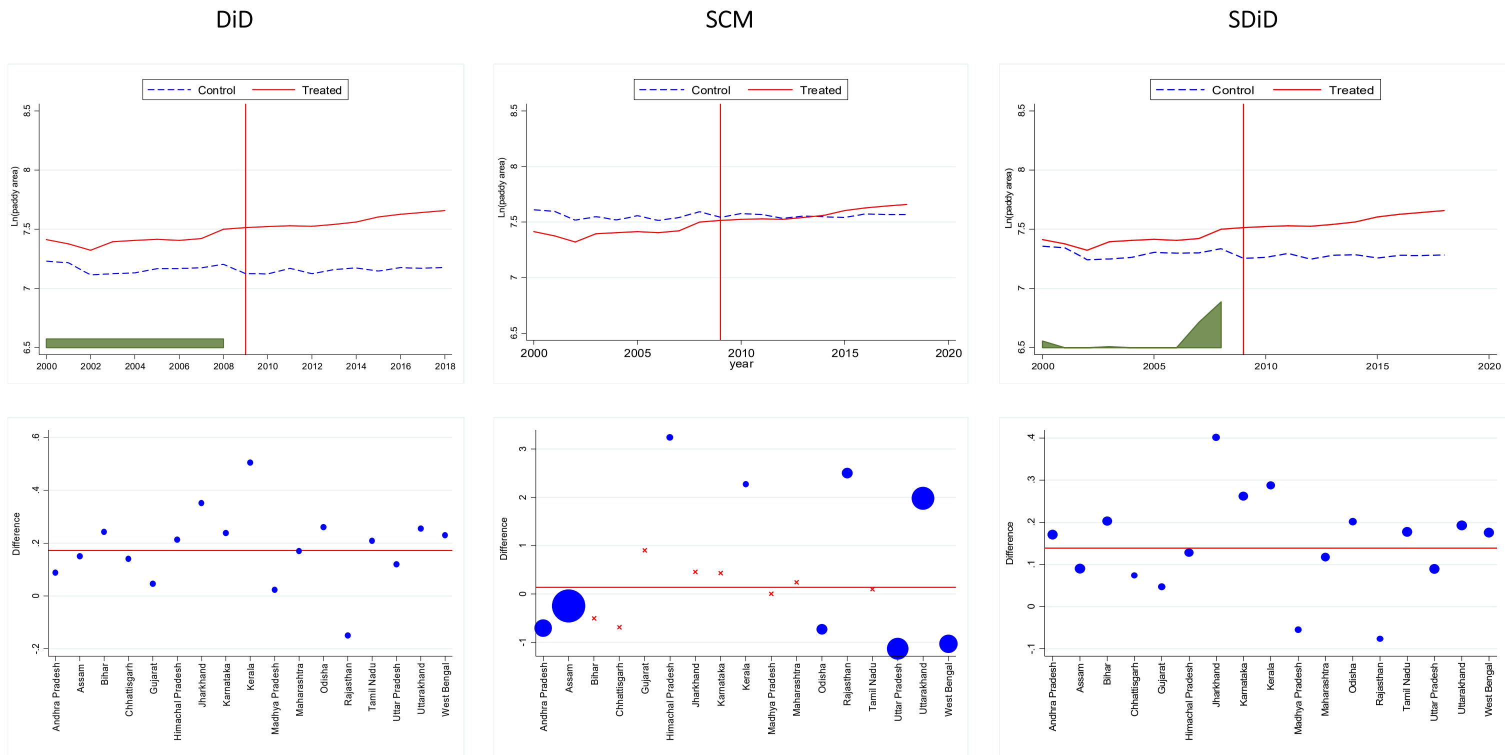
Table 10. Estimated impact of Acts on paddy acreage in Punjab and Haryana (with covariates)

State	Average treatment effect on treated (ATT)		
	DiD	SCM	SDiD
Punjab	0.138 (0.093)	0.135 (0.120)	0.149* (0.080)
Haryana	0.222** (0.092)	0.189 (0.127)	0.146* (0.081)
Punjab and Haryana (combined-bootstrap standard errors)	0.172** (0.069)	0.140 * (0.080)	0.139** (0.060)

Note: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<01.

Extraction capacity change (pumps' power and irrigation hours): Our estimating models include irrigation hours per hectare of paddy-cropped area, which could have affected extraction of groundwater. Total change in groundwater extraction could be more if farmers apply more irrigation. Although not tested as an explanation, Sekhri (2012) has pitched for this delineation. More applications of irrigation in a shorter cropping cycle could be a behavioural response to the regulations. In a scenario where pumping technology may also change in post-regulation period, demand for groundwater may decrease only if entire cultivable land can be irrigated using new pumping technology that reduces water use compared to old technology in pre-treatment period. If a short-duration paddy variety is chosen based on perceived yield (i.e., comparatively high yield from a long-duration variety), it is quite possible that irrigation applications may increase.

Figure 6. Estimated impact of Acts on paddy acreage in combined Punjab and Haryana (with bootstrapped standard errors)



Note: First row shows trend in paddy acreage for treated units and weighted average of control units, with the time weights for average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

Water requirement of substitute crops: Both the PPSWA and HPSWA set cut-off dates for paddy sowing (nursery raising and transplanting). In run up to late transplanting, farmers are free to sow any crop but not paddy. Other crops, if grown would also require irrigation and face same situation of groundwater dependence and high evapotranspiration loss. One would expect a rational farmer to utilize land for crops of duration that does not overrun sowing of paddy to earn equivalent returns. Short-duration maize (spring maize) if sown after mid-April would require at least 15 irrigations before arrival of monsoon. Manan *et al.* (2017) have estimated water requirement of spring maize at 9500-10125 cubic meter/ha, which is marginally less than 12000 cubic meter/ha required by paddy (Srivastava *et al.*, 2015).

Measure of response to policy change: None of the earlier studies has evaluated impact of the regulation on groundwater draft, a more relevant outcome than groundwater level. We uniquely estimate impact of the Acts on groundwater draft per unit of gross cropped area. Results show that groundwater draft goes up significantly relative to counterfactual, i.e., in absence of the Acts (Table 11, and Figure A2 a-f in the appendix).

Based on official estimates (GoP, 2020), under ideal conditions delayed transplanting of paddy should have reduced groundwater extraction at least by 1000 cubic meter per hectare. Our estimates show overextraction of groundwater to the extent of 988 cubic meters per hectare for combined Punjab and Haryana. However, when estimated separately, overextraction is at least three times more in Punjab (1520 cubic meters per hectare) than in Haryana (503 cubic meters per hectare). This is because conditions are not ideal with offsets where paddy acreage has increased and extraction capacity of pumps expanded.

Table 11. ATT for groundwater draft (cubic meters per hectare of gross cropped area)

Punjab			Haryana			Combined with bootstrap standard error		
DiD	SCM	SDiD	DiD	SCM	SDiD	DiD	SCM	SDiD
Without covariates								
700*** (207)	2000*** (351)	1520*** (189)	416** (207)	600* (352)	503*** (189)	558** (157)	890* (219)	988*** (140)
With covariates								
653*** (182)	2640*** (175)	783*** (183)	493*** (182)	445** (174)	433** (183)	573*** (138)	1360** (142)	600** (134)

*Note: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1*

The Acts have failed to arrest falling groundwater level, rather it deteriorated in post-implementation period. Therefore, it is imperative to understand causes for such as perverse outcome.

Change in groundwater level is net outcome of groundwater demand and supply. Thus, failure of the Acts to check falling level of groundwater implies their ineffectiveness in reducing net demand for groundwater. Evidence from Cost of Cultivation data reveals a reduction in paddy irrigation hours from 309 per hectare in 2009-10 to 217 per hectare in 2018-19. With delayed paddy transplantation and concomitant reduction in irrigation hours what factors could explain this perverse outcome? In principle, there could have been a reduction in groundwater dependence on account of delayed sowing of paddy. However, despite reduction in irrigation hours, total groundwater demand increased from 30.3 bcm in 2004 to 34.56 bcm 2017, and as a response the type and source of power of pumps also changed. To understand this, we look at determinants of groundwater demand and supply and how they could possibly have changed in post-regulation period.

First, procurement of paddy at MSP is a strong incentive for farmers to allocate more area to its cultivation. In both states, paddy area increased in post-Act period due to ever-increasing procurement of paddy. Long duration paddy varieties are often associated with higher yield (at least in farmers' perception), and if their yield is perceived to be lower with delayed transplanting, a logical response is to allocate more area to paddy. In post-Act period, paddy acreage was causally impacted, increasing from 2795 thousand hectares in 2009-10 to 3102 thousand hectares in 2018-19 (11%) in Punjab, and from 1206 thousand hectares to 1447 thousand hectares (20%) in Haryana, which led to greater demand for groundwater.

Second, with increasing procurement of paddy there has been a significant expansion of rice milling industry. Currently, there are more than 4500 rice mills in Punjab and 1300 in Haryana. Capital requirement for establishing a rice mill is quite significant, and once established it cannot be utilized or modified for commodities other than paddy. Thus, any policy to reduce paddy acreage may be resisted by millers.

Third, if farmers perceive more irrigation for short-duration paddy varieties (Shekhri, 2012), more powerful and efficient pumps (submersible) will be deployed. We do find that power and type of pumps interacted with irrigation hours did increase in post-regulation period.

Fourth, free or heavily subsidized electric power does not reflect scarcity value of groundwater; hence its overextraction. We have estimated causal impact of the Acts on groundwater draft itself, which increased significantly in post-regulation period.

Fifth, increasing demand for groundwater (despite reduction in irrigation hours) has not been accompanied by increase in its recharge, which hovered around 23-24 bcm in pre- as well as post-regulation periods.

On the whole, groundwater-energy-food nexus remains in operation even after implementation of the Preservation of Subsoil Water Acts. This unbroken nexus offsets their effects despite a marginal positive effect of delayed paddy transplantation on groundwater use.

7 Conclusion and Implications

Agriculture in Punjab and Haryana is at a crossroads. Technological gains realized during initial phase of the Green Revolution have started tapering off in both states–yield growth of paddy has decelerated to less than one percent during 2009-2018 from about 2% during 2000-2008 due to increasing scarcity of water, among others. Irrigation serves a dual role of improving crop yield and reducing its sensitivity to extreme climate events such as droughts and heat-waves (Birthal *et al.*, 2015; Birthal *et al.*, 2021; Zaveri and Lobell, 2019). Nonetheless, its effect has started slowing-down.

Punjab and Haryana enacted an identical regulation in 2009 to prevent overextraction of groundwater by altering sowing date of paddy towards onset of monsoon. This paper by employing 'synthetic difference-in-difference' technique to a long-series of panel data from 2000-01 to 2018-19 has constructed a counterfactual trajectory of groundwater draft/level, and compared it with actual trajectory before and after implementation of the regulation. Findings demonstrate that despite regulation being in force, overextraction of groundwater continued, leading to further decline in its level by more than 4 meters.

How a policy that aimed at improving an outcome could result in worsening it? Such a perverse outcome could be several possible policy-engendered behavioural responses.

Paddy emerged as the most important crop in Punjab and Haryana despite their climatic conditions (semi-arid) being not conducive to its cultivation. This happened because of continued policy support in terms of its procurement at pre-announced minimum support price, and subsidy on electric power for irrigation and fertilizers. Besides, as compared to other crops, yield of paddy is significantly higher. Currently, over 90% paddy produced in these states is procured at MSP, rendering it virtually free from price and market risks. Farmers are often risk-averse, and might have perceived that delayed paddy transplantation may reduce yield of its own and of subsequent crops by condensing sowing window. Wheat, the most widely-grown crop grown after paddy, is also insulated from price and market risks.

Importance of a regulation not being a direct or price instrument is evident from our findings. This calls for reforms in agri-food policy in a manner that help conserve and optimize groundwater use.

To control overextraction of groundwater, it is often advocated to switch over to its volumetric pricing from a free or subsided flat rate electricity tariff (Singh, 2012; Sidhu *et al*., 2020; Chand *et al*., 2022). Nonetheless, policy of free or subsidised electric power for irrigation has continued because of political considerations. Differential pricing of groundwater based on an its optimal use or threshold level (ones using less than threshold are rewarded, and those using above it are penalized through electricity tariff) can reduce paddy area and consequently groundwater draft without any adverse effect on farm income (Chand *et al*., 2022). However, such reforms require hard policy decisions.

Diversification of crop portfolio towards less water-intensive crops is another important option to curb overextraction of groundwater and improve its long-term sustainability. Besides, it can provide several other benefits such as reduction in fertilizer consumption and air pollution, mitigation of greenhouse gas emission, and improvement in soil fertility. However, farmers' decisions to diversify away from paddy depend on multiple factors including its profitability relative to other crops. Economics of different crops reveals that in Punjab and Haryana, hardly there is a crop, except horticultural crops, which generates as much profit as paddy. Maize, soybean, pigeon-pea, and groundnut are often-suggested alternatives to paddy but their yield is too low to compensate for revenue foregone.

A crop has its own cultivation niches, and cannot exhibit its production potential in all types of agro-ecologies. This suggests for crop planning at lower geographical scales (i.e., district or block or cluster of villages) based on their natural resource endowments. However, for crop planning to succeed, it must be backed by a package of compensation for revenue foregone from paddy. In long-run, more research is needed to improve yield of crops competing with paddy for land and water.

Horticultural crops generate significantly higher profit than paddy or any other crop. Leaving aside a few, most horticultural crops can be grown in all types of agro-ecologies. Their cultivation in protected environments is also an option. However, these crops are labour-intensive, and scope for mechanization in horticulture is limited. Further, horticultural crops are perishable and prone to high production and market risks. Post-harvest, these require immediate transportation to markers or storage or processing into less perishable forms. Hence, there is a need to invest in cold storages, refrigerated transportation and processing, and develop value chains to link farmers to markets.

Re-purposing existing agricultural incentives to adoption of technologies and practices that are compatible with principles of natural resource conservation is a politically feasible policy option. The Preservation of Subsoil Water Acts could have induced adoption of such technologies but it did not happen due to several factors including farmers' risk aversion and lack of incentives. The Green Credit Scheme launched recently by the Government of India offers monetary incentives for the adoption of sustainable agricultural practices.

Farmers have heavily invested in groundwater irrigation, possibly acquiring subsidized credit from financial institutions. By law, water rights are embedded in land rights; hence, it is difficult to prevent farmers to invest in groundwater irrigation. Nonetheless, individual ownership of new tube-wells should be discouraged by restricting their access to institutional credit and electric power. And if not, make their provision conditional upon adoption of water-saving technologies and agronomic practices. Further, farmers should be incentivized for community-managed irrigation system and water sharing and trade (Chaudhuri *et al*., 2023).

Canals are an important source of irrigation and groundwater recharge but these have been suffering from poor maintenance due to stagnation or even declining investment. It is, therefore, imperative to rehabilitate canal irrigation and promote its conjunctive use with groundwater.

Governments should increasingly involve grass-root institutions like village panchayats or non-governmental organizations to create awareness about negative externalities of overextraction of groundwater and its economic, social and environmental consequences, to motivate farmers for participatory management of groundwater, and to coordinate, implement and monitor land and water conservation programmes.

These measures should be accompanied by reforms in agricultural price and food distribution policies. On procurement front, one can think of limiting procurement of paddy at MSP to the extent of its requirement for buffer stocking. The rest of the marketable surplus may be covered under price deficiency scheme. Rice may partially be substituted by millets and pulses in the PDS. Other option is to explore possibility of cash transfer in lieu of grains.

In essence, groundwater management requires an integrated approach, encompassing policy and institutional reforms in and outside agriculture.

References

Abadie, A, Diamond, A., & Hainmueller, J. 2015. Comparative politics and the synthetic control method. *American Journal of Political Science* 59(2): 495-510.

Abadie, A. & Gardeazabal, J. 2003. The economic costs of conflict: a case study of the Basque country. *American Economic Review* 93(1): 113-132.

Abadie, A., Diamond, A., & Hainmueller, J. 2010. Synthetic control methods for comparative case studies: estimating the effect of California's Tobacco Control Program. *Journal of the American Statistical Association* 105(490): 493-505.

Arkhangelsky, D., Athey, S., Hirshberg, D.A., Imbens, G.W., & Wager, S. 2021. Synthetic difference-in-differences. *American Economic Review* 111(12): 4088–4118.

Aryal, J. P., Mehrotra, M. B., Jat, M. L., & Sidhu, H. S. 2015. Impacts of laser land levelling in rice–wheat systems of the north–western Indo-Gangetic plains of India. *Food Security* 7: 725–738.

Bhatt, R. & Sharma, M. 2010. Management of irrigation water through tensiometer in paddy: a case study in Kapurthala district of Punjab. In: Proceedings of regional workshop on water availability and management in Punjab, Chandigarh: Punjab University

Bhatt, R., Kukal, S. S., Busari, M A, Arora, S., & Yadav, M. 2016. Sustainability issues on rice-wheat cropping system. *International Soil and Water Conservation Research* 4(1): 68–83.

Birthal, P.S., Hazrana, J., Negi, D.S., & Pandey, G. 2021. Benefits of irrigation against heat stress in agriculture: evidence from wheat. *Agricultural Water Management* 255: 106950.

Birthal, P.S., Negi, D.S., Khan, M. T., & Agarwal, S., 2015. Is Indian agriculture becoming resilient to droughts? *Food Policy* 56: 1-12.

Chahal, S. S., Kataria, P., Abbott, S., & Gill, B. S. 2014. Role of cooperatives in institutionalization of custom hiring services in Punjab. *Agricultural Economics Research Review* 27: 103–110.

Chand,P., Singh, J.M., Sachdeva, J., Singh, J., Agarwal, P., Jain, R., Rao, S., & Kaur, B. 2022. Irrigation water policies for sustainable groundwater management in irrigated north-western plains of India. *Current Science* 123(10):1225-1231.

Chaudhuri, S. Roy, M., & Suresh, M. 2023. Can cap-and-trade be a regulatory option to address groundwater depletion and irrigation crises in India: Reflections, issues & options. *Environmental Management*. https://doi.org/10.1007/s00267-023-01908-8.

Clarke, D., Pailanir, D., Athey, S., & Imbens, G.W. 2023. Synthetic difference-in-differences estimation. IZA Discussion Paper No. 15907. http://dx.doi.org/10.2139/ssrn.4346540.

Famiglietti, J.S. 2014. The global groundwater crisis. *Nature Climate Change* 4 (11): 945–948.

Fishman, R., Devineni, N., & Raman, S. 2015. Can improved agricultural water use efficiency save India's groundwater? *Environment Research Letter* 10: 084022.

Gautam, M. 2015. Agricultural subsidies: resurging interest in a perennial debate. *Indian Journal of Agricultural Economics* 70(1): 83-105.

Gleeson, T., VanderSteen, J., Sophocleous, M.A., Taniguchi, M., Alley, W.M., Allen D.M., & Zhou, Y. 2010. Groundwater sustainability strategies. *Nature Geoscience* 3:378–379.

GOI- Government of India. 2022. Groundwater Year Book of Haryana State, 2021-22. North Western Region, Ministry of Jal Shakti, Government of India, New Delhi.

GoI-Government of India. 2023. National Compilation on Dynamic Groundwater Resources of India. Ministry of Jal Shakti, Government of India, New Delhi.

Goodman-Bacon, A. 2021. Difference-in-Differences with Variation in Treatment Timing. *Journal of Econometrics* 225: 254–277.

GoP-Government of Punjab. 2020. Punjab Guidelines for Groundwater Extraction and Conservation, Punjab Water Regulation and Development Authority, Government of Punjab, Chandigarh.

Kaur, R. & Arora, V.K. 2018. Assessing spring maize responses to irrigation and nitrogen regimes in north-west India using CERES-Maize model. *Agricultural Water Management* 209: 171-177.

Kreif, N., Grieve, R., Hangartner, D., Turner, A.J., Nikolova, S., & Sutton, M. 2016. Examination of the synthetic control method for evaluating health policies with multiple treated units. *Health Economics* 25(12): 1514–1528.

Manan, J., Sharma, M., Singh, G., & Singh, G. 2017. Water productivity and profitability of spring maize hybrids. *Indian Journal of Economics and Development* 13(4): 785-788.

Mitra, A., Balasubramanya, S., & Brouwer, R. 2023. Can cash incentives modify groundwater pumping behaviours? evidence from an experiment in Punjab. *American Journal of Agricultural Economics* 105(3): 861-887.

Negi, D.S., Birthal, P.S., Roy, D., & Hazrana J. 2020. Market Access, Price Policy and Diversification in Indian Agriculture. Working Paper 2020-009, Indira Gandhi Institute of Development Research, Mumbai.

Pahuja, S., Tovey, C., Foster, S., & Garduno, H. 2010. Deep Wells and Prudence: Towards Pragmatic Action for Addressing Groundwater Overexploitation in India. Study and Technical Assistance Initiative Report, World Bank, Washington DC.

Qureshi, M. E., Schwabe, K., Connor, J., & Kirby, M. 2010. Environmental water incentive policy and return flows. *Water Resources Research* 46(4):1-12.

Rambachan, A. & Roth, J. 2023. A More Credible Approach to Parallel Trends. *Review of Economic Studies* 90:2555–2591.

Repetto R. 1994. The "Second India" Revisited: Population, Poverty, and Environmental Stress Over Two Decades. World Resources Institute, Washington DC.

Rodell, M., Velicogna, I., & Famiglietti, J.S. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* 460: 999-1002.

Rosencranz, A., Puthucherril, T. G., Tripathi S., & Gupta, S. 2021. Groundwater management in India's Punjab and Haryana: a case of too little and too late? *Journal of Energy and Natural Resources Law* 40(2): 225-250.

Roth, J., Sant'Anna, P. H. C., Bilinski, A., & Poe, J. 2022. What's Trending in Difference-in-Differences? A Synthesis of the Recent Econometrics Literature. https://arxiv.org/abs/2201.01194.

Sekhar, C.S.C. 2021. Price or Income Support to Farmers? Policy Options and Implications. IEG Working Paper No. 420, Institute of Economic Growth, New Delhi.

Sekhri, S. 2012. Sustaining groundwater: role of policy reforms in promoting conservation in India, Indian Policy Forum, National Council of Applied Economic Research, New Delhi.

Shah, T. 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environmental Research Letter* 4(3): 035005.

Shah, T., Giordano, M., & Mukherji, A. 2012. Political economy of the energy-groundwater nexus in India: exploring issues and assessing policy options. *Hydrogeology Journal* 20: 995–1006.

Sharghi, K. 2023. India's Disappearing Water. NASA's Goddard Space Flight Centre Scientific Visualization Studio. https://svs.gsfc.nasa.gov/10764#section_credits

Sharma, M., Singh, O., Singh, G., & Kaur, G. 2014. A Snap shot of spring maize cultivation in Kapurthala and Jalandhar districts under Central Plain Zone of Punjab. *Journal of Krishi Vigyan* 3(1).

Sharma, Y., Sidana, B.K., Kumar, S., Kaur, S., Sekhon, M.K., Mahal, A.K., & Mehan, S. 2023. Pre and post water level behaviour in Punjab: impact analysis with DiD approach. *Sustainability* 15(2426).

Sharma, B.R., Gulati, A., Mohan, G., Manchanda, S., Ray, I., & Amarasinghe, U. 2018. Water Productivity Mapping of Major Indian Crops. NABARD- ICRIER. Available at https://icrier.org/publications/water-productivity-mapping-of-major-indian-crops/

Sidhu, B.S., Kandlikar, M., & Ramankutty, N. 2020. Power tariffs for groundwater irrigation in India: a comparative analysis of the environmental, equity, and economic trade-offs. *World Development* 128 104836.

Sidhu, R. S. & Vatta, K. 2012. Improving economic viability of farming: a study of cooperative agro machinery service centres in Punjab. *Agricultural Economics Research Review* 25: 427–434.

Siebert, S., Henrich, V., Frenken, K., & Burke, J. 2013. Update of the global map of irrigation areas to version 5. University of Bonn/FAO, Bonn, Germany/Rome.

Singh, K. 2009. Act to save groundwater in Punjab: its impact on water table, electricity subsidy and environment. *Agricultural Economics Research Review* 22: 365–586.

Singh, K. 2012. Electricity subsidy in Punjab agriculture: extent and impact. *Indian Journal of Agricultural Economics* 67(4): 617-632.

Srivastava, S.K., Chand, R., Raju S.S., Jain, R., Kingsly I., Sachdeva, J., Singh, J., & Kaur, A. 2015. Unsustainable groundwater use in Punjab agriculture: insights from cost of cultivation survey. *Indian Journal of Agricultural Economics* 70(3): 365-378.

Tripathi, A., Mishra, A., & Verma, G. 2016. Impact of Preservation of Subsoil Water Act on groundwater depletion: the case of Punjab, India. *Environmental Management* 58(1): 48–59.

United Nations. 2023. The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water, UNESCO, Paris.

Vanham, D., Alfieri, L., Flörke, M., Grimaldi, S., Lorini, V., De Roo, A., & Feyen, L. 2021. The number of people exposed to water stress in relation to how much water is reserved for the environment: a global modelling study. *The Lancet Planetary Health* 5(11). doi.org/10.1016/S2542-5196(21)00234-5

Vatta, K., Sidhu, M. S., & Kaur, A. 2013. Pattern of growth and emerging challenges for Punjab agriculture. Mimeo. Punjab Agricultural University, Ludhiana.

Vatta, K., Sidhu, R.S., Lall, U., Birthal, P.S., Taneja, G. Kaur, B. Devineni, N., & MacAlister, C. 2018. Assessing the economic impact of a low-cost water-saving irrigation technology in Indian Punjab: the tensiometer. *Water International* 43(2): 305-321.

Wada, Y., Wisser, D., & Bierkens, M.F.P. 2014. Global modelling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth System Dynamics* 5(1):15–40.

Ward, F. A. & Pulido-Velazquez M. 2008. Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences* 105(47):18215–18220.

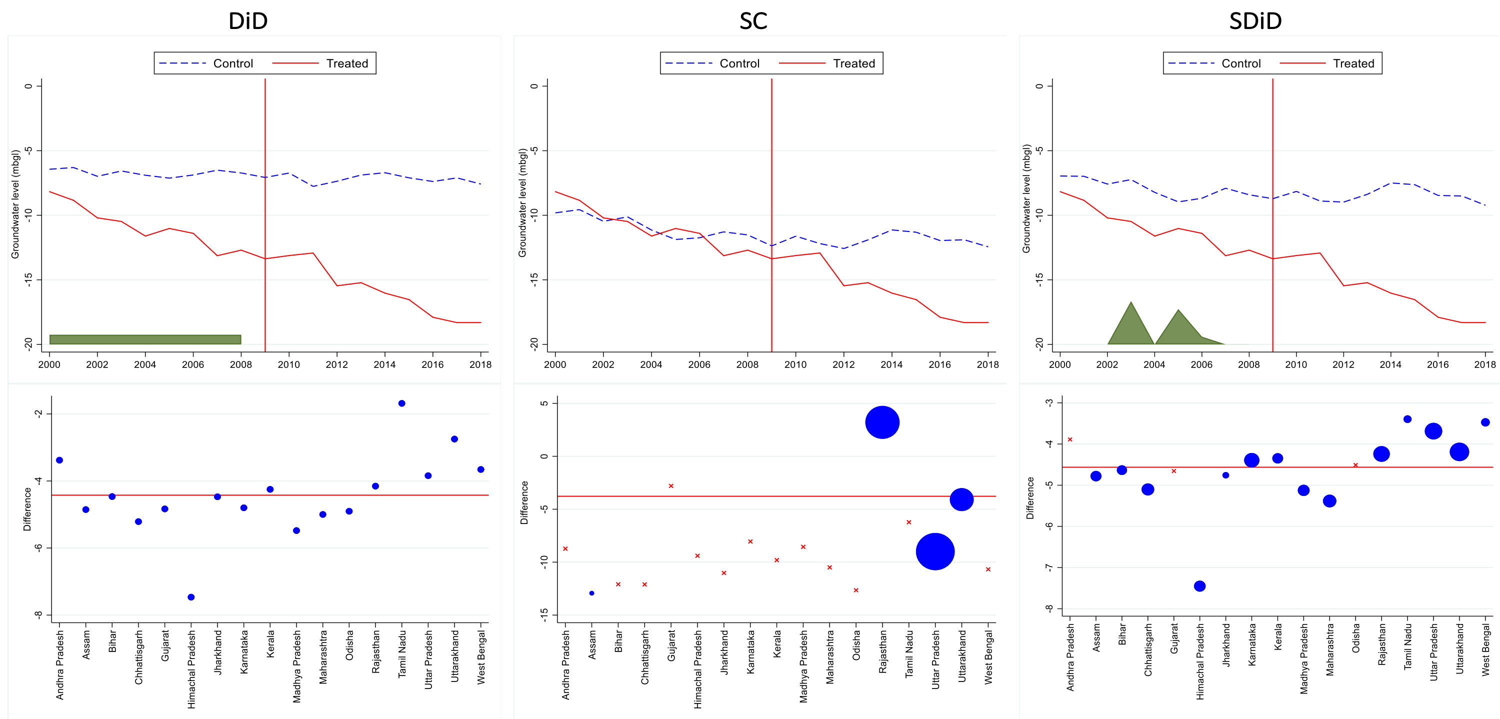
World Bank. 2010. Deep wells and prudence: towards pragmatic action for addressing ground water overexploitation in India. Washington DC.

Zaveri, E. & Lobell, D.B. 2019. The role of irrigation in changing wheat yields and heat sensitivity in India. *Nature Communications* 10: 4144.

Appendix Tables

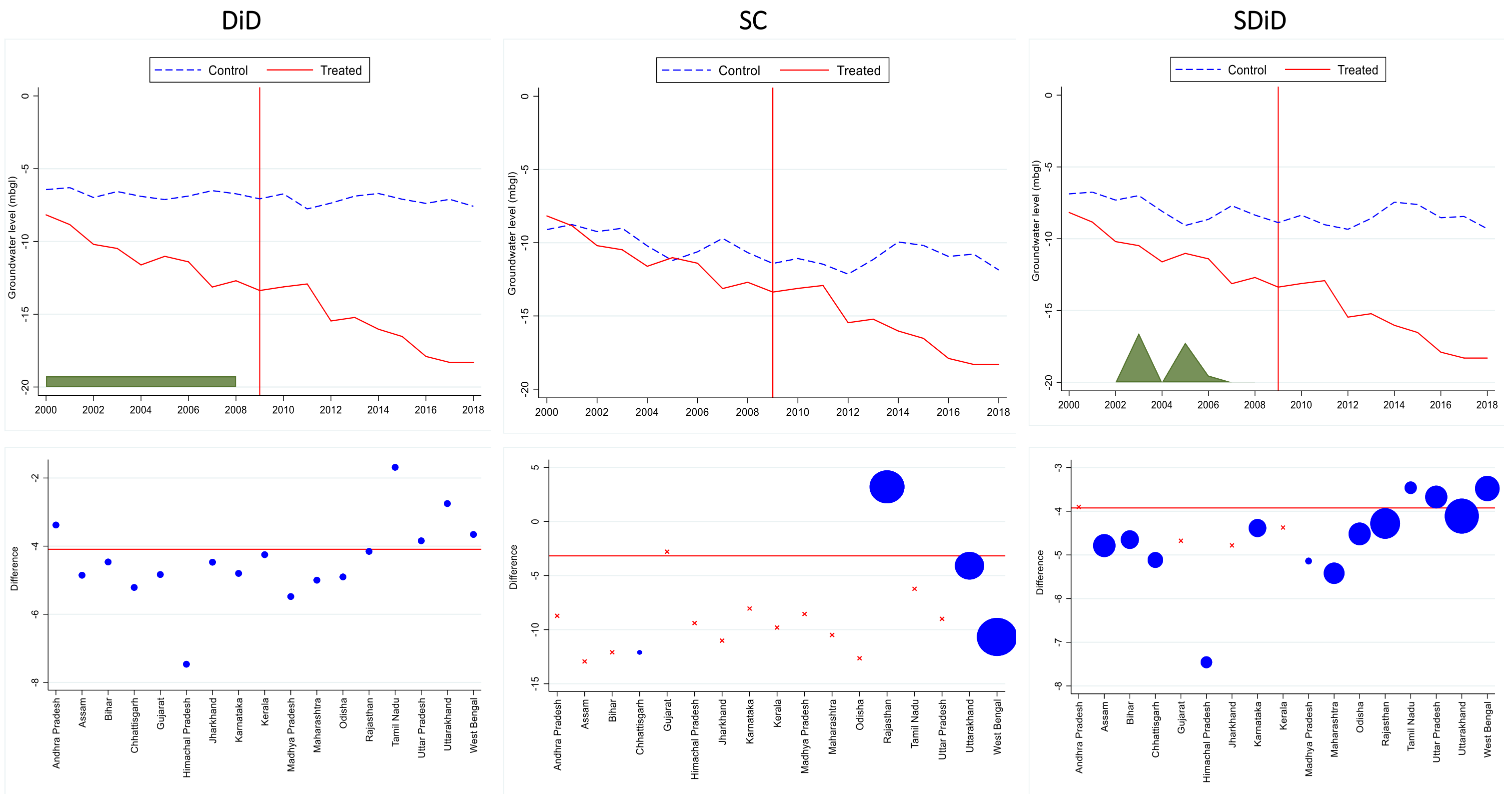
Figure A1a-b. Estimated impact of PPSWA on post-monsoon groundwater level in Punjab

Figure A1a. Estimates without covariates



Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

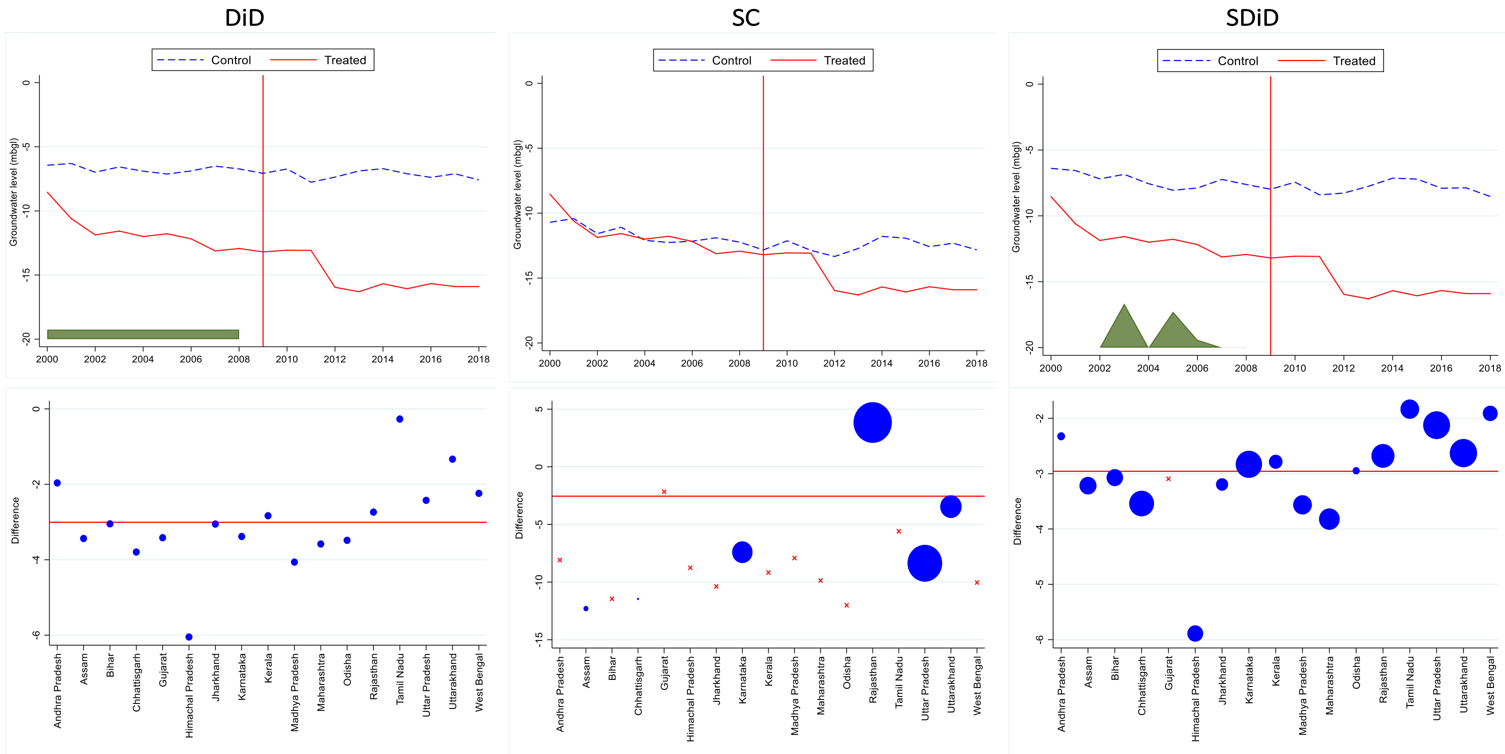
Figure A1b: Estimates with covariates



Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

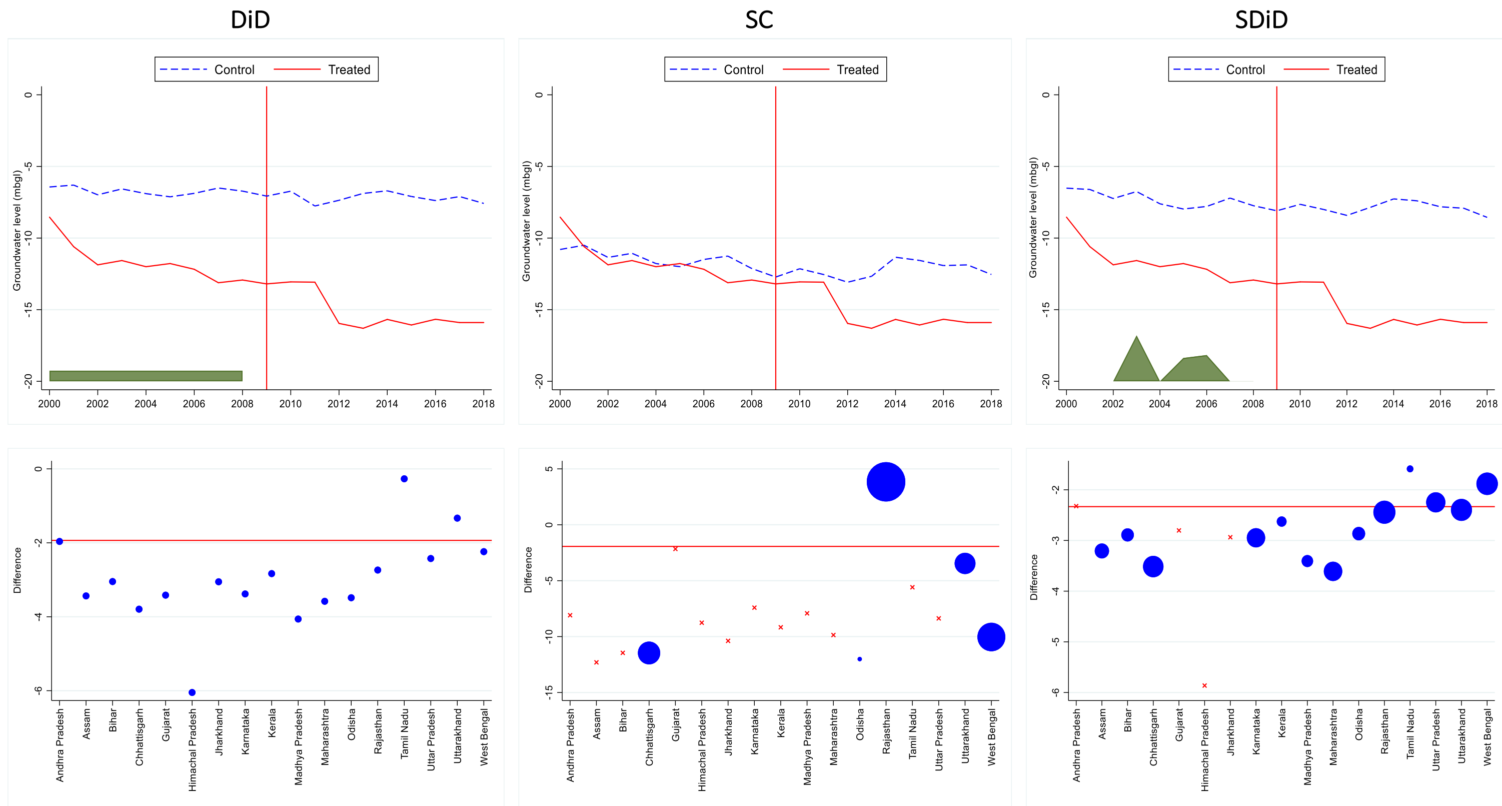
Figure A1c-d: Estimated impact of Act on post-monsoon groundwater level in Haryana

Figure A1c: Estimates without covariates



Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

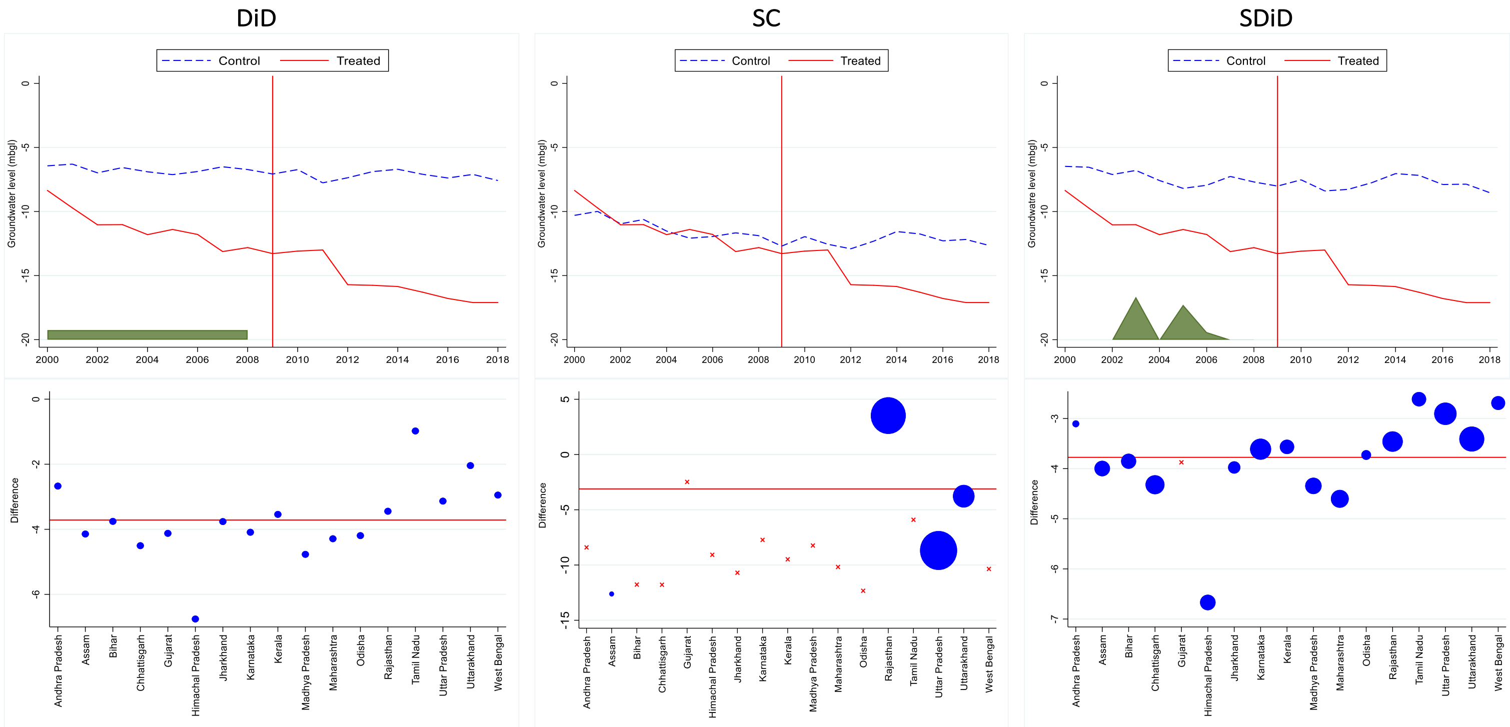
Figure A1d: Estimates with covariates



Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

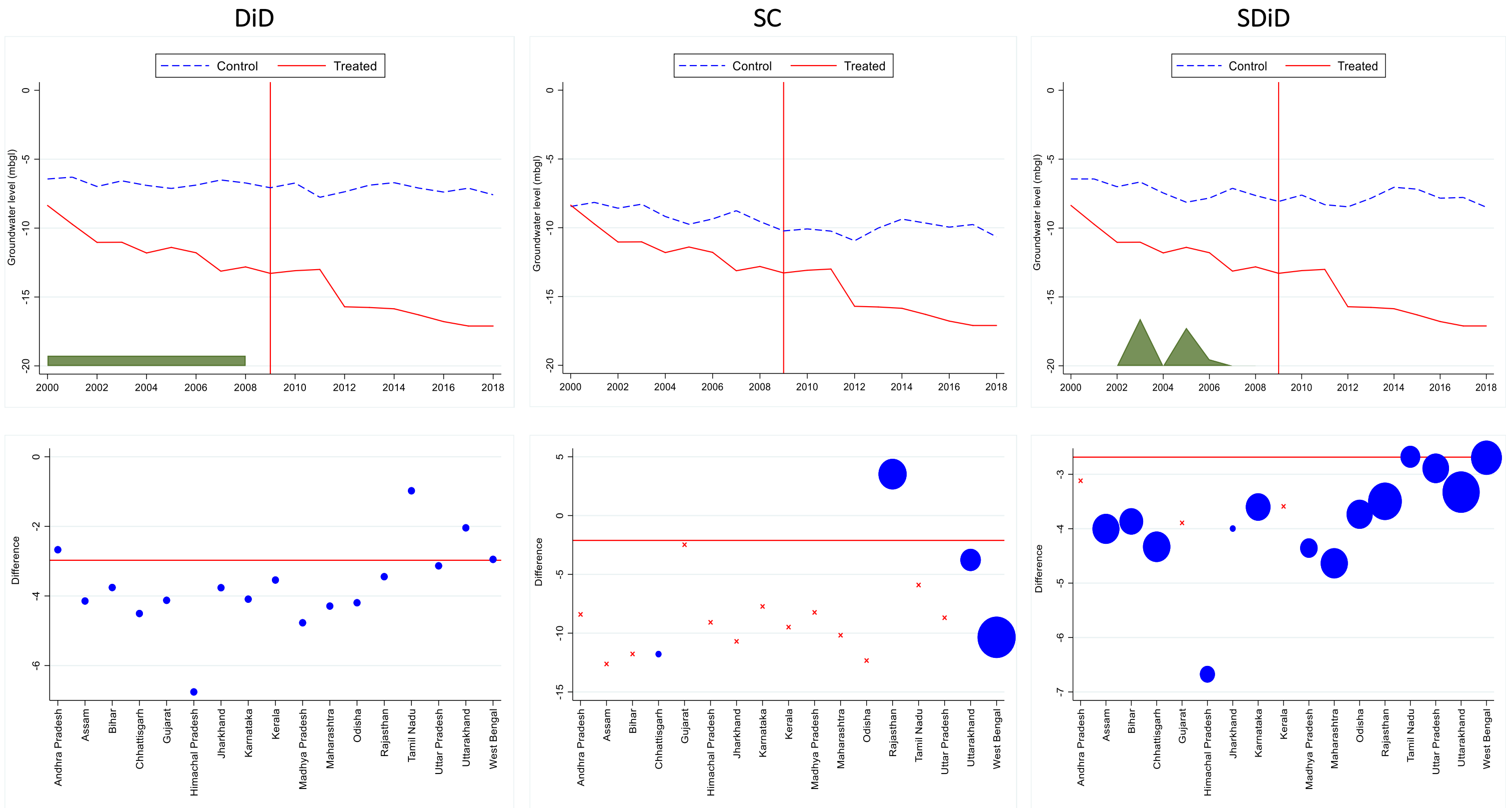
Figure A1e-f. Estimated impact of Acts on post-monsoon groundwater level in combined Punjab and Haryana (using bootstrap)

Figure A1e: Estimates without covariates



Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

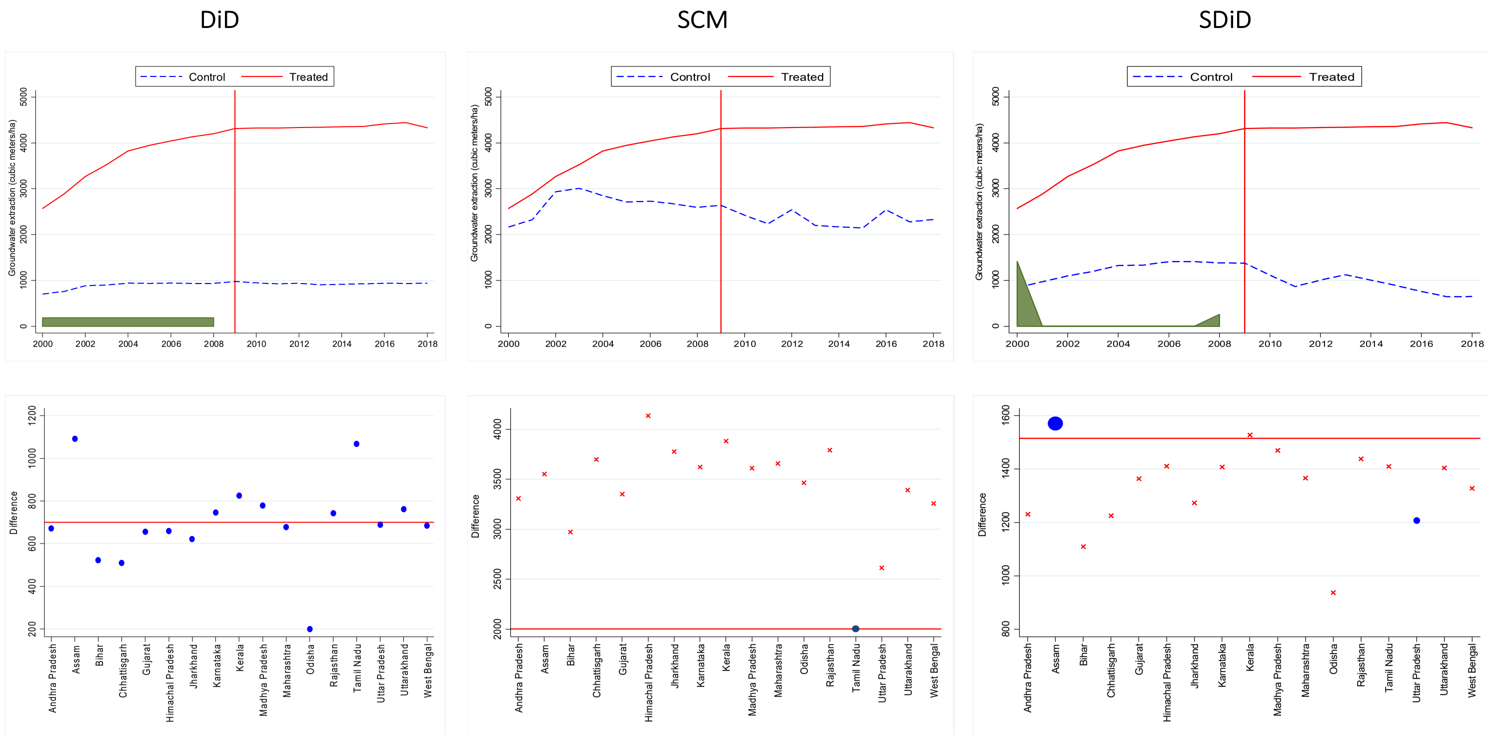
Figure A1f: Estimates with covariates



Note: First row shows trend in groundwater level for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

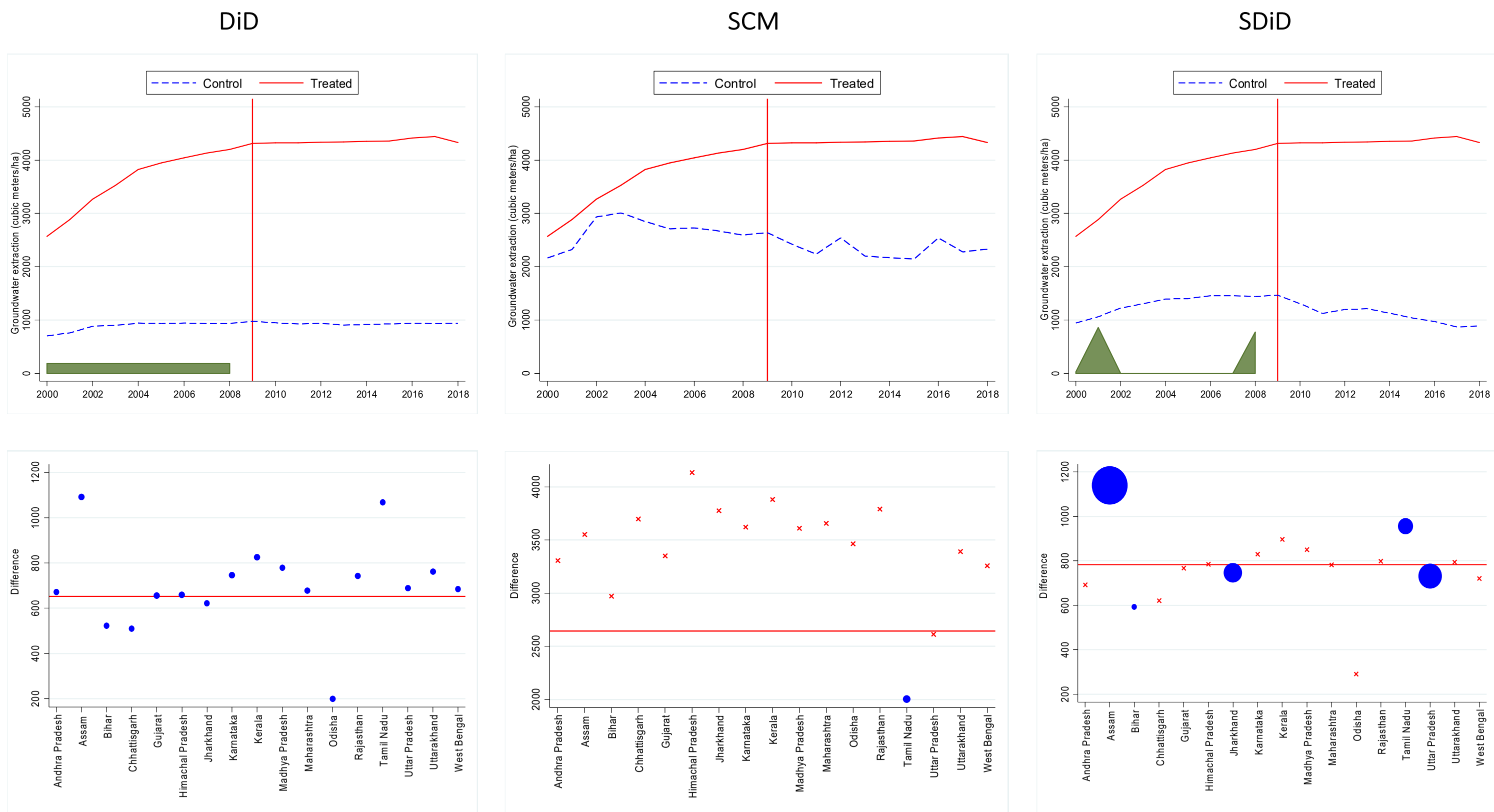
Figure A2a-b: Estimated impact of PPSWA on groundwater extraction in Punjab

Figure A2a: Estimates without covariates



Note: First row shows trend in groundwater extraction for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

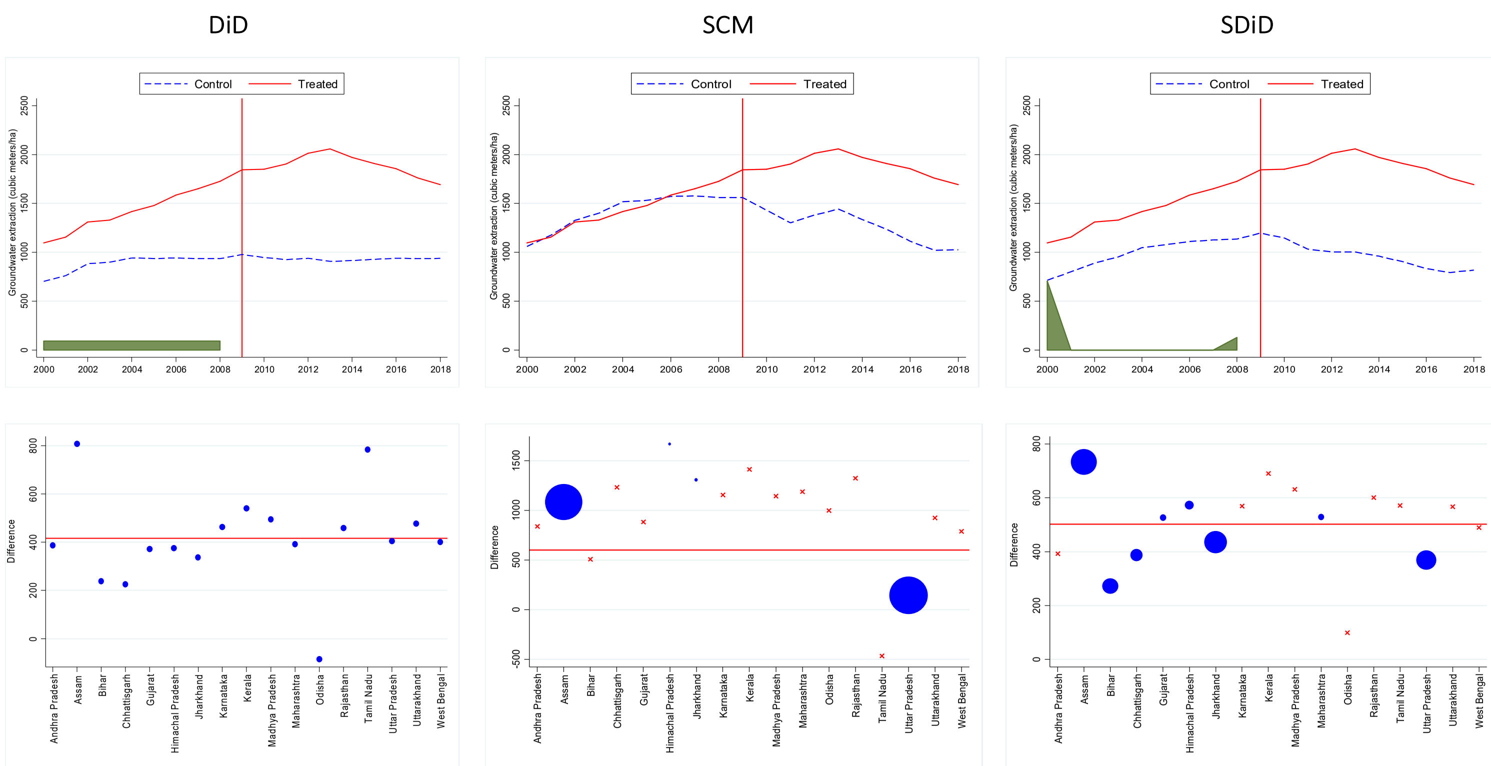
Figure A2b. Estimates with covariates



Note: First row shows trend in groundwater extraction for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

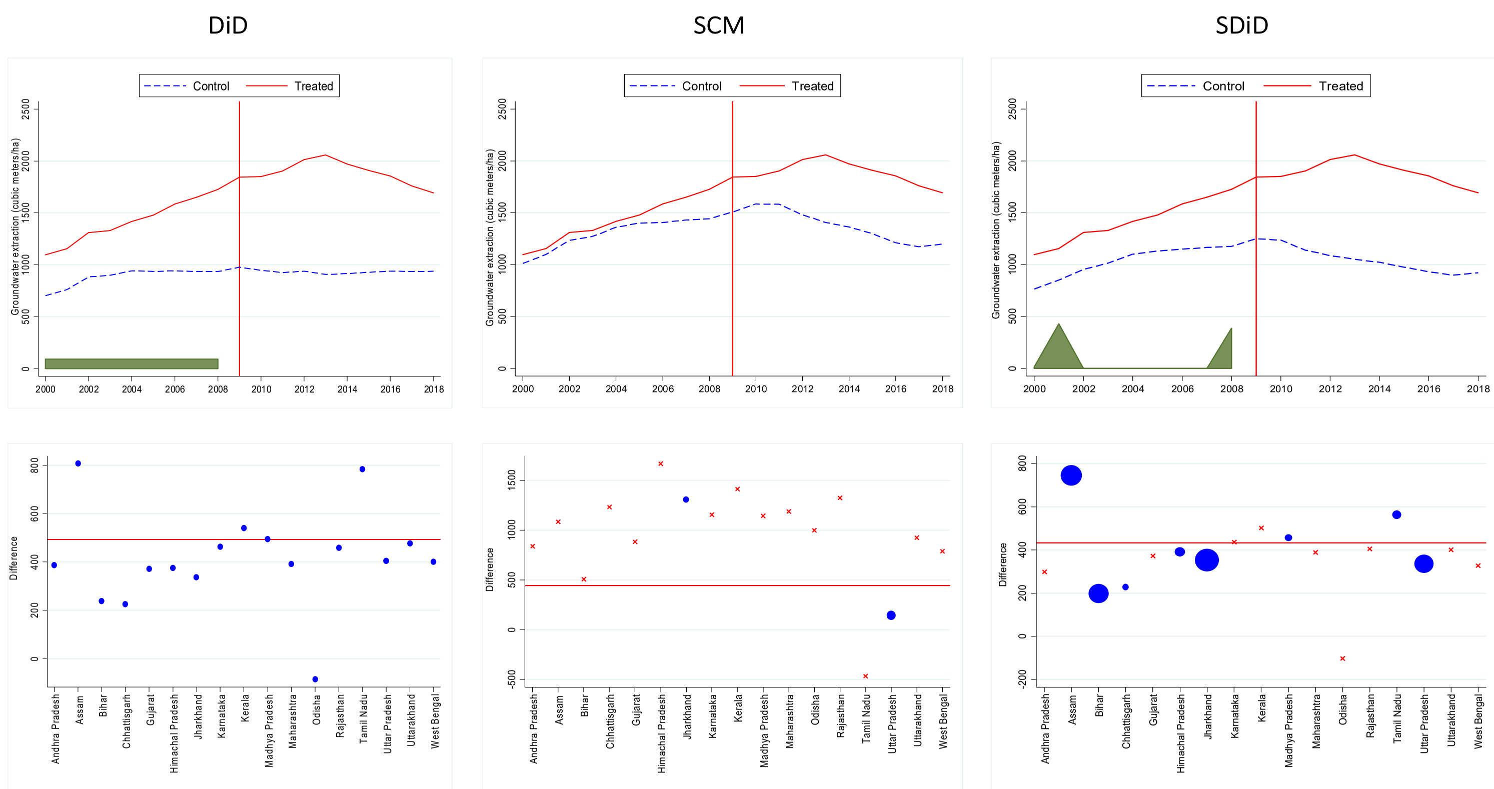
Figure A2c-d: Estimated impact of HPSWA on groundwater extraction in Haryana

Figure A2c. Estimates without covariates



Note: First row shows trend in groundwater extraction for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

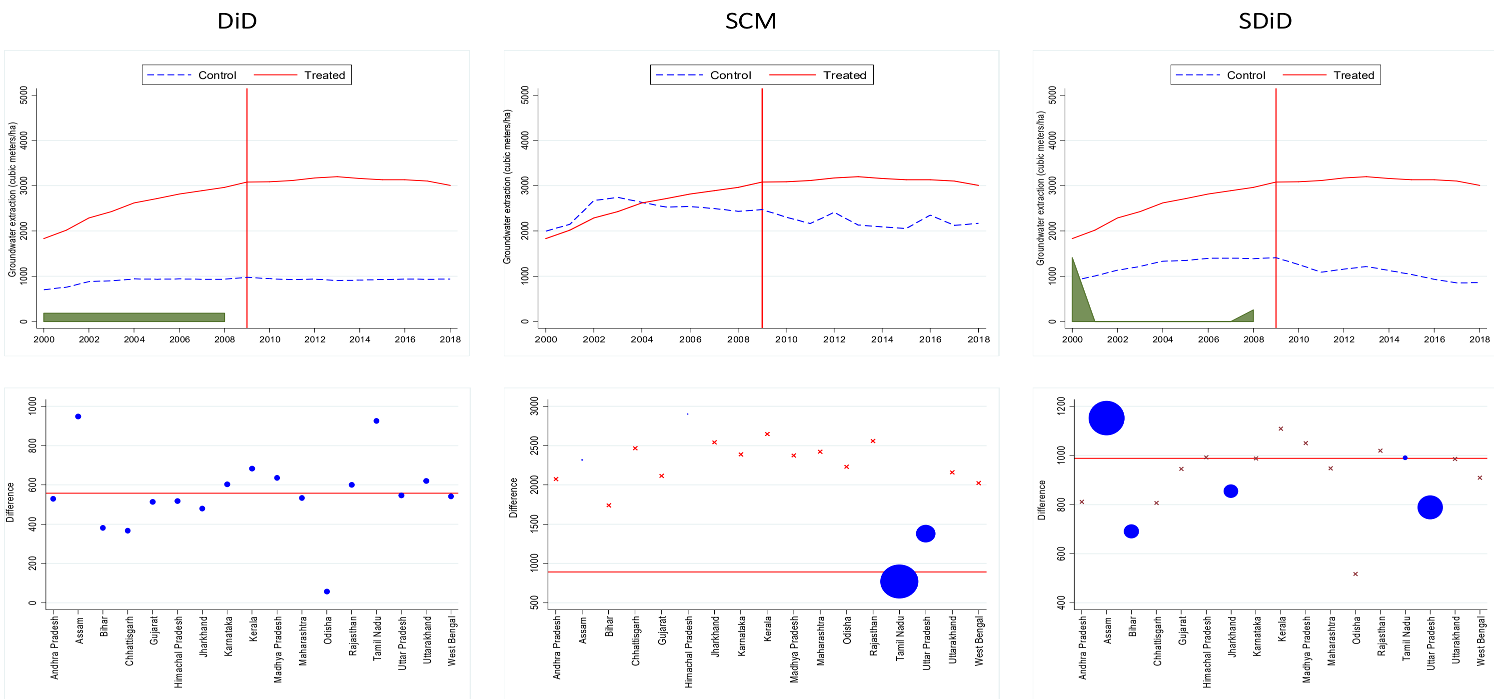
Figure A2d. Estimates with covariates



Note: First row shows trend in groundwater extraction for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

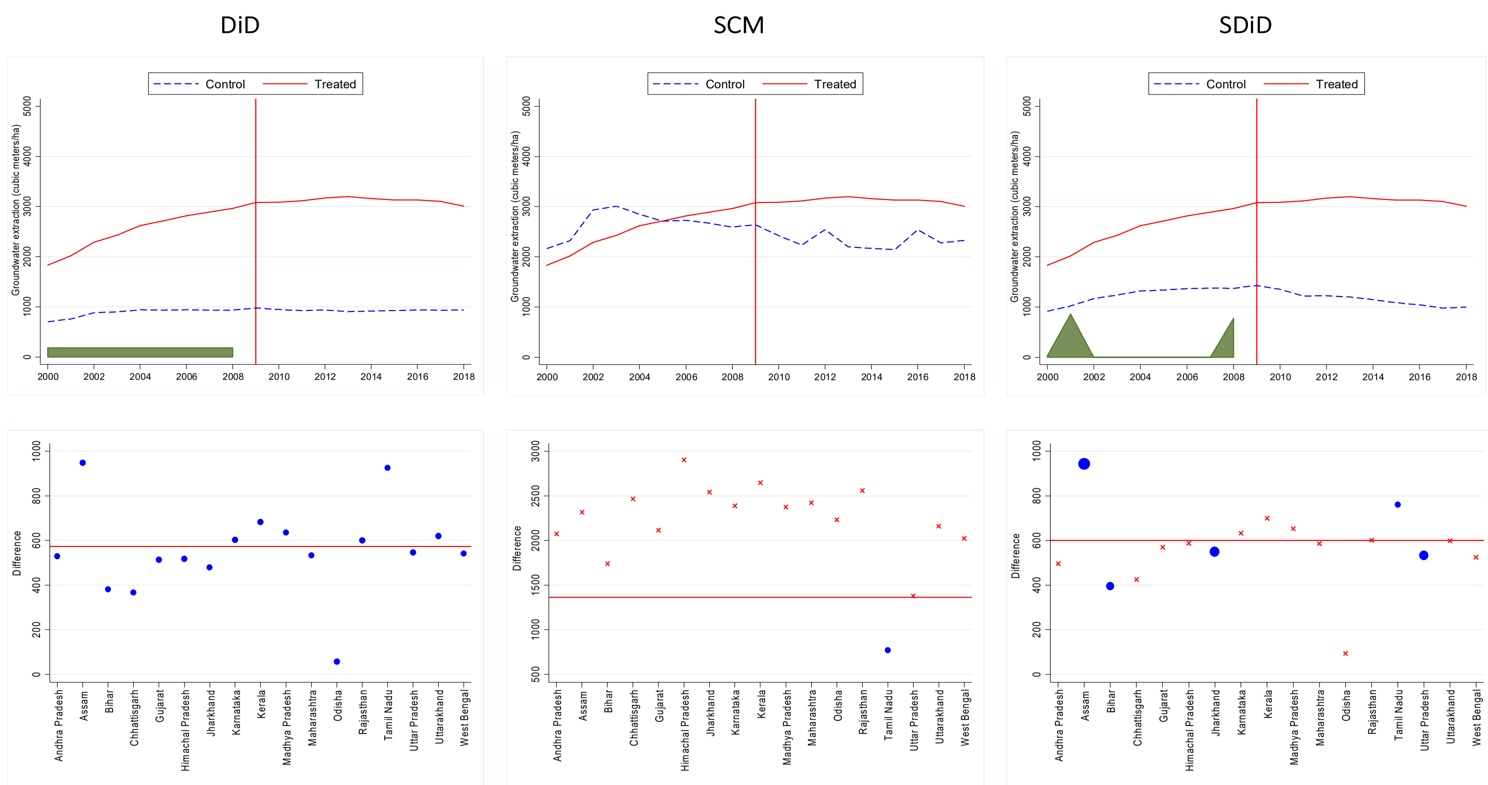
Figure A2e-f. Estimated impact of Acts on groundwater extraction in combined Punjab and Haryana (using bootstrap)

Figure A2e. Estimates without covariates



Note: First row shows trend in groundwater extraction for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

Figure A2f. Estimates with covariates



Note: First row shows trend in groundwater extraction for treated unit and weighted average of control units, with the time weights used to average pre-treatment time periods at bottom. Second row shows state-by-state adjusted outcome difference, with the weights indicated by dot size, and the weighted average of these differences (the estimated effect) indicated by a horizontal line. States are ordered alphabetically. Observations with zero weight are denoted by an x.

NIAP Publications

Policy Papers

27. Raju, S.S, P. Shinoj, R. Chand, P.K. Joshi, P. Kumar, and S. Msangi. 2012. *Biofuels in India: Potential, Policy and Emerging Paradigms.*
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29. Birthal, P.S, S. Kumar, D.S. Negi, and D. Roy. 2016. *The Impact of Information on Returns from Farming.*
30. Birthal, P.S, D.S. Negi, and D. Roy. 2017. *Enhancing Farmers' Income: Who to Target and How?*
31. Saxena, R, N.P. Singh, S.J. Balaji, U.R. Ahuja, and D. Joshi. 2017. *Strategy for Doubling Income of Farmers in India.*
32. Singh, N. P, A. Ashok, S. Pavithra, S.J. Balaji, B. Anand, and M. A. Khan. 2017. *Mainstreaming Climate Change Adaptation into Development Planning.*
33. Saxena, R and R. Chand. 2017. *Understanding the Recurring Onion Price Shocks: Revelations from Production-Trade-Price Linkages.*
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37. Subash, S.P, A. Jhajharia, and S. Pal. 2020. *Trade and Investment Policy for Overseas Acquisition of Fertilizers and Raw Materials: Role of the Government.*
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39. Saxena, R, S. K. Srivastava, S. J. Balaji, A. Jhajhria, and M. A. Khan. 2023. *Changes in Indian Agriculture: Household-level Evidence.*
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ICAR - NATIONAL INSTITUTE OF AGRICULTURAL ECONOMICS AND POLICY RESEARCH
(Indian Council of Agricultural Research)
Dev Prakash Shastri Marg, Pusa, New Delhi - 110 012, INDIA
Ph: +91(11) 2584 7628, 2584 8731 Fax: +91 (11) 2594 2684
Email : director.niap@icar.gov.in, Website : www.niap.icar.gov.in