



Chintan
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RESEARCH ARTICLE NO. 03/2027

THE COSTS BENEATH PRODUCTIVITY

Groundwater Dependence in
Indian Agriculture



JUNE 2026

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Abstract

Groundwater plays a central role in Indian agriculture, yet its contribution often remains invisible in conventional measures of agricultural performance. This study examines the relationship between groundwater dependence and agricultural surplus in selected Indian states using a residual-based accounting framework inspired by the System of Environmental-Economic Accounting. Using secondary data from the Commission for Agricultural Costs and Prices, the Central Ground Water Board, and the Department of Agriculture & Farmers Welfare, the study estimates groundwater-linked agricultural surplus across Punjab, Haryana, Rajasthan, Maharashtra, Karnataka, and Andhra Pradesh for the year 2023-24.

The analysis combines crop-level surplus estimates with state-level indicators of groundwater dependence to develop indicative estimates of groundwater-linked value and groundwater depletion costs within agricultural production systems. The findings reveal that states with higher agricultural surplus also tend to have a higher dependence on groundwater. However, the study finds that higher groundwater-linked value does not necessarily indicate sustainable groundwater use. Punjab and Haryana show high estimated groundwater-linked surplus alongside severe groundwater stress, while states with lower groundwater stress generally record lower estimated groundwater-linked values.

The study suggests that current measures of agricultural performance may partly reflect dependence on groundwater without explicitly recognising the condition of the underlying resource. By making groundwater dependence more visible within agricultural surplus, the paper contributes to discussions on environmental accounting, groundwater governance, and the links between agricultural policy, groundwater use, and long-term resource sustainability in India.

Keywords: Agricultural productivity; agricultural surplus; crop diversification; environmental accounting; groundwater depletion; groundwater dependence; groundwater governance; India; resource sustainability; SEEA; sustainable agriculture

Introduction

Groundwater forms the backbone of India's agricultural economy and plays a major role in supporting food security for more than a billion people (UNESCO World Water Assessment Programme 2022). Over the last five decades, India has gradually shifted from a system mainly dependent on surface irrigation towards one heavily reliant on decentralised private groundwater extraction (Singh and Goyal 2025; Gulati and Pahuja 2015). Today, India ranks as the world's largest consumer of groundwater, extracting nearly 245.64 billion cubic metres (BCM) every year (Central Ground Water Board [CGWB] 2024). Approximately 25 per cent of global groundwater extraction takes place in India, and close to 87 per cent of this water is used by agriculture for irrigation (CGWB 2024).

The move toward groundwater irrigation became a major driver of the Green Revolution because it provided a more reliable and 'on-demand' source of water for high-yield crop varieties. However, this reliability has brought serious environmental pressures over time (Kumar and Sekher 2026). The CGWB classifies nearly 11 per cent of assessment units as 'over-exploited', while extraction levels in states such as Punjab and Rajasthan have reached critically high levels relative to annual recharge. Even with these visible signs of stress, the economic role of groundwater often remains hidden within conventional agricultural accounting systems.

In most traditional accounting systems, the contribution of nature is either ignored or indirectly accounted for in broader indicators such as crop output or land productivity (Ferrini et al. 2025). Since groundwater is not traded like a normal market commodity and lacks a clearly observable price, its economic value is rarely captured adequately in policy and production assessments. As a result, high agricultural productivity can often mask the gradual depletion of groundwater resources, fostering a disconnect between short-

term agricultural gains and long-term sustainability (Ferrini et al. 2025).

This problem is further compounded by existing policy incentives. In many states, electricity used for agricultural pumping is either heavily subsidised or unmetered, keeping the perceived cost of groundwater extraction extremely low (Gulati and Pahuja 2015; Khara 2023). This encourages continuous extraction to support water-intensive crops such as rice and wheat (Gulati and Pahuja 2015). At the same time, Minimum Support Price (MSP) systems and assured procurement policies continue to reinforce cropping patterns that are often not suited to local water availability (Ramachandra et al. 2023). In several regions, current agricultural surplus is therefore closely tied to the continued overuse of groundwater resources, with short-term production gains sustained by the long-term depletion of aquifers (Ferrini et al. 2025).

These concerns highlight the need for an approach that exposes groundwater's economic footprint within agricultural production systems. In line with the System of Environmental-Economic Accounting (SEEA)¹, improving the visibility of natural resource use is critical for better water governance and policy planning (Ferrini et al. 2025). While conventional agricultural indicators mainly focus on land productivity and output, resource-based accounting approaches attempt to identify resource rent – the surplus value linked to natural resource use – after accounting for other production costs (Markandya et al. 2022).

This study attempts to address this gap by estimating groundwater-associated agricultural surplus across selected Indian states. Using a residual-based accounting framework inspired by SEEA and resource rent approaches, the study approximates groundwater's economic contribution by subtracting measurable production costs from the gross value of agricultural output. The remaining surplus reflects the combined return to fixed factors and natural

¹The SEEA is an international accounting framework developed by the United Nations to integrate environmental resources and ecosystem contributions into conventional economic accounting systems.

resources and provides an indicative measure of the extent to which agricultural surplus is supported by groundwater use (United Nations et al. 2017).

The study adopts a descriptive and diagnostic approach rather than a causal one. It does not attempt to model behavioural responses or estimate marginal productivity through econometric methods. Instead, it provides a comparative state-level assessment of production systems using secondary administrative data. By examining variations in groundwater dependence across states with different hydrological conditions, the study aims to develop a broader understanding of how agricultural surplus remains linked to groundwater use under conditions of increasing resource stress.

Research Question

Against this background, the study addresses the following research question:

To what extent is observed agricultural surplus in selected Indian states associated with groundwater use when examined through a residual-based accounting framework?

This question is supported by the following analytical sub-questions:

- How can groundwater-linked agricultural surplus be estimated using a residual accounting framework combined with state-level indicators of groundwater dependence?
- How does the magnitude of groundwater-linked surplus vary across states with contrasting levels of groundwater reliance and extraction intensity?
- To what extent can conventional measures of agricultural surplus be interpreted as implicitly capturing returns to groundwater as an unpriced natural input?

Literature Review

This literature review examines the key themes relevant to understanding groundwater's role in Indian agriculture and its treatment within economic accounting frameworks. It reviews patterns of groundwater dependence and irrigation use,

discusses resource rent and environmental accounting approaches, examines the accounting treatment of water in agricultural production systems, and highlights the methodological challenges associated with estimating groundwater's contribution to agricultural output. The review also considers how policy incentives influence groundwater extraction and agricultural decision-making, thereby providing the conceptual foundation for the analytical framework adopted in this study.

Groundwater Use and Irrigation Dependence in Indian Agriculture

Groundwater has become increasingly important for agricultural production in India and is now a primary irrigation source. India uses an estimated 230-251 billion cubic metres of groundwater each year, making it the world's largest groundwater consumer (Kapoor and Anand 2024). Of this, the lion's share (8990 per cent) is used by the agricultural sector for irrigation (Sharma et al. 2018; Gandhi, Johnson, and Singh 2021). This trend became more noticeable after the Green Revolution of the late 1960s. According to the UNESCO World Water Assessment Programme (2022), decentralised tubewells delivered water more reliably than traditional gravity-fed canals, particularly after the introduction of high-yield seed varieties and fertilisers. The productivity of groundwater-irrigated farms is roughly double that of surface water farms, prompting significant private investment in tubewells and pumps (Gulati and Pahuja 2015; Rajkhowa 2024).

State-level energy policy, including the supply of unmetered or subsidised electricity for agricultural pumps, is strongly linked to this increase (Kapoor and Anand 2024). Farmers are encouraged to irrigate water-intensive crops such as sugarcane and paddy since extraction costs are perceived to be extremely low (Sharma et al. 2018).

Dependency varies greatly by region. Most irrigation in northwestern regions such as Punjab, Haryana, and Rajasthan relies on groundwater, which frequently exceeds annual recharge (Kumar and Sekher 2026). The CGWB classifies groundwater units by extraction to recharge ratio into four brackets: safe

(≤ 70 per cent), semi-critical (70-90 per cent), critical (90-100 per cent), and over-exploited (> 100 per cent) (Kumar and Sekher 2026). Currently, 11.13 per cent of units suffer from over-exploitation (Kumar and Sekher 2026).

This long-term reliance on groundwater means that agricultural surplus often includes value derived from depleting natural capital – a dependence that conventional economic measures fail to capture (Akhtar and Cavalletti 2025).

Resource Rent and Residual Approaches in Environmental Accounting

Groundwater's economic impact on agricultural productivity is hard to quantify since it lacks a clearly defined market price. Environmental and resource economics therefore employs methods such as the resource rent approach to determine the value of natural inputs.

Resource rent is important in environmental and resource economics because it measures the economic value of natural assets used in production. It measures surplus after accounting for production costs and normal returns to capital (United Nations et al. 2017).

Groundwater is one of several natural resources that are not traded in competitive markets and whose economic worth is not reflected in observed prices. In these situations, resource rent acts as a stand-in for the exchange value that would result from assigning a market price (Edens and Graveland 2014). The residual surplus method is a widely used estimation technique that deducts the costs of additional paid and imputed inputs from the gross value of final marketed output, such as agricultural revenue (Ramachandra et al. 2023).

Common deductions include labour, intermediate inputs, and the user cost of capital. Depreciation and the anticipated return on assets such as machinery or irrigation infrastructure are factored into this calculation (Markandya et al. 2022; Ferrini et al. 2025). The residual is attributed to the natural resource and serves as an accounting estimate of

its contribution (Markandya et al. 2022).

Accounting systems differ in how they treat natural inputs. Traditional national accounts, following the System of National Accounts (SNA), have generally left the contribution of nature implicit. As ecosystem services are not produced by an institutional economic unit and their contribution to production is rarely explicitly documented, they fall beyond the production boundary of the SNA (Edens and Graveland 2014; Markandya et al. 2022). Adopted in 2021, the SEEA – Ecosystem Accounting (SEEA-EA) combines economic and ecological data to enable systematic measurement of ecosystem contributions.

That said, residual estimation methods face certain limitations. The value contribution of an ecosystem is difficult to determine, particularly when joint factor attribution causes the residual to absorb unaccounted factors such as managerial ability and institutional structures. In addition, the value estimated differs depending on input prices and commodity prices; therefore, residual methods are heuristic in nature (Markandya et al. 2022).

In India, this framework is crucial for measuring the role of groundwater in agriculture. In the absence of a direct market price for groundwater, its contribution remains embedded within residual measures of agricultural surplus, alongside more general metrics such as crop yield or land value (Ramachandra et al. 2023; Edens and Graveland 2014). This may obscure the true extent to which agricultural output depends on a finite natural resource.

Accounting Treatment of Water in Agricultural Production Systems

Groundwater's accounting treatment depends on how irrigation inputs are documented. The Comprehensive Scheme for Studying the Cost of Cultivation of Principal Crops (CS), which provides farm-level cost data used by the Commission for Agricultural Costs and Prices (CACP) to set agricultural price policy, is the main method used in India to gather this data (Department of Agriculture and Farmers Welfare [DA&FW] 2023). Irrigation is recorded as a distinct operational expense, typically

under 'irrigation charges', covering both payments for water and operational costs of self-extraction, such as electricity or fuel for pumps (CACP 2025).

Production costs are calculated through nested aggregates. The farmer's actual paid-out expenses fall under A2, and the imputed value of family labour is included in A2+FL. The interest on fixed capital and the rental value of owned property are also included in the most complete measure, C2. Groundwater resource depletion is typically omitted from C2, even though it records interest and depreciation on irrigation infrastructure (Government of India et al. 2024). Natural resource extraction is not reported as a deduction from income under the SNA, but rather as a change in asset volume (United Nations et al. 2017).

Groundwater from privately owned wells thus often enters production without a recorded resource cost (UNESCO World Water Assessment Programme 2022). This is reinforced by state-level electricity policies that heavily subsidise or exempt irrigation pumping. The marginal cost of extraction appears near-zero to farmers, so financial irrigation costs reflect only private expenditures and ignore the scarcity or environmental costs of aquifer over-extraction (Gulati and Pahuja 2015).

This creates a gap between financial and economic costs. Conventional accounts record observable expenditures, whereas environmental-economic

frameworks such as the SEEA estimate natural input values more explicitly using the resource rent method (United Nations et al. 2017). The remainder obtained after subtracting labour costs, intermediate consumption, and the user cost of produced capital from gross operating surplus is known as resource rent (Ramachandra et al. 2023). Groundwater is often regarded as an abundant or 'free' input under current pricing regimes. In water-stressed regions, this can result in very low resource rents and, in some cases, even negative values (United Nations et al. 2017).

The absence of explicit groundwater valuation carries important consequences for agricultural surplus measurement, especially in regions reliant on groundwater irrigation (UNESCO World Water Assessment Programme 2022; Rajkhowa 2024). In practice, groundwater's contribution is typically subsumed within broad measures such as crop output or land productivity (Government of India et al. 2024). As a result, high levels of agricultural production can occur alongside a gradual decline in groundwater levels, meaning that Gross Value Added (GVA) may remain high even as underlying natural capital is depleted (Ramachandra et al. 2023).

Challenges in Estimating Groundwater's Contribution to Agriculture

Estimating groundwater's contribution is difficult because agriculture depends on multiple interacting



inputs. Joint factor attribution constitutes a major obstacle. The residual accounting methodology measures the surplus left after expenses related to purchased inputs are deducted. The supply of ecosystem services is frequently linked to this residual. Yet it might also reflect the impact of other non-priced factors, such as management skills or local institutional conditions (Markandya et al. 2022). If other inputs are disregarded, residual estimates may overstate the contribution of groundwater (United Nations et al. 2017).

Input contributions can be estimated using econometric production functions such as Cobb-Douglas², although these approaches require detailed farm-level data that are often unavailable for groundwater extraction (Huang et al. 2023).

Agricultural datasets have certain limitations. Even when farmers use both private wells and canals, land-use statistics often indicate irrigated land under a single source, usually canals. Groundwater dependency may be consistently underestimated as a result (Huang et al. 2023). When groundwater conditions are aggregated at the state or national level, local water scarcity can be obscured. This is mainly because hydrogeological conditions are heterogeneous, and aggregated statistics struggle to capture the variability in precipitation, aquifer properties, and water use across different regions (Sharma et al. 2018; Chen et al. 2025).

The financial estimates generated from residual approaches may be sensitive to changes in the definitions of prices and costs; therefore, fluctuations in the prices for a particular input, such as fuel, fertilisers, or crops, could lead to substantial variation in the financial estimates year after year (Markandya et al. 2022). Resource rent estimates may also be skewed by incomplete information on the user cost of fixed capital, such as depreciation and estimated returns for pumping infrastructure (Ferrini et al. 2025). Although market-consistent pricing is reflected

in exchange values used in accounting systems, consumer surplus and broader welfare factors are not taken into account (Chen et al. 2025).

It is important to differentiate between hydrological and accounting approaches. Hydrological physical depletion is estimated using hydrological models (extraction volumes, recharge, changes in storage) and concerns what is extracted, recharged, and how storage changes over time. By contrast, the SEEA-EA and other environmental-economic accounting methodologies assign a value to the ecosystem function that groundwater delivers to production systems (Markandya et al. 2022). Currently, biophysical water accounts are more developed than monetary accounts, creating an asymmetry between physical and economic measurement (Edens and Graveland 2014).

While accounting-based estimations of groundwater surplus show how structurally dependent agriculture is on groundwater, they do not offer precise causal measures of extraction or depletion; groundwater's impact remains largely obscured in traditional narratives (Shen and Lin 2017; Markandya et al. 2022).

Policy Incentives and Groundwater Use in Agriculture

In policy contexts, the way groundwater use and agricultural production are measured depends heavily on the accounting methods applied. Although natural resources can be taken into account in the assessment of production using economic accounting systems, the economic value of ecosystem services is not accounted for because such contributions are not recognised under international economic accounts (Edens and Graveland 2014; Ferrini et al. 2025). Its value groundwater goes unrecognised as a distinct production factor and is instead incorporated into agricultural GVA (Ferrini et al. 2025; United Nations et al. 2017). Extraction is therefore treated as a change in asset volume rather than a deduction from agricultural income (United Nations et al. 2017).

²The Cobb–Douglas production function is a commonly used econometric model that represents output as a function of multiple inputs, typically labour and capital, allowing researchers to estimate the relative contribution of each factor to production.

This accounting treatment affects economic signals. Prices are meant to indicate scarcity and guide efficient allocation (Sharma et al. 2018). In theory, the marginal benefit of the last unit of water can be used to measure its scarcity value, also referred to as its shadow price³ (Chen et al. 2025; Shen and Lin 2017). However, water prices rarely reflect this value because of government intervention, price controls, and unclear water rights (Chen et al. 2025). Incentives to cut back on extraction or switch to less water-intensive activities are weak in the absence of consistent price signals. This is further aggravated by policy instruments. Electricity used for irrigation is either unmetered or significantly subsidised in a number of states (Sharma et al. 2018; Gulati and Pahuja 2015). The perceived marginal cost of groundwater is therefore extremely low, and cost-of-cultivation statistics account only for private costs rather than aquifer depletion (Gulati and Pahuja 2015). Irrigation-dependent cropping patterns are reinforced by MSP for water-intensive commodities, including sugarcane and rice (UNESCO World Water Assessment Programme 2022; Chen et al. 2025). As a result, even under resource stress, agricultural returns may seem high.

Irrigation expansion programmes, such as the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), aim to increase coverage and improve application efficiency (Gandhi, Johnson, and Singh 2021). Programme evaluation usually relies on indicators such as Irrigation Potential Created (IPC) and irrigated area. These indicators capture infrastructure expansion, but ignore groundwater sustainability (Huang et al. 2023). Declining water tables are therefore invisible in economic and administrative assessments.

The key policy challenge is economic visibility. When groundwater extraction is not reflected in agricultural surplus, production systems may appear robust even in over-exploited regions. Intensive groundwater extraction has maintained high production in a number of Green Revolution states (Sharma et al.

2018). Financial success can be evaluated without considering the underlying resource base since depletion goes completely unrecorded (Edens and Graveland 2014). Accounting structures thus influence perceptions of agricultural performance by capturing the benefits of groundwater extraction while largely leaving resource depletion unrecorded. This gap between observed agricultural surplus and the underlying depletion of groundwater resources highlights the need for approaches that explicitly account for groundwater's contribution to agricultural production.

Methodology

This section describes the data sources, sample selection, and analytical procedures used in the study. It outlines the construction of the crop-state dataset, the criteria used for selecting states and crops, and the approach adopted to combine agricultural and groundwater information. The section also explains how agricultural surplus and groundwater-linked estimates are derived using a residual accounting framework.

Data Sources and Coverage

This study uses data from official government sources to construct a consistent dataset for analysing the relationship between agricultural production and groundwater use. The datasets are administrative and widely used in policy analysis, which helps ensure comparability across states. This dataset provides detailed estimates of paid-out costs (A2), imputed family labour (FL), and the gross value of output (GVO) per hectare for various crops. These variables are used to estimate agricultural surplus. Such data are first gathered collected primarily to assist in support agricultural price policy, in particular, particularly the determination of Minimum Support Prices. The Central Ground Water Board (CGWB), Ministry of Jal Shakti, provides information on groundwater extraction levels, recharge, and the stage of groundwater development through the National

³In economic theory, a shadow price refers to the implicit value of a resource that does not have an observable market price and is often estimated through models to reflect its scarcity or marginal contribution to production.



Compilation on Dynamic Ground Water Resources of India (CGWB 2024). These data are summarised to assess and monitor groundwater resources. Data on crop-wise cultivated area isare sourced from the Department of Agriculture & Farmers Welfare (DA&FW (n.d.), which maintains records of cultivated area, production, and yield . The states considvered in the study are Punjab, Haryana, Andhra Pradesh, Karnataka, Maharashtra, and Rajasthan. These states have been chosen because they exhibit differences in their irrigation systems and in their dependence on groundwater resources, which can be analysed and compared.

The unit of analysis for agricultural variables is the crop-state combination, while groundwater data are consistently available only at the state level. The dataset is cross-sectional and based on a single reference year (2023-24). As a result, the analysis focuses on differences across states at a given point in time rather than changes over time.

Sample Selection and Data Preparation

The study is based on four major irrigated crops in each of the chosenselected states. Three criteria are used to govern the selection of crops: the significance of the crop in irrigated agriculture, the availability of consistent cost-of-cultivation data, and the requirement that the estimated surplus be non-negative. Although some crops occur in two or more states, such as paddy, wheat, and cotton, the final

choice is based onreflects local cropping patterns. Consequently, the sample reflects economically viable, surplus-generating crop systems rather than the entire range of agricultural production.

The dataset is organised at the crop-state level, with four crops selected for each of the six states, resulting in a total of 24 crop- state observations. For each observation, crop-level variables, such as gross output value and production costs, are expressed on a per-hectare basis.

To enable aggregation, crop-level surplus estimates are scaled using cultivated area data. This allows crops with larger area coverage to contribute proportionally more to state-level estimates.

Data from different sources are harmonised before analysis. Economic variables are expressed in ₹ per hectare, while groundwater data, originally reported in billion cubic metres (BCM), are converted into cubic metres for consistency in valuation.

Agricultural data are available at the crop level, whereas groundwater data are available at the state level. Groundwater-related estimates are combined with crop-level surplus through a consistent attribution approach. The dataset is cross-sectional as well. It thus presents a picture of agricultural production and groundwater consumptionuse under prevailing conditions, but not the long-term trends.

Measurement and Variable Construction

This subsection defines the variables used in the analysis and explains how they are constructed from the underlying agricultural and groundwater datasets. The variables follow a sequential accounting structure, beginning with crop-level surplus estimation and progressing to state-level measures of groundwater-associated value and depletion cost.

Variable Construction

This study constructs a set of variables to translate agricultural production data into estimates of groundwater-associated value using a residual accounting framework. The variables are defined sequentially, moving from crop-level production to state-level groundwater valuation.

Crop Surplus (S_c)

$$S_c = GVO_c - (A2_c + FL_c)$$

This represents the residual surplus per hectare for crop c , after accounting for paid-out costs and family labour. It captures returns to factors that are not directly priced, such as natural resources like groundwater.

Total Crop Surplus (TS_{cs})

$$TS_{cs} = S_c \times Area_{cs}$$

This converts per-hectare surplus into total surplus for each crop–state combination by scaling it with cultivated area. This step ensures that crops with a larger area contribute proportionally more to the total surplus.

Groundwater-Associated Surplus (GS_s)

$$GS_{cs} = TS_{cs} \times \theta_s$$

This assigns a share of the total crop surplus to groundwater using a state-level attribution parameter θ_s , defined as the calibrated proportion of agricultural surplus associated with groundwater use in states.

State-Level Groundwater-Associated Surplus (GS_s)

$$GS_s = \sum_c GS_{cs}$$

This aggregates groundwater-associated surplus across all selected crops within a state to obtain a total estimate.

Groundwater Value ($GWValue_s$)

$$GWValue_s = (GS_s) / (GWExtraction_s)$$

This represents the implied average value of groundwater per unit of extraction, expressed in ₹ per cubic metre.

Groundwater Depletion Volume ($DepletionVolume_s$)

$$DepletionVolume_s = \max(0, GWExtraction_s - GWRecharge_s)$$

This measures the extent to which groundwater extraction exceeds annual recharge, capturing overuse.

Groundwater Depletion Cost ($DepletionCost_s$)

$$DepletionCost_s = GWValue_s \times DepletionVolume_s$$

This estimates the economic magnitude associated with groundwater depletion under current production conditions.

Taken together, these variables form a step-by-step structure that links crop-level surplus to groundwater extraction, enabling consistent estimation of groundwater-associated value at the state level.

Groundwater Attribution Approach

While individual crops yield detailed statistics on agricultural production, groundwater statistics are only available in aggregate at the state level. To address this gap, the study employs a proxy-based attribution parameter.

The attribution parameter θ_s corresponds to the level of groundwater dependence for each state. This is an estimate calibrated using existing data on groundwater abstraction and depletion levels, as well as the extent of irrigation. Unlike groundwater extraction levels, these estimates show the degree of agricultural dependence on groundwater within each state. These parameters are applied as fixed proportions, based on the observed level of groundwater dependency within each state. They capture the overall dependence of agricultural production on groundwater within that state.

For each crop, the total surplus is first calculated and scaled by cultivated area. A fixed share of this surplus, given by the state-level parameter, is then attributed to groundwater. In effect, the proportional relationship is the same for all crops selected in a state.

This attribution, however, should be interpreted carefully. The share allocated is not the actual amount of groundwater used by a given crop. The estimates capture system-level dependence rather than crop-level measurements. The approach also assumes that dependence on groundwater is broadly uniform across the crops selected in a state. This may simplify analysis, but it overlooks differences in crop water-use intensity.

The agricultural extraction indicators reported in this study have been constructed specifically for analytical purposes and should not be interpreted as identical to the official CGWB ‘stage of groundwater extraction’ metric. The CGWB indicator is computed using total annual groundwater extraction relative to net annual groundwater availability after accounting for natural discharge. In contrast, this study uses irrigation groundwater extraction relative to total annual recharge in order to examine groundwater dependence within agricultural production systems. Consequently, the estimates presented here are author-calculated from CGWB data and not directly comparable with official CGWB stage-of-extraction estimates.

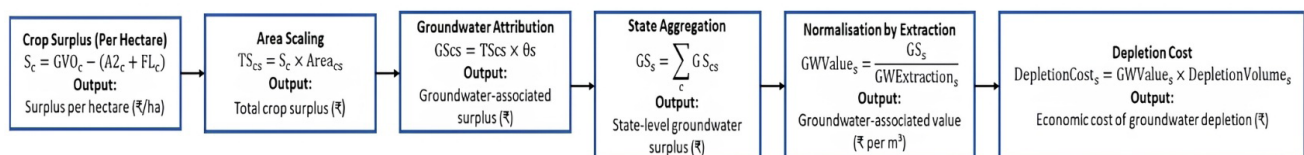
Analytical Methods and Strategy

This section outlines the analytical framework used to link agricultural surplus estimates with groundwater extraction and recharge data for the valuation of groundwater resources.

Analytical Framework

The analysis is conducted in follows a structured, step-by-step process framework that links agricultural production data to groundwater using a residual-based approach.

Figure 1: Stepwise Analytical Framework for Estimating Groundwater Value



Source: Author’s Illustration

First, crop-level surplus is estimated. In every state, the difference between the gross value of output and total production costs (A2 + FL) is computed for each crop. This provides a per-hectare value of surplus within agricultural production.

Second, the surplus is scaled using crop area. The per-hectare surplus is multiplied by the cultivated

area of each crop to obtain total crop-level surplus at the crop-state level.

Third, a share of this total surplus is attributed to groundwater. Given that groundwater use cannot be directly observed at the crop level, a state-level attribution parameter is applied. This is done to determines the share of total agricultural surplus

that is associated with groundwater dependence.

Fourth, these groundwater-associated values are aggregated across all selected crops within each state. This results in a state-level estimate of total groundwater-associated surplus.

Fifth, groundwater value is obtained by dividing the total groundwater-associated surplus by total groundwater extraction in the state. This gives an average value per unit of groundwater, expressed in rupees per cubic metre. Here, recharge is taken as total recharge from all sources, while extraction refers to irrigation use, since the analysis focuses on agriculture.

Sixth, groundwater depletion is computed as the difference between extraction and recharge, where extraction exceeds recharge. This identifies the volume of overuse.

Finally, depletion cost is derived by multiplying the unit groundwater value with the depletion volume. This provides an indicative measure of the economic magnitude associated with groundwater over-extraction under current production conditions.

Sensitivity Analysis

Sensitivity analysis investigates how estimated groundwater values respond to changes in the groundwater attribution parameter. As groundwater use is not directly monitored at the crop level, the attribution factor (θ_s) is based on assumptions. It is necessary to analyse the sensitivity of the results to these assumptions.

Baseline estimates of groundwater-associated surplus are calculated using a central attribution parameter (θ_s) for each state. This central value is used in the main groundwater valuation estimate presented in the study.

To account for uncertainty in groundwater dependence, the same estimation process is repeated using lower and upper bounds of the attribution parameter, denoted as θ_s^{Low} and θ_s^{High} .

At the crop-state level, groundwater-associated surplus under different scenarios is calculated as:

$$GS_{cs}^{Low} = TS_{cs} \times \theta_s^{Low}$$

$$GS_{cs}^{High} = TS_{cs} \times \theta_s^{High}$$

These values are then aggregated across crops to obtain state-level estimates:

$$GS_s^{Low} = \sum_c GS_{cs}^{Low}$$

$$GS_s^{High} = \sum_c GS_{cs}^{High}$$

The groundwater value under each scenario is then computed as:

$$GWValue_s^{Low} = (GS_s^{Low}) / (GWExtraction_s)$$

$$GWValue_s^{High} = (GS_s^{High}) / (GWExtraction_s)$$

The central estimate follows the same structure using θ_s .

This entails carrying out the full estimation process under alternative assumptions about the degree of groundwater attribution. The resulting estimates are provided as ranges rather than single-point estimates to demonstrate the extent to which groundwater value varies under different assumptions about its dependence. Since the groundwater attribution approach uses proxies, the ranges should be interpreted as indicative rather than exact measures.

Findings and Interpretation

The analysis derives an implicit groundwater value per unit, expressed in ₹/m³, for a chosen set of states using agricultural surplus at the crop level and irrigation extraction data. The economic cost associated with groundwater depletion in a particular state is determined by the difference between irrigation groundwater extraction and recharge.

The disparities in groundwater value and depletion rates across states are, however, significant. For example, groundwater resources are valued higher in Haryana and Punjab, according to the crops chosen for the study, but lower in Karnataka and Andhra Pradesh.

One important finding from the study is that there

is no clear correlation between groundwater value and its depletion. States with high estimated groundwater value per unit do not always exhibit the highest depletion rates. This shows that while economic returns from groundwater use are reflected in one dimension of the agricultural

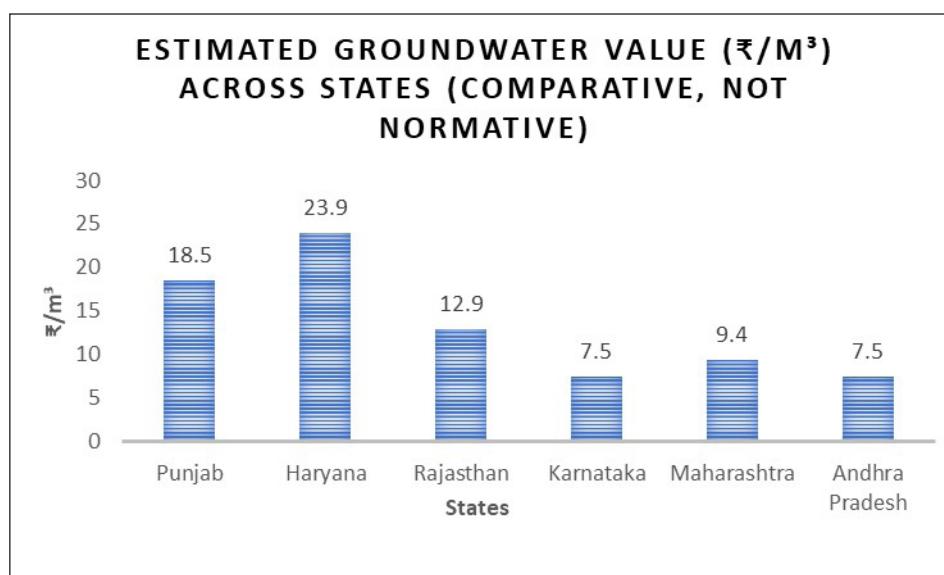
production process, the physical scale of extraction is another dimension that does not directly correlate with those returns. The distinction is important because it indicates that observed agricultural performance may not fully reflect underlying resource stress.

Table 1: Summary of Groundwater Valuation Across States

State	Economic Value (₹/m ³)	GW Draft (BCM)	GW Draft/ha	Dominant Crops
Punjab	18.5	26.24	3746	Paddy, Wheat
Haryana	23.9	11.47	2276	Wheat, Paddy
Rajasthan	12.9	14.51	2523	Wheat-dominant
Karnataka	7.5	10.15	2511	Maize-heavy
Maharashtra	9.4	15.07	1360	Soybean, Cotton
Andhra Pradesh	7.5	6.75	2294	Paddy-dominated

Source: Author's calculations based on data from CACP, CGWB, and DA&FW

Figure 2: Economic Value of Groundwater Across States



Source: Author's calculations based on data from CACP, CGWB, and DA&FW

Table 1 and Figure 2 present a comparative overview of the estimated economic value of groundwater across the selected states, together with differences in groundwater extraction intensity and dominant cropping patterns.

Crop-Level Composition of Groundwater Value

Groundwater value at the state level is not a standalone measure but is constructed from crop-level contributions weighted by area. Each crop contributes to the overall value based on its economic surplus and its relative share of the cultivated area. As a result, differences in

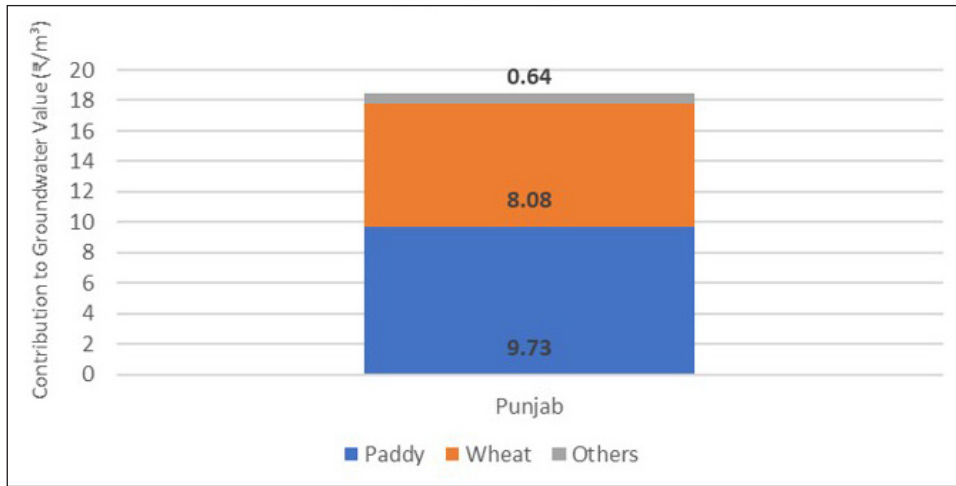
cropping patterns play a central role in shaping the estimated groundwater value across states. To present this information clearly and facilitate comparisons, a breakdown of groundwater values by crop is provided for three representative states. Corresponding figures for the remaining selected states are shown in Annexure 2.

Punjab

The value of groundwater in Punjab is heavily skewed towards two crops: paddy and wheat. These crops together account for nearly the entire estimated groundwater value, with other crops making only a small contribution. This suggests a

highly concentrated system in which agricultural surplus and reliance on groundwater are driven by a narrow crop base. The dominance of paddy and wheat suggests that groundwater use is strongly associated with water-intensive crops.

Figure 3: Crop-Wise Contribution to Estimated Groundwater Value (₹/m³) in Punjab



Source: Author’s calculations based on data from CACP, CGWB, and DA&FW

Haryana

Haryana shows a strong contribution from cereal crops, particularly wheat and paddy.

from crop-level components, Table 2 presents the detailed calculation for Haryana. It shows how crop-wise surplus, groundwater attribution, and area weights combine to produce a state-level estimate of groundwater value.

To illustrate how groundwater value is constructed

Table 2: Crop-Wise Construction of Groundwater Value (₹/m³) for Haryana

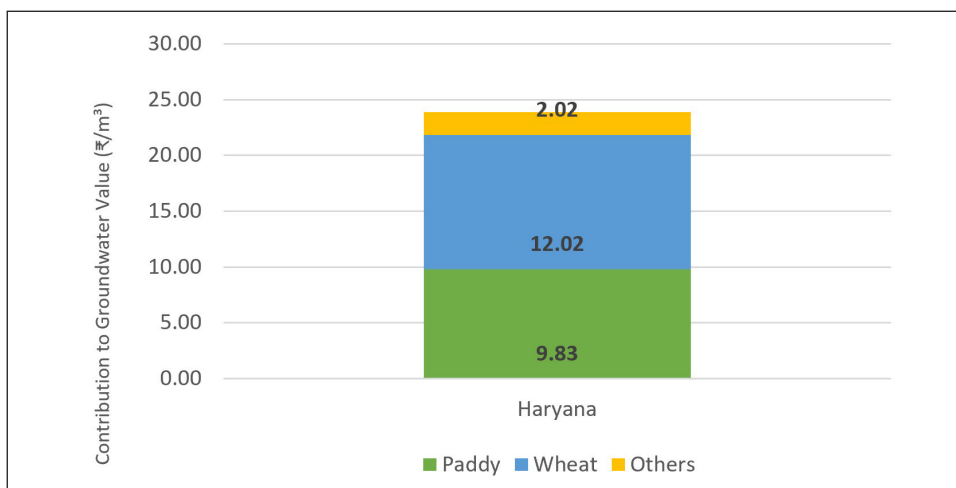
Crop	Area (lakh ha)	Area (ha)	Resource Rent (₹/ha)	Adjusted Resource Rent (₹/ha)	GW draft per ha (m³)	GW value (₹/ha)	Area Weight	Weighted GW value
Paddy	15.63	1563000	87413	72115.73	2276.25	31.68	0.31	9.83
Wheat	23.7	2370000	70518	58177.35	2276.25	25.56	0.47	12.02
Bajra	5.28	528000	10631	8770.575	2276.25	3.85	0.1	0.4
Cotton	5.78	578000	39031	32200.58	2276.25	14.15	0.11	1.62
Total cropped area (ha)		5039000						Economic value of groundwater (₹/ha) 23.9
GW draft (BCM)		11.47						
GW draft (m³)		11470000000						
GW draft per ha (m³/ha)		2276.245287						

Source: Author’s calculations based on data from CACP, CGWB, and DA&FW

From the table, it can be observed that wheat and paddy account for the largest share of groundwater value due to their large surpluses and area under cultivation, while other crops contribute relatively smaller shares. (Detailed crop-wise tables for other states are provided in Annexure 1).

The distribution, however, is less concentrated than in Punjab. Although wheat is the largest contributor, other crops account for a larger share of the total groundwater value. This implies a system that, although dominated by a few crops, is comparatively more distributed in terms of economic contribution.

Figure 4: Crop-Wise Contribution to Estimated Groundwater Value (₹/m³) in Haryana



Source: Author's calculations based on data from CACP, CGWB, and DA&FW

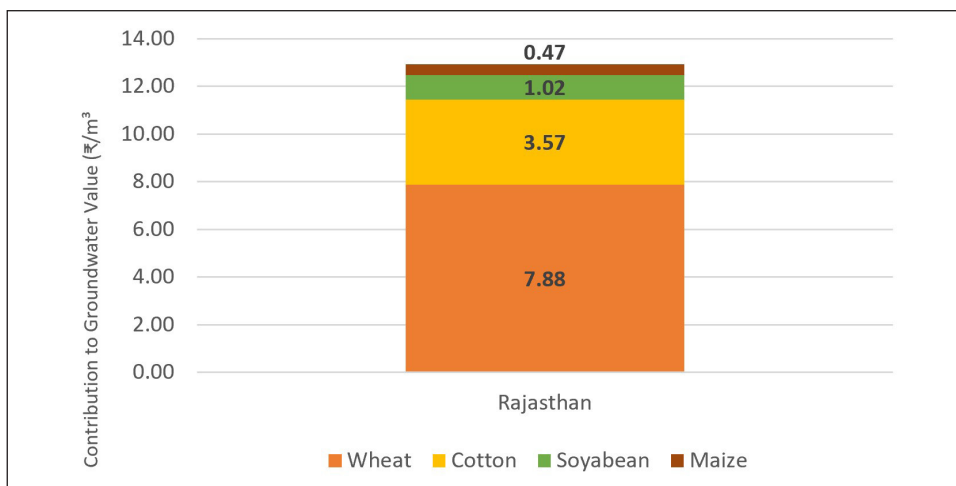
Rajasthan

The situation in Rajasthan is different as groundwater value is distributed among various crops. The highest contribution comes from wheat, although cotton, soybean, and maize also contribute significantly. No single crop dominates the structure as in Punjab. This more diversified pattern of contributions indicates that the value of groundwater in Rajasthan is determined by a mixed pattern of crops rather

than a single dominant system.

These disparities indicate that groundwater value cannot be determined solely by extraction. It is strongly dependent on the cropping patterns and relative economic returns of individual crops. As a result, states with similar groundwater use can yield different value estimates depending on the structure of agricultural production.

Figure 5: Crop-Wise Contribution to Estimated Groundwater Value (₹/m³) in Rajasthan



Source: Author's calculations based on data from CACP, CGWB, and DA&FW

Comparative Analysis of Groundwater Value Across States

The economic value of groundwater varies markedly across the selected states. According to central estimates, groundwater values range from ₹7.5 per cubic metre in Karnataka and Andhra Pradesh to ₹23.9 per cubic metre in Haryana. Punjab and Rajasthan occupy intermediate positions at ₹18.5 and ₹12.9 per cubic metre, respectively, while Maharashtra registers a value of ₹9.4 per cubic metre. This difference indicates that the economic returns to groundwater use vary widely across states in the selected crop sample.

Comparing Haryana and Punjab reveals a definite trend. Although Haryana and Punjab are major groundwater-dependent states with similar cropping patterns, the estimated groundwater value per unit is higher in Haryana than in Punjab. The difference relates to the crop mix included in the study, their

returns, and area proportions. In Haryana, the value is more evenly distributed among crops, with wheat and paddy accounting for a significant share. In Punjab, the value is more concentrated in a smaller group of crops. Consequently, the average price per unit of groundwater is greater in Haryana within the selected set of crops.

Groundwater Extraction, Recharge, and Resulting Depletion

The study of groundwater extraction and recharge shows notable differences between states. Recharge is considered for the whole system, while extraction is only for irrigation, since the analysis focuses on agriculture. The study uses annual groundwater recharge as a broad indicator of groundwater availability and does not separately account for natural discharge adjustments incorporated in official extractable groundwater resource estimates.

Table 3: Physical Groundwater Records and Depletion Cost

State	Annual Groundwater Extraction for Irrigation (BCM)	Annual Groundwater Recharge (BCM)	Net Irrigation Groundwater Balance (BCM)	Stage of Agricultural Groundwater Extraction (%)	Depletion Volume (BCM)	Groundwater Value (m ³)	Depletion Cost (₹ crore)
Punjab	26.24	19.19	-7.05	137	7.05	18.5	13042.5
Haryana	11.47	10.32	-1.15	111	1.15	23.9	2748.5
Rajasthan	14.51	12.58	-1.93	115	1.93	12.9	2489.7
Karnataka	10.15	18.74	8.59	54	0	7.5	0
Maharashtra	15.07	33.03	17.96	46	0	9.4	0
Andhra Pradesh	6.75	27.8	21.05	24	0	7.5	0

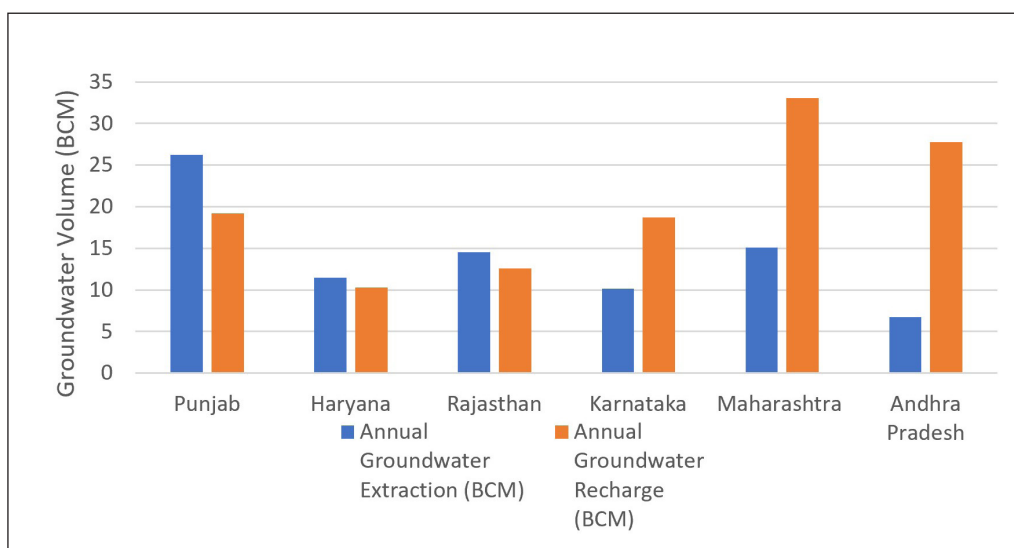
Note: Extraction and recharge data are drawn from CGWB (2024). However, the 'stage of agricultural groundwater extraction' reported in this study is author-calculated using irrigation extraction relative to total annual recharge and therefore differs from the official CGWB stage-of-extraction estimates based on net annual groundwater availability.

In Punjab, Haryana, and Rajasthan, extraction rates exceed annual recharge rates. This depicts a pattern of ongoing over-extraction of groundwater. The largest deficit occurs in Punjab, with extraction of 26.24 BCM and recharge of 19.19 BCM. The same holds for Rajasthan and Haryana, where the extraction rate exceeds the recharge rate, albeit less severely. However, Karnataka, Maharashtra,

and Andhra Pradesh have kept extraction within recharge limits at the state level.

These distinctions become more evident when considering the stage of groundwater extraction in agriculture. States exceeding annual recharge are Punjab at 137 per cent, Rajasthan at 115 per cent and Haryana at 111 per cent, indicating that they

Figure 6: Groundwater Extraction and Recharge Across States in BCM



Source: Author's calculations based on data from CACP, CGWB, and DA&FW

rely heavily on groundwater, more than what can be replenished naturally. By contrast, Karnataka (54 per cent), Maharashtra (46 per cent), and Andhra Pradesh (24 per cent) are within the safe range, indicating low stress. This indicates that, in addition to the degree, different states also exhibit varying patterns of groundwater use.

Analysis of extraction and recharge patterns also reveals significant differences in groundwater depletion. In the current agricultural framework, groundwater depletion occurs when irrigation extraction exceeds annual recharge. The highest groundwater depletion occurs in Punjab (7.05 BCM), Rajasthan (1.93 BCM), and Haryana (1.15 BCM). There is no groundwater depletion at the aggregate state level in Karnataka, Maharashtra, and Andhra Pradesh, as recharge exceeds extraction.

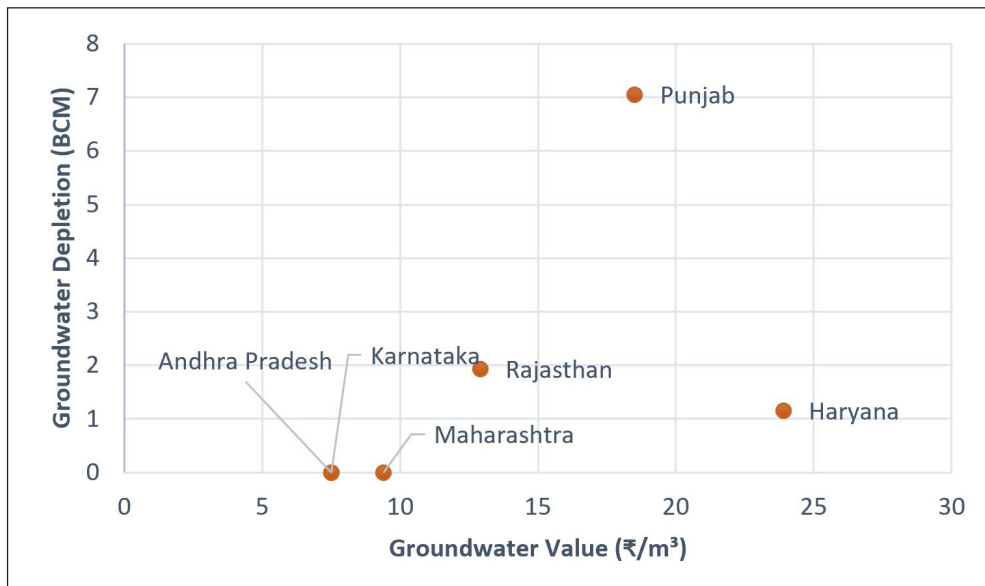
Overall, groundwater stress is concentrated in a few regions rather than evenly spread across all states. These results are not directly linked to the economic value generated by groundwater use. States with high agricultural surplus or higher groundwater value are not necessarily managing their groundwater sustainably. This shows that groundwater stress depends on the balance between extraction and recharge, rather than on how efficiently groundwater is used.

Relationship Between Groundwater Value and Depletion

The relationship between groundwater value and depletion varies across the selected states. Figure 7 shows that a higher economic value per unit of groundwater does not necessarily lead to greater depletion. Rather, the pattern varies across states, suggesting that groundwater value and extraction pressure reveal distinct aspects of groundwater use.

The maximum depletion is recorded in Punjab; however, the groundwater value is lower than that in Haryana. Conversely, Haryana records the highest groundwater value per unit (even though it is not as depleted as Punjab). Rajasthan occupies an intermediate position, with moderate groundwater values and depletion levels. At the same time, positive groundwater balance is observed in Karnataka, Maharashtra, and Andhra Pradesh due to higher recharge than extraction. There is no case of depletion in the state-level assessment used in this study; however, localised groundwater depletion occurs in certain blocks or regions. This trend shows that groundwater value reflects the economic returns generated per unit of groundwater, rather than the total pressure on groundwater resources. A state can generate high value from groundwater without extracting groundwater beyond recharge levels. At the same time, another state may experience

Figure 7: Relationship Between Groundwater Value and Depletion Across States



Source: Author's calculations based on data from CACP, CGWB, and DA&FW

significant groundwater depletion even without achieving the highest groundwater value. This shows that groundwater value and groundwater sustainability are not synonymous.

Economic Cost of Groundwater Depletion

Monetising groundwater depletion helps quantify the economic costs associated with unsustainable extraction. In Punjab, the cost of groundwater depletion is the highest at ₹13,042.5 crore per year due to excessive groundwater use and its higher economic valuation. The cost in Haryana stands at ₹2748.5 crore per year, and in Rajasthan, it is ₹2,489.7 crore per year. This indicates that economic costs vary across states, depending on the volume of groundwater extracted and its economic value. Physical depletion plays an important role in determining depletion cost, but depletion volume alone does not fully explain the pattern. Punjab's position is mainly due to its high level of depletion. Rajasthan records a slightly higher groundwater depletion volume than Haryana. However, the depletion cost is higher in Haryana because the estimated value assigned to each unit of groundwater is higher. This shows that depletion cost depends on both the level of over-extraction and the value assigned to each unit of groundwater.

These costs represent the implicit economic burden of groundwater overuse within the agricultural system. They are not actual financial losses but estimates of the value of groundwater being depleted under current production conditions. In this sense, they show how heavily agricultural output depends on continued groundwater overuse.

The results also suggest that in states with high depletion, a portion of agricultural production is supported by groundwater use beyond sustainable limits. This has important policy implications because groundwater is not priced, and these costs are absent from current decision-making. As a result, agricultural profitability in such regions may appear higher than it actually is in the long run, especially where over-extraction is a regular feature.

Sensitivity Analysis of Groundwater Value Estimates

This section examines the responsiveness of the estimated groundwater values to changes in key assumptions. This is not aimed at determining the correct estimate, but at assessing whether the overall pattern across states remains stable under variation. The analysis changes the proportion of agricultural surplus attributed to groundwater use. This attribution is not fixed and depends on irrigation intensity, crop composition, and regional water-use

patterns, which differ among states. State-specific ranges are used to represent these differences.

These ranges are used to generate the low, central, and high estimates discussed below.

Table 4: Sensitivity Ranges for Selected States

State	GW Attribution Range	Basis for Range Selection
Punjab	0.80-0.95	High irrigation dependence, dominance of paddy-wheat system
Haryana	0.75-0.90	Similar to Punjab but with slightly more crop variation
Rajasthan	0.70-0.90	Region-specific groundwater stress with more varied cropping and irrigation dependence
Karnataka	0.50-0.70	Mixed irrigation sources and less groundwater intensity
Maharashtra	0.45-0.65	Rainfed dominance with partial irrigation
Andhra Pradesh	0.35-0.55	Lower groundwater dependence, higher surface irrigation

Note: The attribution ranges are analytical parameters selected for the residual accounting framework and are intended to reflect relative differences in groundwater dependence across states. They do not represent directly observed values.

Three scenarios are considered for each state: a low estimate, a central estimate, and a high estimate.

Table 5: Sensitivity of Groundwater Value Estimates by State

State	Base GW Value (₹/m³)	Lower Bound Value	Upper Bound Value	% Change Range	Sensitivity Type
Punjab	18.5	16.9	20	16.76	Low
Haryana	23.9	21.7	26	17.99	Low
Rajasthan	12.9	11.3	14.6	25.58	Moderate
Karnataka	7.5	6.3	8.8	33.33	Moderate
Maharashtra	9.4	7.5	11.3	40.43	Moderate
Andhra Pradesh	7.5	5.3	9.6	57.33	High

Source: Author's calculation

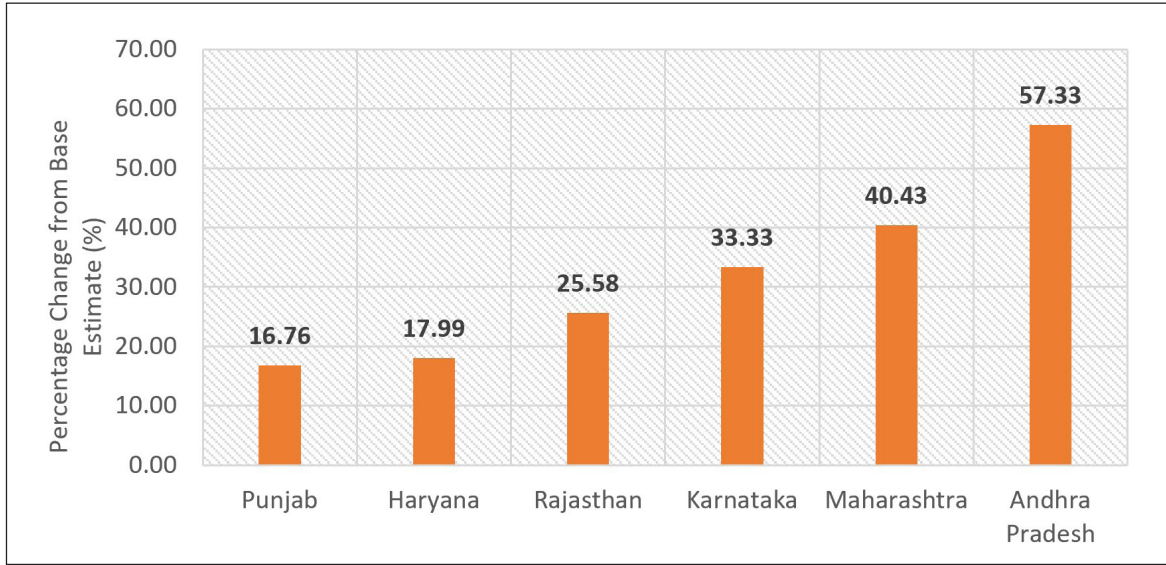
There is a relatively low variation in Punjab and Haryana. In Punjab, values range from 16.9 to 20.0 ₹/m³. In Haryana, from 21.7 to 26.0 ₹/m³. The percentage change is approximately 16-18 per cent in both. Although there is variation, it is not large enough to change the general interpretation. These states show higher values across all scenarios.

This indicates their crop structures, which are always groundwater-intensive. Sensitivity is moderate in Rajasthan. It ranges from 11.3 to 14.6 ₹/m³, translating to approximately a 25.6 per cent variation. This means that the estimate is

more sensitive to the assumptions. Rajasthan has a more diverse crop mix, and groundwater usage is distributed among multiple crops. As a result, parameter adjustments have a greater impact on the overall estimate.

Karnataka, Maharashtra, and Andhra Pradesh show higher sensitivity. Karnataka ranges from 6.3 to 8.8 ₹/m³, Maharashtra from 7.5 to 11.3 ₹/m³, and Andhra Pradesh from 5.3 to 9.6 ₹/m³. The percentage changes increase to 33.3 per cent, 40.4 per cent, and 57.3 per cent, respectively.

Figure 8: Percentage Change in Estimated Groundwater Value Across Scenarios

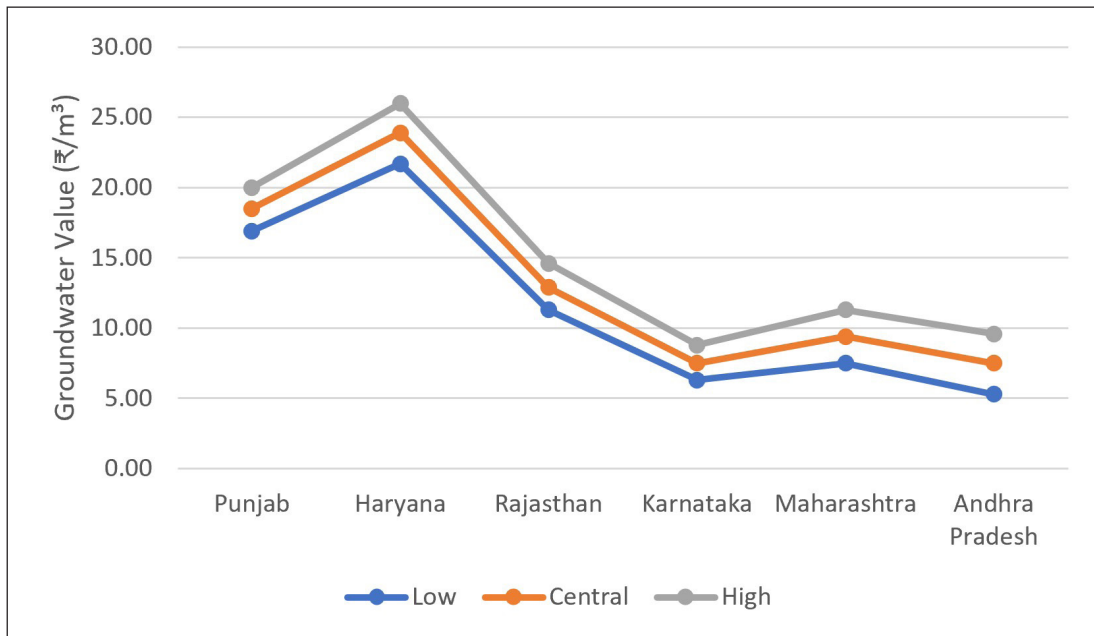


Source: Author's calculation

The differences between the absolute values are not large. In Andhra Pradesh, the full range is slightly more than 4 ₹/m³. This increased percentage change

is mainly due to the low base value. When the initial estimate is small, even small absolute changes appear comparatively large.

Figure 9: Groundwater Value Estimates Under Low, Central, and High Assumptions



Source: Author's calculation

More importantly, the relative ranking of states is not affected by different scenarios. Haryana is still the highest-value state, followed by Punjab. Karnataka and Andhra Pradesh are in the lower end, and Rajasthan and Maharashtra occupy intermediate

positions. This uniformity is important. It implies that the primary findings are not driven by a particular set of assumptions. Two conclusions follow. First, the estimated groundwater value is sensitive to parameter variations, especially in states with low

values. Second, the general trend across states is stable despite this variation. The estimates are thus to be interpreted as suggestive of structural differences in groundwater dependence, rather than as precise point values.

Cross-Cutting Insights on Groundwater Use and Agricultural Systems

This section draws together the key patterns observed throughout the analysis and outlines their implications.

Insight 1: Hidden Groundwater Dependence

A significant share of agricultural surplus can be attributed to the use of groundwater that is not directly priced. Since groundwater extraction is rarely considered a cost, the surplus produced by agriculture includes an implicit contribution from this resource.

As a result, the estimated groundwater value indicates the extent to which agricultural production depends on an unpriced input. The dependence is most evident in states with intensive irrigation, where a considerable share of surplus reflects groundwater use rather than land or labour productivity.

Insight 2: Value Does Not Imply Sustainability

The study demonstrates that the economic value per unit of groundwater is not always associated with sustainable levels of extraction. For example, states with high groundwater value may not necessarily have high levels of depletion, while states with high levels of depletion do not necessarily generate the highest value. This means there is no direct alignment between economic returns and physical resources use. In practice, a system may appear economically efficient in terms of value per unit while generating long-term resource stress. Such a mismatch is pivotal for understanding agricultural performance in water-scarce regions.

Insight 3: Role of Crop Composition

Crop patterns exert a significant impact on the estimated value of groundwater. The crop mix directly influences the outcome, as the final value is calculated from crop-level contributions weighted by area. States dominated by a small number of

water-intensive crops tend to exhibit concentrated contributions, whereas more diverse systems have a larger distribution of value across crops.

The results, therefore, reflect not only how much groundwater is used, but also how agricultural production is structured.

Limits of Inference

This study develops an accounting-based estimate of groundwater value within agricultural production using a residual framework and secondary data. The purpose is not to calculate an exact market value of groundwater, but to make its economic contribution within agricultural surplus more visible. Since groundwater is not directly observed or priced in the production process, the analysis necessarily relies on assumptions and indirect estimation. In this sense, groundwater enters agricultural production as an economically unpriced input. The findings should therefore be interpreted within the data and methodological limits discussed below.

Data and Aggregation Constraints

The study uses secondary data from official government sources, including cost of cultivation surveys and groundwater assessments. These datasets are widely used and internally consistent, but they also carry limitations:

Agro-Climatic Variance: Crop cost data are available at the sample level and may not fully capture differences within states in agro-climatic conditions, irrigation practices, input intensity, or farm-level production systems.

Mismatched Aggregation: At the same time, groundwater extraction and recharge data are available only at the aggregate state level. This creates a difference in the level of aggregation used in the analysis. Agricultural surplus is estimated at the crop level, whereas groundwater availability and extraction are measured at the state level. As a result, the relationship between groundwater use and crop-level production is estimated indirectly rather than through direct measurement.

Cropping Structure Omissions: Another limitation is that the analysis is confined to selected major irrigated crops for which consistent data are available. These crops represent important irrigated production systems, but they do not capture the full cropping structure of each state. The estimates therefore reflect groundwater dependence within selected crop systems rather than the entire agricultural economy.

Static Snapshot: The study is also cross-sectional and based on a single reference year. It provides a snapshot of agricultural production and groundwater use under the conditions prevailing during that year. It bypasses year-to-year changes in rainfall, recharge, prices, or input costs and therefore should not be interpreted as representing long-term trends or averages.

Absence of Direct Metering: Direct crop-level measurement of groundwater use is not available in the data. This remains one of the main constraints of the analysis and is mitigated through the attribution approach discussed below.

Proxy-Based Attribution and Residual Assumptions

Since groundwater use is not systematically measured at the crop level, the study uses a proxy-based attribution approach to estimate the share of agricultural surplus associated with groundwater. State-level attribution parameters are deployed to represent the degree of groundwater dependence within each state. These parameters are based on observed patterns of groundwater extraction, irrigation intensity, and relative dependence across states rather than direct crop-level measurement of water use.

This introduces limitations because groundwater use intensity differs significantly across crops and production systems. The attribution parameters do not separately account for differences in irrigation frequency, application rates, water-use efficiency, or local irrigation practices. As a result, states with similar attribution values may still differ substantially in actual groundwater use across crops and regions.

The analysis also isolates groundwater within the agricultural production process and does not include other natural water inputs such as rainfall or soil moisture. It therefore does not attempt to estimate the contribution of water as a whole within agriculture. The purpose is specifically to examine the role of groundwater in agricultural surplus.

The estimation follows a residual approach. Agricultural surplus is calculated as the difference between gross output value and observed production costs. Groundwater is not directly identified in this framework, but is treated as part of the residual surplus together with other factors that are not fully priced or separately measured.

A fixed share of this surplus is then attributed to groundwater using the state-level dependence parameter. This means that the proportional relationship between surplus and groundwater dependence is assumed to remain broadly similar across the selected crops within a state. In reality, however, groundwater may contribute differently across crops depending on irrigation intensity and production conditions. This is especially important because groundwater often differs from other water sources in reliability and timing of availability.

The conversion of total surplus into a per-unit groundwater value also assumes an average relationship between total groundwater extraction and total surplus generation within a state. This can hide variation across crops, districts, and production systems. Similarly, cropping patterns are treated as fixed in the analysis even though, in practice, they are influenced by groundwater availability, policy incentives, procurement systems, and market conditions. Interactions between groundwater and other production inputs are also not explicitly modelled within the framework.

Methodological Boundaries

The study follows a descriptive accounting framework rather than an econometric or behavioural model. The analysis does not estimate causal effects between groundwater use and agricultural production, nor does it model how farmers respond to changes in

groundwater availability, prices, or policy incentives.

The framework is also static in nature. It does not incorporate long-term groundwater recharge dynamics, technological adjustment, future depletion pathways, or behavioural adaptation over time. Similarly, the sensitivity analysis only examines changes in the groundwater attribution parameter and does not capture all possible sources of uncertainty, such as measurement errors, changes in prices, or changes in groundwater productivity.

The purpose of the framework is therefore not to predict future outcomes or evaluate policy impacts, but to provide a structured estimate of how groundwater is embedded within current agricultural production systems.

Interpretation of Estimates

The estimated groundwater value in this study is an imputed economic measure derived from agricultural surplus and not a market price or normative valuation of groundwater. Likewise, the estimated depletion cost represents the economic magnitude associated with groundwater over-extraction under existing production conditions. These estimates should not be interpreted as direct welfare losses or as complete measures of environmental damage or long-term scarcity.

Instead, the estimates function as accounting tools that make the contribution of groundwater within agricultural production more visible. They help show how agricultural surplus in different states is linked to groundwater dependence, extraction, and depletion.

The analysis identifies broad and internally consistent patterns across the selected states, especially in relation to groundwater dependence, crop structure, extraction pressure, and depletion. However, the results should be interpreted as structured approximations rather than precise measurements. They are intended to provide a consistent basis for understanding the economic role of groundwater within agricultural production under current conditions, while recognising the limitations of the available data and methodology.

Policy Discussion: Economic Dependence and the Governance of Groundwater

Groundwater governance in India reflects a long-standing disconnect between agricultural policy incentives and hydrological sustainability (Sharma et al. 2018). Policy frameworks have mostly focused on maximizing agricultural output and land productivity, without considering the resource base on which this production rests (Cullet 2014).

This study's findings introduce an economic perspective to this issue. By demonstrating that a measurable portion of agricultural surplus across the selected states is associated with groundwater use, the analysis reveals the extent to which current agricultural systems rely on a resource that is not directly accounted for in economic terms. These findings are based on crop-sample-based estimates across selected states and serve to illustrate broader patterns rather than provide definitive state-level conclusions.

In addition, the study shows that the economic value of groundwater per unit is not related to the sustainable level of extraction.

The Energy-Groundwater-Food Nexus and Incentive Structures

The relationship between agricultural policy and input subsidies shapes the contemporary policy framework. Energy subsidies for irrigation reduce the cost of groundwater extraction, thereby weakening incentives for efficient water use (Kapoor and Anand 2024; Gulati and Pahuja 2015). Meanwhile, the assured procurement system and MSP for crops such as rice and wheat provide stable demand conditions, encouraging the continued expansion of these water-intensive crops even in water-scarce regions (Sharma et al. 2018). These factors, combined, favour production systems in which groundwater-intensive crops are economically viable.

High land productivity and low irrigation water productivity prevail in a number of northwestern states. This implies that agricultural surplus is

closely related to intensive groundwater use, even in areas where extraction exceeds recharge.

The state-level policy systems prevailing in Karnataka and Maharashtra reveal some recognition of the connection between energy and groundwater. For example, in Karnataka's water policy, there are provisions such as feeder separation, metering of electricity consumption, and local budgeting of groundwater that signal an effort to regulate groundwater extraction through energy consumption (KJA Task Group 2019). Likewise, in the legal system of Maharashtra, there is a provision for micro-irrigation along with the regulated use of groundwater (Government of Maharashtra 2019). This suggests that, although groundwater may not be priced, policies seek to manage its extraction.

Legal Frameworks and the Economic Invisibility of Groundwater

A foundational barrier to effective groundwater governance is its limited visibility within the economic and institutional systems. According to the Easement Act of 1882, groundwater is deemed to be a continuation of land ownership, which can be extracted privately to a large extent (Khara 2023; Trivedi n.d.).

This framework does not adequately recognise aquifers as shared resources and does not fully account for the wider impacts of depletion (KJA Task Group 2019). As a result, groundwater drawn from private wells enters the production process without a clearly recorded cost.

This implies that agricultural surplus incorporates groundwater contributions, which are not separately identified.

Regional Trade-Offs: Growth, Access, and Sustainability

Groundwater extraction and its impact on agriculture vary by location. Groundwater that was underutilised, despite not being part of the current sample, has promoted the transition to market-based farming in certain regions of eastern

India, such as Odisha, through irrigation and crop diversification (Rajkhowa 2024).

On the other hand, areas on the nation's northern and western flanks still face stress on their groundwater resources. The use of groundwater resources in these regions enables high agricultural productivity despite declining groundwater levels.

Irrigation policy schemes, such as the PMKSY, have emphasised the need to expand irrigation access and infrastructure. Nevertheless, these programmes emphasise the need to enhance irrigation capacity without considering the condition of groundwater resources in regions where extraction exceeds replenishment.

Policy Transitions: Improving Alignment Between Incentives and Resource Use

The results show that dependence on groundwater is embedded in the agricultural surplus but is loosely linked to the incentives that influence production decisions. To address these issues, it is necessary to reconcile agricultural incentives with groundwater use. This study's results indicate that current policy tools do not depend substantially on groundwater conditions, suggesting that reliance on the resource is not factored into production. Although the study does not attempt to prescribe specific policy interventions, the available literature suggests several directions for enhancing this alignment.

Revisiting Incentive Structures

One way to overcome these distortions in the use of inputs is to gradually change existing input-based subsidies to income-based support schemes such as Direct Benefit Transfers (DBT), which leave farmer incomes unchanged (Sharma et al. 2018). Currently, subsidised electricity and irrigation make groundwater extraction cheaper, which reduces the incentive to use groundwater carefully. One possible alternative is to shift gradually towards direct income support for farmers. This could allow farmers to make decisions based more on local resource conditions rather than on subsidised inputs. In practice, such a transition would need to be gradual and adapted to regional conditions.

Pilot programmes could first be introduced in groundwater-stressed regions to understand how farmers respond to changes in subsidy systems. This approach does not directly price groundwater, but it may still help reduce excessive extraction by changing the overall incentive structure.

Crop Diversification

Promoting a shift towards less water-intensive crops lies at the heart of reducing groundwater pressure. Diversification, however, is not limited to production decisions, but also requires changes in market and purchase system design. The cultivation of crops like rice and wheat is closely linked to support for MSP and guaranteed purchase, which reduces farmers' risk. A significant shift would then entail changes in procurement policies to favour a broader crop portfolio, as well as to enhance market access, storage, and value chains for alternative crops such as pulses, oilseeds, and millets (CGWB 2024). In the absence of these enabling conditions, farmers face significant uncertainty when abandoning established cropping systems, even in situations where water scarcity is apparent.

Energy Management

Since groundwater extraction is closely tied to energy use, managing electricity supply provides an indirect but feasible way to influence water use. Subsidised or unmetered power currently allows farmers to extract groundwater at very low cost. Measures such as feeder segregation and controlled or scheduled power supply can help regulate the timing and extent of groundwater extraction without requiring direct metering at the farm level.

These measures operate by altering the conditions under which pumping occurs without specifying water costs. For large agricultural schemes, they will ultimately help reduce extraction volumes while remaining administratively feasible.

Improving Data and Monitoring Systems

One limitation of existing policy frameworks is that groundwater data are not integrated with agricultural data. The gap could be addressed by strengthening data systems to improve visibility into

resource use in economic and policy analysis. This could include more effectively linking groundwater extraction data to crop production data, enhancing spatial data on groundwater status, and integrating indicators of groundwater stress into agricultural performance assessments. These enhancements would facilitate more informed policy-making and allow for closer monitoring of the relationship between agricultural outcomes and resource use. In this regard, both Karnataka and Maharashtra are improving their groundwater data and management practices. The former focuses on creating an integrated data framework and local participation in the mapping of aquifers, whereas the latter involves periodic evaluation of groundwater and aquifer-based planning (Cullet 2014; KJA Task Group 2019). Such developments seek to overcome one of the major weaknesses highlighted above, which is the lack of direct data on groundwater use. However, such improvements have yet to be fully incorporated in economic analysis.

Targeted and Region-Specific Approaches

This study shows that groundwater dependence is not the same across all states and cropping systems. Because of this, the same policy may not work equally well everywhere. States such as Punjab, Haryana, and Rajasthan, where groundwater extraction is very high, may need stronger measures to reduce pressure on groundwater, such as crop diversification and better management of electricity use. On the other hand, states with lower groundwater stress may be better positioned to expand irrigation in a regulated manner. These differences are important because they show that policies should be tailored to regional conditions rather than adopt a one-size-fits-all approach.

Even an accounting-based estimate of groundwater value affects how policy tools are perceived. Even though no specific price is derived in this evaluation, nor is any form of pricing suggested, a benchmark figure in monetary terms may serve to highlight groundwater reliance.

Even policy measures linked to economic indicators, such as changes in incentives, conditional support,

or measures discouraging excessive resource use, require some benchmark of value, even if it is only approximate. The estimates developed in this study are not sufficient to support direct pricing or groundwater trading systems, especially because there is no proper volumetric measurement system or enforceable groundwater rights in place. However, the estimates can still help identify regions where dependence on groundwater is structurally high. In this sense, the study does not aim to promote a market-based system for groundwater allocation. Instead, it offers an economic perspective that can help integrate groundwater concerns into existing agricultural policy frameworks. This can support better alignment between agricultural incentives and underlying resource conditions without requiring a formal groundwater pricing regime.

Policy Implications and Interpretation

This study shows that groundwater makes a significant but often unrecognised contribution within agricultural production systems. The analysis does not estimate causal impacts or prescribe pricing mechanisms. Rather, it offers an accounting perspective on the relationship between agricultural surplus and groundwater use. Agricultural profitability can still obscure dependence on a resource that is becoming increasingly stressed, when the economic contribution of groundwater is not explicitly recognised within production systems. Better visibility of groundwater in economic analysis and data systems can aid more informed policy discourse and help align agricultural outcomes with long-term sustainability.

Conclusion

This study contributes to the literature by providing an accounting-based framework for examining the relationship between groundwater dependence and agricultural surplus across Indian states. While earlier research has extensively documented groundwater depletion, irrigation dependence, and policy challenges in Indian agriculture, groundwater's economic role often remains obscured in conventional measures of agricultural performance. By combining residual accounting methods with

state-level groundwater dependence indicators, the study attempts to make this relationship more visible within agricultural production systems.

The study also contributes methodologically by adapting accounting approaches commonly used in environmental-economic accounting to the context of groundwater-dependent agriculture in India. Rather than viewing groundwater only as a physical resource, the study examines how agricultural surplus may be associated with groundwater-dependent irrigation systems. The findings show that states with high groundwater-linked agricultural value can also experience significant groundwater stress, highlighting that strong agricultural performance and sustainable groundwater use do not necessarily occur together.

At the same time, the study highlights important data limitations. The absence of direct crop-level groundwater extraction data remains a major challenge for analysing groundwater use in agriculture. Future research could improve the framework by using district-level groundwater datasets, crop-specific irrigation information, remote sensing data, or farm-level estimates of groundwater extraction. Analysis over multiple years could also help examine how groundwater dependence changes in response to rainfall conditions, technological change, energy policies, and shifts in cropping patterns.

Future studies may also probe the links between groundwater dependence and agricultural policy incentives in greater detail, particularly the interaction between electricity subsidies, procurement systems, irrigation expansion, and groundwater stress. More advanced analytical approaches could further deepen our understanding of how groundwater dependence influences agricultural production under different policy and environmental conditions. •

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Annexure

Annexure 1: Crop-Wise Construction of Groundwater Value (₹/m³) in the Selected States

Punjab

Table A.1.1: Crop-Wise Construction of Groundwater Value (₹/m³) for Punjab

Crop	Area (lakh ha)	Area (ha)	Resource Rent (₹/ha)	Adjusted Resource Rent (₹/ha)	GW draft per ha (m ³)	GW value (₹/ha)	Area Weight	Weighted GW value
Paddy	31.79	3179000	91830	80351.25	3746.43	21.45	0.45	9.73
Wheat	35.16	3516000	68896	60284	3746.43	16.09	0.5	8.08
Maize	0.95	95000	9345	8176.875	3746.43	2.18	0.01	0.03
Cotton	2.14	214000	85770	75048.75	3746.43	20.03	0.03	0.61
Total cropped area (ha)		7004000					Economic value of groundwater (₹/ha)	18.5
GW draft (BCM)		26.24						
GW draft (m ³)		26240000000						
GW draft per ha (m ³ /ha)		3746.430611						

Source: Author's calculations based on data from CACP, CGWB, and DA&FW

Rajasthan

Table A.1.2: Crop-Wise Construction of Groundwater Value (₹/m³) for Rajasthan

Crop	Area (lakh ha)	Area (ha)	Resource Rent (₹/ha)	Adjusted Resource Rent (₹/ha)	GW draft per ha (m ³)	GW value (₹/ha)	Area Weight	Weighted GW value
Wheat	27.40	2740000	52134	41707.2	2523.04	16.53	0.48	7.88
Maize	8.81	881000	9685	7748	2523.04	3.07	0.15	0.47
Soyabean	11.26	1126000	16445	13156	2523.04	5.21	0.2	1.02
Cotton	10.04	1004000	64526	51620.8	2523.04	20.46	0.17	3.57
Total cropped area (ha)		5751000					Economic value of groundwater (₹/ha)	12.9
GW draft (BCM)		14.51						
GW draft (m ³)		14510000000						
GW draft per ha (m ³ /ha)		2523.039471						

Source: Author's calculations based on data from CACP, CGWB, and DA&FW

Karnataka

Table A.1.3: Crop-Wise Construction of Groundwater Value (₹/m³) for Karnataka

Crop	Area (lakh ha)	Area (ha)	Resource Rent (₹/ha)	Adjusted Resource Rent (₹/ha)	GW draft per ha (m³)	GW value (₹/ha)	Area Weight	Weighted GW value
Paddy	9.53	953000	37254	22352.4	2511.75	8.9	0.24	2.10
Maize	19.72	1972000	28629	17177.4	2511.75	6.84	0.49	3.34
Groundnut	3.73	373000	17324	10394.4	2511.75	4.14	0.09	0.38
Cotton	7.43	743000	38719	23231.4	2511.75	9.25	0.18	1.70
Total cropped area (ha)		4041000					Economic value of groundwater (₹/ha)	7.5
GW draft (BCM)		10.15						
GW draft (m³)		10150000000						
GW draft per ha (m³/ha)		2511.754516						

Source: Author's calculations based on data from CACP, CGWB, and DA&FW

Maharashtra

Table A.1.4: Crop-Wise Construction of Groundwater Value (₹/m³) for Maharashtra

Crop	Area (lakh ha)	Area (ha)	Resource Rent (₹/ha)	Adjusted Resource Rent (₹/ha)	GW draft per ha (m³)	GW value (₹/ha)	Area Weight	Weighted GW value
Soyabean	51.15	5115000	25736	12868	1360.23	9.46	0.46	4.37
Maize	13.26	1326000	51765	25882.5	1360.23	19.03	0.12	2.28
Bajra	4.04	404000	3811	1905.5	1360.23	1.40	0.04	0.05
Cotton	42.34	4234000	19491	9745.5	1360.23	7.16	0.38	2.74
Total cropped area (ha)		11079000					Economic value of groundwater (₹/ha)	9.4
GW draft (BCM)		15.07						
GW draft (m³)		15070000000						
GW draft per ha (m³/ha)		1360.231068						

Source: Author's calculations based on data from CACP, CGWB, and DA&FW

Andhra Pradesh

Table A.1.5: Crop-Wise Construction of Groundwater Value (₹/m³) for Andhra Pradesh

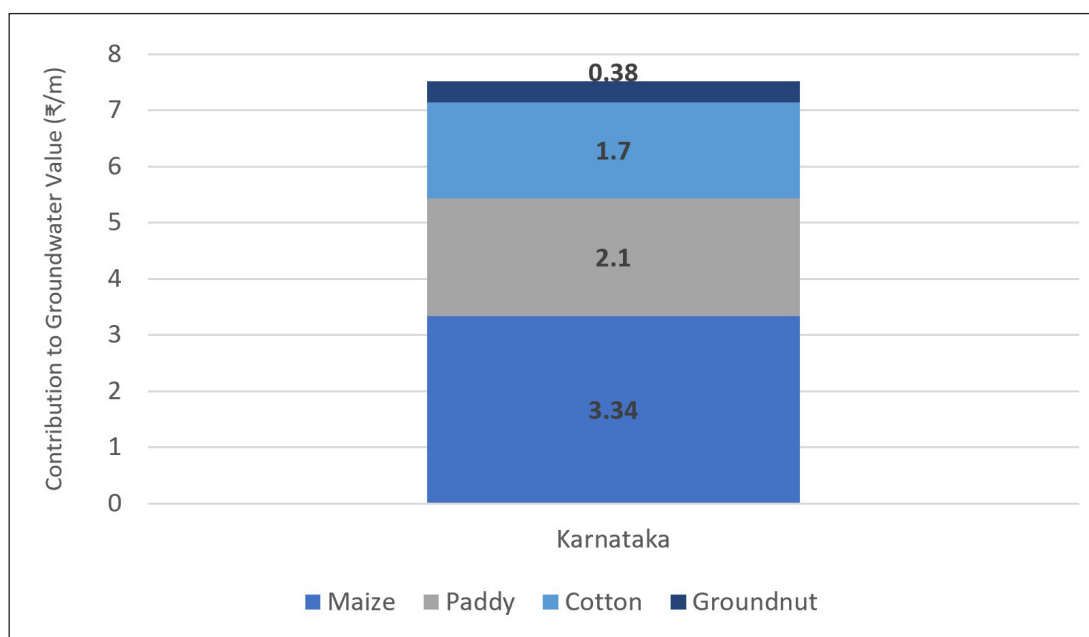
Crop	Area (lakh ha)	Area (ha)	Resource Rent (₹/ha)	Adjusted Resource Rent (₹/ha)	GW draft per ha (m³)	GW value (₹/ha)	Area Weight	Weighted GW value
Paddy	19.21	1921000	49103	17186.05	2294.36	7.49	0.65	4.89
Maize	2.92	292000	66157	23154.95	2294.36	10.09	0.10	1.00
Urad	3.07	307000	42352	14823.2	2294.36	6.46	0.10	0.67
Cotton	4.22	422000	41417	14495.95	2294.36	6.32	0.14	0.91
Total cropped area (ha)		2942000					Economic value of groundwater (₹/ha)	7.5
GW draft (BCM)		6.75						
GW draft (m³)		6750000000						
GW draft per ha (m³/ha)		2294.35758						

Source: Author's calculations based on data from CACP, CGWB, and DA&FW

Annexure 2: Crop-Wise Contribution to Estimated Groundwater Value (₹/ha) in Selected States

Karnataka

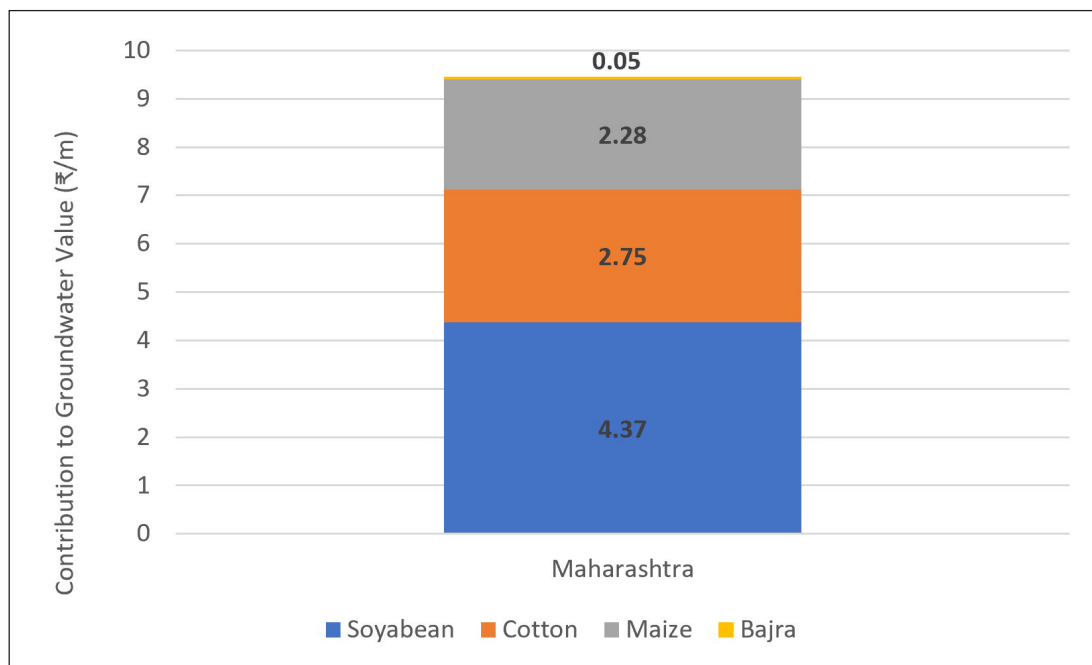
Figure A.2.1: Crop-Wise Contribution to Estimated Groundwater Value (₹/ha) in Karnataka



Source: Author's calculations based on data from CACP, CGWB, and DA&FW

Maharashtra

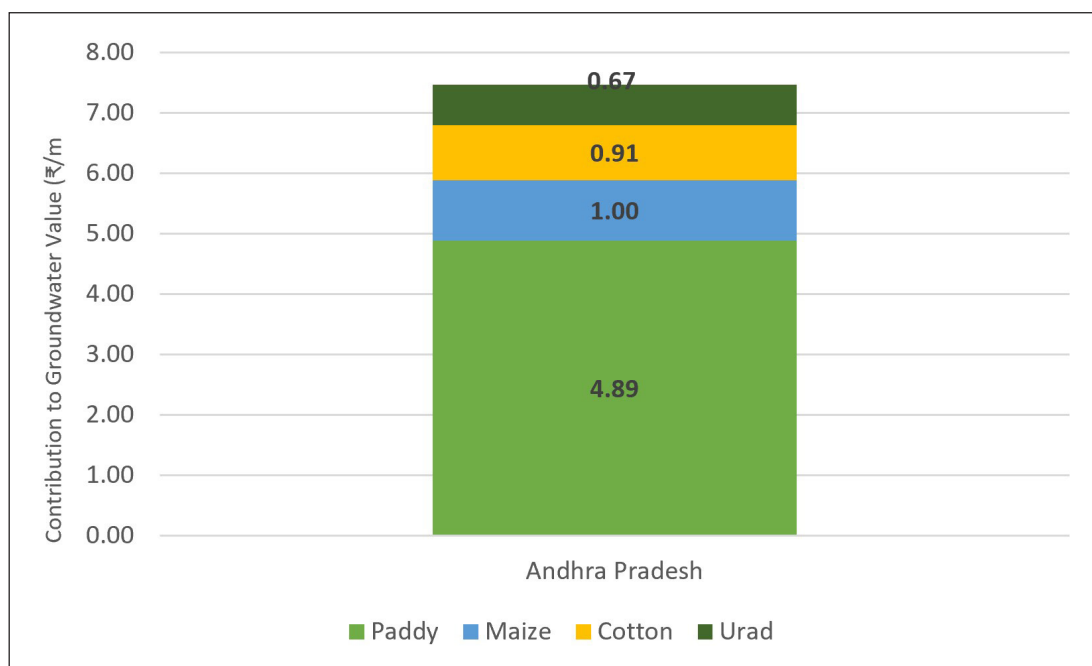
Figure A.2.2: Crop-Wise Contribution to Estimated Groundwater Value (₹/m³) in Maharashtra



Source: Author's calculations based on data from CACP, CGWB, and DA&FW

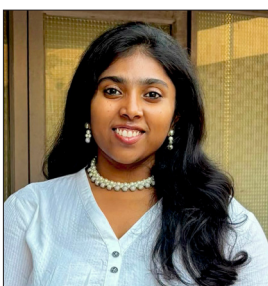
Andhra Pradesh

Figure A.2.3: Crop-Wise Contribution to Estimated Groundwater Value (₹/m³) in Andhra Pradesh



Source: Author's calculations based on data from CACP, CGWB, and DA&FW

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Designed by: **Nikhil Arora**

Edited by: **Shraddha Ratori, Editorial Consultant**

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Recommended Citation

Job, F. (2026). The Costs Beneath Productivity: Groundwater Dependence in Indian Agriculture, Chintan Research Foundation (CRF), New Delhi



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