"Economic Viability of Alternative Irrigation Sources: A Comparative Analysis of Canal and Tube Well Irrigation Systems in Telangana"

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Abstract:
This study examines the economic viability of canal and tube well irrigation systems in Telangana, India, focusing on cost structures, water availability, crop productivity, and farmer profitability. Using primary data from 240 farmers across four districts (Warangal, Nalgonda, Medak, and Karimnagar) and secondary data from government sources, we employ comparative cost-benefit analysis and regression modeling to assess the economic performance of both systems. Results indicate that tube well irrigation provides greater water control and reliability but incurs 47% higher operational costs (₹18,450/ha/year) compared to canal irrigation (₹12,550/ha/year). Canal-irrigated farms demonstrate lower energy costs but face water scarcity during critical crop stages, reducing yields by 15-22%. Net returns per hectare are marginally higher for tube well users (₹45,320) versus canal users (₹42,180), though this advantage diminishes with rising electricity tariffs. The break-even analysis reveals tube well investments require 7-9 years for cost recovery under current conditions. Policy implications emphasize the need for sustainable groundwater management, improved canal infrastructure, and differential electricity pricing to ensure long-term agricultural sustainability in Telangana's semi-arid regions.

Keywords: irrigation economics, tube well, canal irrigation, cost-benefit analysis, agricultural sustainability, Telangana, water resource management, groundwater depletion.

1. INTRODUCTION

Water scarcity represents one of the most critical challenges facing agricultural development in semi-arid regions of India, particularly in Telangana state, where agriculture employs approximately 55% of the workforce and contributes 20% to the state's GDP (Government of Telangana, 2023). The state's irrigation infrastructure comprises two primary systems: surface water-based canal networks and groundwater-dependent tube wells, each presenting distinct economic advantages and constraints for farming communities.

Telangana's irrigation landscape has undergone significant transformation since the state's formation in 2014. Major irrigation projects including Kaleshwaram, Sitaram, and Devadula have expanded canal coverage, yet tube wells continue to dominate, accounting for 68% of irrigated area compared to 32% under canal systems (Directorate of Economics and Statistics, 2023). This disparity reflects complex economic decisions farmers make regarding capital investment, operational costs, water reliability, and crop productivity.

The economic viability of irrigation systems extends beyond simple cost comparisons to encompass water use efficiency, environmental sustainability, and long-term resource availability. Singh and Kumar (2023) demonstrate that groundwater depletion in Telangana has accelerated at 0.8 meters annually over the past decade, raising concerns about the sustainability of tube well irrigation. Conversely, canal systems face challenges including inequitable water distribution, infrastructure deterioration, and reduced flow during critical agricultural periods (Reddy & Srinivasan, 2022).

Previous studies have examined irrigation economics in various Indian contexts. Narayanamoorthy (2021) compared irrigation systems across multiple states, finding significant regional variations in cost structures and returns. Palanisami et al. (2022) analyzed groundwater economics in South India, highlighting the hidden costs of aquifer depletion. However, limited research specifically addresses Telangana's unique context following recent infrastructural investments and policy changes.

This research addresses three fundamental questions: (1) What are the comparative capital and operational costs of canal versus tube well irrigation systems? (2) How do these systems affect crop productivity and farmer income? (3) What factors influence farmers' choice between irrigation systems? By answering these questions, this study contributes empirical evidence to inform policy decisions regarding irrigation investment, electricity subsidies, and sustainable water resource management.

The study's significance lies in its timing, coinciding with Telangana's ambitious irrigation expansion plans and increasing concerns about groundwater sustainability. Understanding the true economic costs and benefits of alternative irrigation sources enables evidence-based policy formulation that balances farmer profitability with environmental conservation objectives.

2. LITERATURE REVIEW

2.1 Theoretical Framework of Irrigation Economics

The economics of irrigation systems has been analyzed through multiple theoretical lenses. Dinar and Zilberman (2020) present irrigation choice as a capital investment decision involving risk assessment, liquidity constraints, and expected returns over extended time horizons. Their framework emphasizes that farmers optimize irrigation investments based on three factors: water availability certainty, energy cost structures, and crop-specific water requirements.

The classical theory of induced innovation, proposed by Hayami and Ruttan (1985) and extended to water resources by Caswell and Zilberman (1986), suggests that farmers adopt water-saving technologies in response to increasing water scarcity and rising costs. In Telangana's context, this theory explains the rapid tube well expansion during periods of canal system failures, despite higher capital requirements.

2.2 Comparative Studies on Irrigation Systems

International research provides valuable insights into irrigation system economics. Shah (2009) conducted comprehensive studies on groundwater irrigation in South Asia, documenting the "groundwater economy" phenomenon where tube well proliferation creates economic growth but threatens long-term sustainability. His work demonstrates that subsidized electricity enables tube well expansion beyond economically optimal levels, creating negative externalities through aquifer depletion.

Mukherji et al. (2022) compared surface and groundwater irrigation across the Indo-Gangetic Plain, finding that tube wells provide 30-40% higher water reliability but incur operational costs 50-80% higher than canal systems. Their study emphasizes how electricity pricing policies significantly influence the relative economic advantage of different irrigation sources.

Within India, state-level studies reveal substantial variations. Kumar (2023) analyzed Punjab's irrigation economics, demonstrating that free electricity for agriculture incentivized over-extraction, leading to severe groundwater depletion. In contrast, Andhra Pradesh's metered electricity system promoted more efficient water use but increased farmer costs significantly (Reddy, 2022).

2.3 Telangana-Specific Research

Limited but growing research examines Telangana's irrigation economics. Rama Krishna et al. (2023) analyzed the impact of the Kaleshwaram Lift Irrigation Project on canal system viability, finding that improved water availability increased canal system attractiveness but infrastructural inefficiencies prevented optimal utilization. Their study reported 35-40% water loss in distribution channels due to seepage and evaporation.

Vaidyanathan and Reddy (2022) investigated tube well economics in Telangana's drought-prone districts, documenting average bore well depths increasing from 120 feet in 2010 to 280 feet in 2022, corresponding to drilling cost escalation from ₹150 per foot to ₹425 per foot. This trend significantly affects the economic viability of new tube well investments.

Research by Bantilan et al. (2023) examined farmer perceptions of irrigation systems in semi-arid Telangana, revealing that water timing flexibility ranked as the primary factor in irrigation choice, surpassing cost considerations. This finding suggests that economic analysis must incorporate reliability and control factors beyond simple financial metrics.

2.4 Research Gaps

Despite existing literature, several gaps warrant investigation. First, most studies predate Telangana's recent major irrigation investments, making updated economic assessments necessary. Second, previous research often examines either canal or tube well systems in isolation, lacking direct comparative analysis within the same agroecological zones. Third, limited attention has been given to how electricity tariff structures affect relative system economics. Finally, few studies integrate environmental costs such as groundwater depletion into economic viability assessments.

This study addresses these gaps by providing contemporary comparative data, incorporating recent policy changes, and presenting a comprehensive economic analysis that includes both private costs to farmers and broader social costs of irrigation system choices.

3. STUDY AREA AND METHODOLOGY

3.1 Study Area Description

Telangana state, located in southern India (17°N latitude, 78°E longitude), spans 112,077 km² with predominantly semi-arid climate characteristics. Annual rainfall averages 900 mm, concentrated in monsoon months (June-September), creating pronounced seasonal water scarcity. This research focuses on four representative districts: Warangal (North Telangana Zone), Nalgonda (South Telangana Zone), Medak (Central Telangana Zone), and Karimnagar (Northern Telangana Zone).

These districts collectively represent 38% of Telangana's irrigated area and exhibit diverse irrigation patterns. Warangal and Karimnagar benefit from Godavari basin canal systems, while Nalgonda and Medak depend heavily on groundwater due to limited canal coverage. The districts encompass varied soil types (red sandy loam, black cotton soils), supporting major crops including paddy, cotton, maize, and horticultural crops.

3.2 Data Collection

3.2.1 Primary Data

Primary data collection occurred during January-April 2024, covering the Rabi (winter) cropping season. A stratified random sampling approach selected 240 farmers (120 canal-dependent, 120 tube well-dependent) across the four districts. Selection criteria included: (a) minimum two years' experience with the current irrigation system, (b) farm size between 2-10 acres (representing small and medium farmers), and (c) primary dependence on a single irrigation source.

Structured questionnaires administered through face-to-face interviews captured:

- Capital costs: Initial investment in irrigation infrastructure
- Operational costs: Energy, maintenance, labor, and water charges
- Crop production details: Area, yield, input costs, and revenue
- Water availability and reliability metrics
- Socioeconomic characteristics: Education, age, family size, landholding

3.2.2 Secondary Data

Secondary data sources included:

- Telangana State Irrigation Department: Canal water distribution, infrastructure investments
- Telangana State Electricity Regulatory Commission: Electricity tariff structures, agricultural consumption
- Directorate of Economics and Statistics: Crop yields, agricultural prices, cost of cultivation
- Central Ground Water Board: Groundwater levels, aquifer characteristics

- Indian Meteorological Department: Rainfall data (2014-2024)

3.3 Analytical Framework

3.3.1 Cost-Benefit Analysis

The economic viability assessment employed standard cost-benefit analysis, calculating:

Annual Equivalent Cost (AEC) for capital investments:

$$AEC = \frac{C \times r \times (1+r)^n}{(1+r)^n - 1}$$

Where:

- C = Initial capital investment
- r = Discount rate (12%, reflecting agricultural credit rates)
- n = Expected lifespan (canal infrastructure: 30 years; tube well: 15 years)

Net Present Value (NPV):

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+r)^t}$$

Where:

- B_t = Benefits in year t
- C_t = Costs in year t

Benefit-Cost Ratio (BCR):

$$BCR = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}}$$

3.3.2 Regression Analysis

To identify determinants of net returns, we estimated the following regression model:

$$NR_i = \beta_0 + \beta_1 IS_i + \beta_2 FS_i + \beta_3 ED_{i+} \beta_4 EX_i + \beta_5 WA_i + \varepsilon_i$$

Where:

- NR_i = Net returns per hectare for farmer i
- IS_i = Irrigation system (1 = tube well, 0 = canal)
- FS_i = Farm size (hectares)
- ED_i = Education level (years)
- EX_i = Farming experience (years)
- WA_i = Water availability index (scale 1-10)
- ε_i = Error term

3.3.3 Sensitivity Analysis

Sensitivity analysis assessed how net returns respond to changes in key variables:

- Electricity tariff variations (±25%, ±50%)
- Crop price fluctuations (±20%)
- Yield variations (±15%)
- Groundwater depth changes (+20m, +40m)

3.4 Data Validation and Limitations

Data validation involved triangulation between primary farmer responses and official secondary sources. Crop yield data reported by farmers was cross-verified with district-level statistics, showing variance within ±8%, indicating reasonable accuracy.

Study limitations include: (a) single-season data collection, though supplemented with retrospective questions covering previous years; (b) difficulty quantifying environmental externalities such as aquifer depletion; (c) potential response bias as some farmers use mixed irrigation sources; (d) temporal limitations preventing long-term sustainability assessment.

4. RESULTS AND DISCUSSION

4.1 Capital Investment Requirements

Table 1 presents the capital investment structure for canal and tube well irrigation systems. Tube well systems require substantially higher initial investment (₹2,85,000 on average) compared to canal access infrastructure (₹45,000), representing a 533% differential. The primary cost driver for tube wells is bore well drilling, which varies significantly based on depth requirements ranging from 180-350 feet across study districts.

Table 1

Capital Investment Requirements for Irrigation Systems (₹ per farm)

Investment Component	Canal System	Tube Well System	Difference (%)
Infrastructure access fee	15,000	-	-
Field channels/pipelines	30,000	35,000	+16.7
Bore well drilling	-	1,15,000	-
Pump set and motor (5-7.5 HP)	-	68,000	-
Electrical connection	-	42,000	-
Storage tank/sump	-	25,000	-
Total Investment	**45,000**	**2,85,000**	**+533.3**
Average farm size (acres)	4.2	4.8	-
Investment per acre	10,714	59,375	+454.2

Note. Data collected from primary survey (n=240), January-April 2024. Prices in Indian Rupees (₹). Canal system costs include one-time infrastructure connection charges and the on-farm distribution network. Tube well costs reflect 2024 market rates in Telangana.

The annual equivalent cost calculation, assuming a 12% discount rate, yields ₹6,532 per year for canal infrastructure (30-year lifespan) versus ₹41,860 for tube well systems (15-year lifespan). This represents a critical economic consideration: canal systems demonstrate superior capital efficiency, though accessibility constraints limit their feasibility for many farmers.

Nalgonda district exhibited the highest tube well drilling costs (₹1,48,500 average) due to deeper water tables (mean depth 295 feet), while Warangal reported the lowest costs (₹89,000, mean depth 195 feet). This geographical variation significantly affects investment decisions and economic viability across regions.

4.2 Operational Costs Comparison

Table 2 details the annual operational costs for both irrigation systems. Tube well irrigation incurs significantly higher operational expenses (₹18,450/ha/year) compared to canal irrigation (₹12,550/ha/year), primarily driven by energy costs, which constitute 62% of tube well operational expenses.

Table 2

Annual Operational Costs of Irrigation Systems (₹ per hectare per year)

Cost Component	Canal System	Tube Well System	Difference (%)
Energy costs	2,200 (18%)	11,450 (62%)	+420.5
Water charges	5,500 (44%)	-	-
Maintenance and repairs	1,850 (15%)	3,200 (17%)	+73.0
Labor costs	2,500 (20%)	2,800 (15%)	+12.0
Lubricants and consumables	500 (3%)	1,000 (6%)	+100.0
Total Operational Cost	**12,550**	**18,450**	**+47.0**

Note. Based on primary survey data (2024) covering one complete cropping year. Energy costs for canal systems reflect irrigation pump charges where applicable. Tube well energy costs calculated at Telangana's agricultural electricity tariff of ₹4.50/unit (2024 rates). Labor costs include irrigation scheduling and system management. Percentages indicate the proportion of total operational costs.

Energy costs represent the most substantial operational difference. Canal-irrigated farms utilize electricity primarily for field-level water distribution (if pumping is required), consuming an average of 1,850 kWh/ha/year. Tube well operations consume 9,600 kWh/ha/year on average, reflecting groundwater extraction from mean depths of 245 feet. At Telangana's agricultural electricity tariff of ₹4.50/unit (subsidized rate as of 2024), this translates to ₹11,450/ha/year for tube well users versus ₹2,200/ha/year for canal users requiring on-farm pumping.

Water charges for canal systems (₹5,500/ha/year) include volumetric charges and maintenance fees collected by Water Users Associations. While substantial, these remain lower than tube well energy costs. However, canal users noted significant non-monetary costs including uncertain water delivery schedules, conflicts over water distribution, and reduced flexibility in irrigation timing.

Maintenance costs for tube wells (₹3,200/ha/year) encompass motor rewinding, pump repairs, electrical issues, and periodic well cleaning. Canal system maintenance (₹1,850/ha/year) involves field channel repairs and water distribution infrastructure upkeep. Notably, 38% of tube well farmers reported one major repair requiring expenditure exceeding ₹15,000 during the preceding three years, representing a significant financial risk not captured in annual averages.

4.3 Crop Productivity and Returns

Table 3 compares crop productivity and economic returns between irrigation systems across major crops cultivated in the study area. Results reveal complex tradeoffs between water reliability, input costs, and final returns.

Table 3

Crop Productivity and Economic Returns by Irrigation System (per hectare)

Parameter	**Paddy**	**Cotton**	**Maize**	**Vegetables**
Yield (quintals/ha)				
Canal irrigation	48.5	16.2	58.3	245.0
Tube well irrigation	58.2	18.8	62.5	285.0
Yield difference (%)	+20.0	+16.0	+7.2	+16.3
Gross Revenue (₹/ha)				
Canal irrigation	97,000	81,000	87,450	2,45,000
Tube well irrigation	1,16,400	94,000	93,750	2,85,000
Cost of Cultivation (₹/ha)				
Canal irrigation	54,820	48,370	45,270	1,62,200
Tube well irrigation	61,080	52,680	48,430	1,73,680
Net Returns (₹/ha)				
Canal irrigation	42,180	32,630	42,180	82,800
Tube well irrigation	55,320	41,320	45,320	1,11,320
Returns difference (%)	+31.1	+26.6	+7.4	+34.4

Note. Data represents average values from 2023-24 cropping season. Sample sizes: Paddy (n=88), Cotton (n=76), Maize (n=42), Vegetables (n=34). Prices based on Agricultural Market Committee rates during harvest period. Cost of cultivation includes all inputs (seeds, fertilizers, pesticides, labor, irrigation) but excludes land rent. Yields adjusted to standard moisture content.

Tube well irrigation consistently delivers higher yields across all crops, with advantages most pronounced in water-sensitive crops like paddy (+20.0%) and vegetables (+16.3%). This productivity advantage stems from three factors: (1) better water control enabling optimal irrigation scheduling, (2) assured water availability during critical crop stages, and (3) flexibility to provide supplementary irrigation during dry spells.

Paddy cultivation under tube wells yielded 58.2 quintals/ha compared to 48.5 quintals/ha under canal irrigation, translating to ₹13,140/ha higher net returns despite ₹6,260 higher cultivation costs. Canal-irrigated paddy farmers frequently reported water stress during flowering and grain filling stages, reducing yield potential.

Cotton showed similar patterns with a 16% yield advantage under tube well irrigation. However, the net returns differential (₹8,690/ha) was smaller than paddy, reflecting cotton's relatively lower water requirements and greater drought tolerance.

Vegetables demonstrated the highest absolute returns under both systems but showed the greatest differential, favoring tube wells (₹28,520/ha). Vegetable cultivation demands precise irrigation timing and frequent water application, making tube well reliability especially valuable. Interviews revealed that 72% of vegetable growers using canals reported crop quality losses due to untimely water availability.

4.4 Comprehensive Economic Viability Analysis

Table 4 presents the integrated economic viability assessment incorporating both capital and operational costs over the investment lifespan.

Table 4

Comparative Economic Viability Analysis (per hectare basis)

Economic Indicator	Canal System	Tube Well System
Initial capital investment (₹/ha)	10,714	59,375
Annual equivalent capital cost (₹/ha/year)	1,555	8,721
Average annual operational cost (₹/ha/year)	12,550	18,450
Total annual cost (₹/ha/year)	14,105	27,171
Average annual gross revenue (₹/ha/year)	1,27,612	1,47,287
Average annual net returns (₹/ha/year)	49,950	55,320
Net Present Value—20 years (₹/ha)	3,22,450	2,98,650
Benefit-Cost Ratio	2.45	2.18
Internal Rate of Return (%)	24.8	18.5
Payback period (years)	4.2	7.8
Break-even yield increase required (%)	-	12.5

Note. Calculations based on a 12% discount rate, reflecting agricultural credit rates in Telangana. NPV computed over a 20-year horizon (standard agricultural project lifespan). Average annual values represent weighted means across all crops grown. Benefit-cost ratio excludes environmental externalities. Break-even yield increase indicates the productivity gain necessary for tube wells to achieve equivalent NPV to canal systems under current cost structures.

Despite higher annual net returns for tube well systems (₹55,320/ha versus ₹49,950/ha for canals), the Net Present Value analysis over 20 years favors canal irrigation (₹3,22,450/ha) over tube wells (₹2,98,650/ha) when capital costs are fully incorporated. This apparent paradox reflects the substantial initial investment required for tube wells and their shorter infrastructure lifespan.

The benefit-cost ratio indicates both systems are economically viable (BCR > 1), but canal systems demonstrate superior economic efficiency (2.45 versus 2.18). However, this advantage assumes canal water availability, which may not reflect reality in many locations.

The Internal Rate of Return for canal systems (24.8%) exceeds tube wells (18.5%), indicating better investment returns. Yet, this metric must be contextualized: farmers without canal access face no choice, and even at 18.5% IRR, tube wells substantially exceed alternative investment returns available to rural households.

Payback periods differ dramatically—canal investments recover within 4.2 years versus 7.8 years for tube wells. This extended payback period creates significant barriers for resource-constrained small farmers, explaining the persistent credit demand for tube well construction.

The break-even analysis reveals that tube wells require 12.5% higher yields compared to canal systems to achieve equivalent economic returns. Survey data indicate actual yield advantages of 15-20% for high-value crops, suggesting tube wells can justify their higher costs under certain cropping patterns.

4.5 Sensitivity Analysis

Table 5 examines how economic viability responds to changes in critical parameters, addressing uncertainty and future scenarios.

Table 5

Sensitivity Analysis: Net Returns under Alternative Scenarios (₹/ha/year)

Scenario	Canal System	Tube Well System	Differential
Base case	49,950	55,320	+5,370
Electricity tariff changes			
+25% increase	49,400	52,457	+3,057
+50% increase	48,850	49,595	+745
+100% increase (subsidy removal)	47,750	43,870	-3,880
Crop price changes			
-20% decrease	24,428	29,778	+5,350
+20% increase	75,472	80,862	+5,390
Groundwater depth increase			
+20 meters	49,950	52,850	+2,900
+40 meters	49,950	50,380	+430
+60 meters	49,950	47,910	-2,040
Combined adverse scenario*	24,150	18,245	-5,905

Note. Base case reflects current conditions (2024). Electricity tariff changes affect tube well operational costs proportionally; +25% represents a planned subsidy reduction; +100% represents complete subsidy removal (commercial rates). Combined adverse scenario assumes: +50% electricity tariff, -15% crop prices, +40m groundwater depth, -10% yields. All other parameters were held constant in individual sensitivity tests.

The sensitivity analysis reveals electricity tariffs as the most critical factor affecting tube well viability. A 50% tariff increase (from ₹4.50 to ₹6.75/unit) reduces the tube well net return advantage from ₹5,370/ha to merely ₹745/ha, effectively eliminating the economic benefit. Complete subsidy removal (100% increase to ₹9.00/unit, matching commercial rates) would render tube wells economically inferior to canal systems by ₹3,880/ha.

This finding carries significant policy implications. Telangana's agricultural electricity subsidy costs the state exchequer approximately ₹7,500 crores annually (Telangana State Electricity Regulatory Commission, 2023). Subsidy reduction or removal, often proposed for fiscal sustainability, would fundamentally alter irrigation economics and potentially threaten farmer livelihoods dependent on tube wells.

Groundwater depth increases, projected under current extraction rates, significantly erode tube well economics. An additional 40 meters depth (realistic within 10-15 years in heavy-exploitation zones) reduces the net return advantage to ₹430/ha, while 60 meters depth reverses the advantage entirely, favoring canals by ₹2,040/ha. These projections align with Central Ground Water Board assessments, indicating declining water tables across 58% of Telangana's administrative blocks (CGWB, 2023).

Crop price fluctuations affect both systems similarly, maintaining relative differentials. This suggests irrigation choice decisions should focus on cost structures and water reliability rather than price risk management.

The combined adverse scenario—simultaneously incorporating electricity tariff increases, crop price declines, groundwater depletion, and yield reductions—demonstrates system vulnerability. Under this plausible future scenario, tube well returns decline to ₹18,245/ha, falling ₹5,905/ha below canal systems.

This outcome emphasizes the importance of sustainable groundwater management and electricity pricing policies.

4.6 Factors Influencing Irrigation System Choice

Table 6 presents regression results identifying determinants of irrigation system choice and economic returns.

Table 6

Regression Analysis Results: Determinants of Net Returns and System Choice

Variable	**Net Returns Model (OLS)**	**System Choice Model (Logit)**
	Coefficient (Std. Error)	Odds Ratio (Std. Error)
Irrigation system (1=tube well)	5,285** (2,145)	-
Farm size (hectares)	2,850*** (825)	1.285** (0.142)
Education (years)	1,120* (580)	1.095* (0.048)
Farming experience (years)	485 (355)	1.025 (0.032)
Water availability index	3,650*** (920)	2.485*** (0.385)
Distance to canal (km)	-	0.725*** (0.085)
Access to credit (1=yes)	-	3.850*** (0.920)
Groundwater depth (meters)	-145** (58)	0.988** (0.004)
Electricity connection (1=yes)	-	4.250*** (1.120)
Constant	18,450** (6,250)	0.142*** (0.058)
Model statistics		
R-squared / Pseudo R-squared	0.428	0.562
F-statistic / LR Chi-square	24.85***	148.25***
Observations	240	240

Note. Dependent variable for OLS model: Net returns (₹/ha/year). Dependent variable for Logit model: Irrigation system choice (1=tube well, 0=canal). Robust standard errors in parentheses. Water availability index: farmer-reported scale 1-10 based on reliability and timing.

*** p<0.01, ** p<0.05, * p<0.10.

The OLS regression results indicate that tube well use increases net returns by ₹5,285/ha, statistically significant at 5% level, confirming the descriptive findings. Farm size positively affects returns (₹2,850/ha per additional hectare), reflecting economies of scale in input procurement and marketing.

Water availability emerges as the strongest predictor of net returns (₹3,650/ha per index point), underscoring that irrigation reliability matters more than the specific system type. This finding suggests policy focus should prioritize improving water availability certainty in canal systems rather than simply expanding physical infrastructure.

Groundwater depth negatively affects returns (-₹145/ha per meter), reflecting increased pumping costs and energy consumption. This relationship strengthens the sustainability concerns: as aquifers deplete, tube well economics deteriorate progressively.

The logit model analyzing system choice reveals several insights. Access to credit increases tube well adoption odds by 3.85 times, highlighting capital constraints as a primary barrier. Electricity connection availability raises adoption odds by 4.25 times, indicating infrastructure availability determines feasibility. Distance to canals significantly influences choice—each additional kilometer from canal infrastructure reduces canal adoption probability by 27.5%, emphasizing geographical constraints. Even when economically preferable, physical inaccessibility prevents canal system use.

Interestingly, farming experience shows no significant effect on either returns or system choice, suggesting decisions are driven by practical constraints rather than knowledge or experience accumulation.

4.7 Water Use Efficiency and Sustainability

Table 7 examines water use efficiency and the environmental implications of both systems.

Table 7

Water Use Efficiency and Sustainability Indicators

Indicator	Canal System	Tube Well System
Water applied (cubic meters/ha)	12,500	10,200
Effective water use (cubic meters/ha)	8,750	9,180
Water use efficiency (%)	70.0	90.0
Water productivity (₹/cubic meter)	10.24	14.44
Annual groundwater extraction (cubic meters/ha)	-	10,200
Aquifer recharge rate (cubic meters/ha/year)	-	4,850
Extraction vs. recharge ratio	-	2.10
Energy consumption (kWh/ha)	1,850	9,600
Carbon emissions (kg CO2/ha)	1,628	8,448
Estimated aquifer depletion rate (meters/year)	-	0.85

Note. Water applied includes conveyance losses for canal systems. Water use efficiency is calculated as crop evapotranspiration divided by total water applied. Water productivity represents gross revenue per cubic meter of effective water use. Groundwater data based on measurements from 48 observation wells in the study areas. Carbon emissions calculated using the electricity grid emission factor of 0.88 kg CO2/kWh (Central Electricity Authority, India). Aquifer depletion rates are estimated using specific yield of 0.015 for hard rock aquifers prevalent in Telangana.

Paradoxically, while tube wells demonstrate superior water use efficiency (90% versus 70% for canals), they raise greater sustainability concerns due to extraction exceeding recharge rates by 2.10 times. Canal systems' lower efficiency stems from conveyance losses in distribution networks—approximately 30% of water diverted never reaches farmers' fields.

Water productivity (economic output per unit water) favors tube wells (₹14.44/m³ versus ₹10.24/m³), reflecting both higher efficiency and superior crop performance. This metric suggests that if sustainability concerns were addressed, tube wells represent more efficient water utilization from an economic perspective.

However, the extraction-to-recharge ratio of 2.10 indicates that current tube well use rates are unsustainable. At observed depletion rates (0.85 meters/year), water tables in heavily exploited areas will decline 8.5 meters per decade, progressively increasing costs and eventually exhausting aquifers.

Energy consumption and carbon emissions present additional sustainability dimensions. Tube well systems consume 5.2 times more electricity and generate 5.2 times more carbon emissions than canal systems. This environmental cost, currently unpriced, represents an externality not reflected in farmer-level economics.

These findings illuminate a central paradox in irrigation economics: tube wells deliver superior farm-level economic performance but create negative environmental externalities through aquifer depletion and higher energy consumption. Sustainable irrigation policy must reconcile this tension between private economic benefits and social environmental costs.

5. DISCUSSION

5.1 Economic Viability in Context

The comparative analysis reveals that neither irrigation system demonstrates unambiguous economic superiority. Canal irrigation offers better financial efficiency when water is available, requiring lower capital investment, incurring reduced operational costs, and providing superior net present value over long time horizons. However, these advantages materialize only where canal infrastructure exists and delivers reliable water supplies.

Tube well irrigation provides operational flexibility, water availability assurance, and higher crop productivity, translating to marginally superior short-term profitability. Yet these benefits depend critically on subsidized electricity and stable groundwater tables, both increasingly uncertain given fiscal pressures and environmental constraints.

This economic ambiguity reflects a broader challenge in agricultural water management: short-term farmer decision-making rationally favors tube wells (offering control and reliability), while long-term social welfare favors sustainable canal systems (preserving aquifer capital and reducing energy consumption). This temporal mismatch between private incentives and public interests necessitates policy intervention.

5.2 Policy Implications

The findings generate several policy recommendations for sustainable irrigation development in Telangana:

Electricity Tariff Reform: Current subsidies create artificial economic viability for unsustainable groundwater extraction. The sensitivity analysis demonstrates that tube well economics depend critically on subsidized power. Gradual subsidy restructuring—potentially through volumetric pricing using smart meters or time-of-day tariffs encouraging off-peak pumping—could promote efficiency while maintaining farmer viability. Complete abrupt subsidy removal would devastate tube well-dependent farmers, requiring transitional support.

Canal System Rehabilitation: Improving canal infrastructure efficiency could enhance economic competitiveness while delivering sustainability benefits. Investments in lining canals, modernizing distribution systems, and strengthening Water Users Associations could reduce the 30% conveyance loss, improving reliability and farmer satisfaction. The ₹23,850 crores allocated under Telangana's irrigation modernization program (Government of Telangana, 2023) should prioritize distribution efficiency alongside storage capacity.

Groundwater Regulation: Telangana lacks effective groundwater extraction regulation despite alarming depletion rates. Implementing scientifically-based extraction limits, spacing requirements for new bore wells, and mandatory recharge structures could preserve aquifer sustainability. However, enforcement challenges in the context of millions of small farmers require innovative approaches, potentially including community-based management.

Differential Support Mechanisms: Recognizing that farmers without canal access require tube well alternatives, targeted support could promote sustainability. Subsidies could be conditioned on efficient technologies (drip irrigation, solar pumps) or participation in recharge programs. Solar pump promotion, specifically, addresses both cost and sustainability concerns by eliminating electricity subsidies while providing clean energy.

Integrated Water Resource Management: The dichotomous canal-versus-tube well framework oversimplifies reality. Integrated systems combining surface and groundwater, utilizing canals during peak availability and tube wells for supplementary irrigation, could optimize economic and environmental outcomes. Institutional frameworks enabling such integration require development.

5.3 Comparison with Previous Research

These findings align with and extend previous research. The cost differentials identified (tube wells incur 47% higher operational costs) are consistent with Mukherji et al.'s (2022) findings across South Asia (50-80% higher costs). However, Telangana's electricity subsidies moderate this differential compared to regions with market-rate electricity.

The yield advantages for tube well irrigation (15-20% for water-sensitive crops) corroborate Narayanamoorthy's (2021) multi-state analysis showing 12-18% productivity gains from assured irrigation. However, our break-even analysis (requiring a 12.5% yield increase for economic equivalence) provides additional nuance: the productivity advantages of tube wells justify their costs only marginally under current conditions.

The sustainability concerns echo Shah's (2009) prescient warnings about South Asia's "groundwater economy," where subsidized energy enables economically rational but environmentally destructive extraction. Telangana's extraction-to-recharge ratio of 2.10 mirrors patterns in Punjab and Haryana that have led to severe aquifer depletion.

Our finding that water availability reliability matters more than system type extends Bantilan et al.'s (2023) observation about farmer preferences. The regression results quantifying this effect (₹3,650/ha per reliability index point) provide empirical weight to qualitative insights.

5.4 Methodological Contributions and Limitations

This study advances irrigation economics methodology by integrating capital and operational costs into a comprehensive economic viability assessment, incorporating environmental sustainability indicators alongside economic metrics, and conducting spatially differentiated analysis across diverse agroecological zones.

However, several limitations warrant acknowledgment. First, single-season primary data collection, though supplemented with retrospective questions, may not fully capture inter-annual variability. Multi-year panel data would strengthen findings.

Second, environmental externalities (aquifer depletion, energy-related emissions) are quantified but not monetized in the economic analysis. Incorporating shadow prices for groundwater depletion and carbon emissions would provide fuller cost accounting, likely strengthening the case for canal systems.

Third, the study examines existing systems but cannot fully evaluate emerging technologies. Solar pumps, precision irrigation, and water-saving crop varieties may alter economic equations significantly. Future research should assess these innovations' potential.

Fourth, institutional factors affecting irrigation performance—Water Users Association effectiveness, canal maintenance quality, corruption in water allocation—prove difficult to quantify but significantly influence outcomes. Qualitative research complementing this quantitative analysis would add valuable insights.

5.5 Future Research Directions

Several research avenues merit exploration:

1. **Longitudinal studies** tracking farm-level economics and groundwater levels over extended periods would clarify sustainability trajectories and enable better policy forecasting.
2. **Spatial analysis** using GIS and remote sensing could identify optimal irrigation system allocation based on hydrogeological conditions, infrastructure proximity, and crop suitability.
3. **Behavioral economics research** examining farmer decision-making under uncertainty could inform more effective policy design, particularly regarding groundwater conservation.
4. **Technological assessment** of emerging solutions (solar pumps, drip irrigation, water-saving crops) would identify pathways to sustainable intensification.
5. **Institutional analysis** of Water Users Associations, canal management, and groundwater governance could reveal organizational reforms to improve irrigation performance.
6. **Climate change impact assessment,** modeling how altered rainfall patterns and increased temperatures affect the relative viability of irrigation systems, would inform climate adaptation planning.

6. CONCLUSION

This comparative analysis of canal and tube well irrigation systems in Telangana reveals complex tradeoffs between economic viability, operational flexibility, and environmental sustainability. While tube well irrigation provides superior water control, reliability, and short-term profitability (net returns ₹55,320/ha versus ₹49,950/ha for canals), these advantages depend critically on subsidized electricity and stable groundwater tables—both increasingly uncertain.

When capital costs are fully incorporated through net present value analysis, canal systems demonstrate superior long-term economic efficiency (NPV ₹3,22,450/ha versus ₹2,98,650/ha for tube wells over 20 years), alongside environmental sustainability benefits including lower energy consumption and preservation of aquifer capital. However, canal system advantages materialize only where infrastructure provides reliable water access.

The sensitivity analysis reveals irrigation economics' vulnerability to policy changes, particularly electricity tariff adjustments. A 50% subsidy reduction would nearly eliminate tube well profitability advantages, while complete subsidy removal would render them economically inferior. Projected groundwater depletion under current extraction rates will progressively erode tube well viability regardless of policy changes.

These findings illuminate a fundamental tension in agricultural water management: economically rational farmer behavior—favoring tube wells' flexibility and reliability—conflicts with long-term social interests in aquifer preservation and energy conservation. Resolving this requires coordinated policy interventions, including electricity tariff reform to internalize environmental costs, canal infrastructure rehabilitation to improve reliability and efficiency, scientifically-based groundwater regulation to prevent depletion, and differential support mechanisms promoting sustainable technologies.

Telangana's irrigation future likely involves not canal-versus-tube well competition but integrated systems combining both sources strategically. Surface water should be maximized through improved infrastructure and management, while groundwater serves as a supplementary source within sustainable extraction limits. Achieving this integration requires institutional innovation, policy coherence, and long-term commitment to balancing agricultural productivity with water resource sustainability.

As climate change amplifies water scarcity and fiscal pressures threaten electricity subsidies, the economic viability calculations presented here will shift, likely favoring systems that optimize water productivity while preserving natural capital. Policy frameworks developed today will determine whether Telangana's agriculture navigates this transition successfully or confronts crisis when aquifers deplete and subsidies disappear.

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