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Assessing Groundwater Pricing and Consumption Behavior in the North-Western Bangladesh: Proposing Sustainable and Equitable Models for Irrigation Management

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ABSTRACT

This research explores the aspects of groundwater consumption in irrigation and pricing attitudes of farmers working in the North-Western Bangladesh, a region that is currently experiencing very serious effects of groundwater depletion, exacerbated by inefficient pricing mechanisms. Utilizing choice experiments and latent class analysis, the research discovers three groups of farmers, based on their price model preferences: small-scale farmers, who prefer tiered pricing for fairness; medium-scale farmers, who prefer volumetric and marginal cost pricing, indicating efficiencies and conservation; and large-scale farmers, who prefer block pricing based on convenience. Higher groundwater prices have been shown to result in lower levels of consumption, which actually suggests water-saving behavior, particularly when using technologies like Alternate Wetting and Drying (AWD). However, the low adoption rates of these technologies underscore the need for government intervention in the form of subsidies and awareness-raising initiatives. The current pricing system supports farmer groups who use privately owned tube wells. This study recommends a hybrid pricing system that consists of tiered and volumetric pricing to address issues of equity and sustainability, as well as improvements to infrastructure, metering systems, and market policies to enhance sustainability and equity in the region's groundwater irrigation markets.

1. Introduction

More than 65% of all fresh water withdrawals worldwide are used for irrigation. Currently, groundwater supplies one-fourth of the world's irrigated land, with 75% of these lands being in Asia [1]. Approximately 79.1% of Bangladesh's agricultural lands are irrigated using groundwater for rice production [2]. In Bangladesh, agriculture is the main consumer of water, with rice farming being the most significant economic sector. The majority of the cultivated land in the nation is used to grow rice, which accounts for 90% of all food grains produced [3]. In Bangladesh, there are three main seasonal varieties of rice grown: Aus, Aman, and Boro.

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Production of Boro rice has increased over the past two decades as a result of its higher yield potential (3.4 tons ha-1) compared to Aus (1.6 tons ha-1) and Aman (2.0 tons ha-1) [4]. Bangladesh's total rice production increased since of Boro, rising from 18.3 million tons in 1991 to 33.8 million tons in 2013 [5]. The massive groundwater exploitation is partly to blame for the sharp rise in boro output. Currently, roughly 80% of groundwater is used for irrigation, with boro farmers using 73% of it entirely [4].

The North-Western Bangladesh produces over 35% of Bangladesh's total rice production with more focus to the Boro rice production, which indicates a large volume of irrigation water required for this water-intensive sector. Up until two programs were introduced to improve groundwater irrigation, the Barind region had an underdeveloped agricultural economy and high poverty levels [1]. New water extraction technology and creative management techniques, such as deep tube wells (DTWs) fitted with smart card-operated electric pumps, were used by the Barind Integrated Area Development Project in 1985 and the Barind Multipurpose Development Authority (BMDA) in 1992 to develop drought-resistant irrigation. Since 2000, rice output has increased very fast in this region, making agriculture a significant factor in this area's efforts to reduce poverty [6]. Raising land productivity and boosting agricultural output diversification are "essential to poverty reduction as well as for food security," according to the United Nations Millennium Development Goals and the government of Bangladesh's policy to fight poverty [7]. The positive impact of the BMDA on agriculture, especially rice output, has been hailed as a success story.. However, as the primary cause of ground water loss in the Barind Tract, this increased use of DTWs has a significant negative influence on groundwater levels [8]. According to a case study in the Rajshahi district of the Barind Tract, the groundwater level in Rajshahi's rural areas has dropped by up to 26 meters in the past ten years, even though the monsoon rains only cover 9 meters of it. As a result, farmers in over 30 communities said that from 2015 to 2018, they were unable to harvest their crops during the dry season [2]

Additionally, The Barind region is characterized by warm, dry weather. All rivers, with the exception of the Padma River, are seasonal, drying up during the dry season [9]. Recently, the FAO revealed that 80% of groundwater withdrawals are due to forced irrigation, placing a great deal of strain on groundwater resources and depleting groundwater storage. Another study revealed that excessive groundwater use had negative effects on drinking water supplies including the contamination of groundwater with arsenic, which is highly prevalent in Bangladesh [10]

The Barind region's Boro paddy is now being irrigated by 15,813 DTWs, according to the BMDA. The pricing of the BMDA controlled DTWs is maintained by pre-paid meters and smart cards. Farmers need to buy smart cards from BMDA dealers before using the DTW. The payment covers only the electricity cost, staff salary and maintenance cost. The other costs such as investment cost, environmental cost, opportunity cost etc. are excluded. As the electricity charge in agricultural sector is much cheaper than the other industries, the farmers need to pay only a little [8]. However, many of these tube wells are owned privately by people who are comparatively wealthy farmers with larger land holdings. The over-extraction of water by deep tube well users causes a tragedy of the commons because everyone has free access to ground water as a common pool resource. The marginal and underprivileged farmers must rely on the owner of the nearby deep tube well for irrigation [11]. It creates an informal market of ground water where the rich farmers owning deep tube wells sell the ground water to the small farmers without paying for the ground water to anyone. The payment system varies from place to place. Prior to now, marginal farmers were required to pay deep tube well owners one-fourth of their total production; however, in the majority of locations, pricing now includes fuel costs, maintenance costs, and an hourly fee for tube well use. This pricing structure has created a glaring disparity between wealthy and poor farmers, as wealthy farmers profit from selling groundwater while poor farmers are forced to pay substantially more for the resource [12]

Water pricing system could be an effective way of solving the over extraction and inequity problem because an efficient market-based incentive for increasing water distribution and decreasing water use has been found to be water price [13], [14], [15]. Effective water markets are very crucial for irrigation water since they have a big impact on the proper management of water sources [16]. In practice, water pricing is expected to provide water suppliers with financial resources to maintain and ensure the long-term viability of the water supply system, reduce demand and promote the sustainable use of water, and allocate water more efficiently by transferring it from lower-value to higher-value uses. To design an efficient water pricing system, it is essential to prioritize key objectives [17], [18]. However, due to the low cost of groundwater, farmers using BMDA DTWs tend to overuse it, and the externalities caused by excessive water consumption are not accounted for in the current pricing system. Additionally, privately owned DTWs impose high fees on marginal farmers, exacerbating inequities. The research gap lies in understanding how the current pricing system fails to address the environmental and social costs of over-extraction, and how alternative pricing models can better balance sustainability and equity. The study aims at (1) exploring the current pricing practice, (2) examining Farmers' Water usage behavior in response to pricing, and (3) assessing farmers' preferences and responses to different potential alternative groundwater pricing Systems in Barind Tract. This study is expected to develop an insight to propose an efficient groundwater pricing system addressing the issues of environmental degradation and social inequity.

2. Methods and Materials

Study Area

The Barind Tracts are in northwestern Bangladesh, consists of parts of 6 Districts, where the rural agricultural economy, lack of precipitation, hot weather, and lower average household income than in other regions of the country make circumstances there challenging. Agriculture is a major part of about 80% of all households, with rice as the primary crop. The Barind Tract was selected for this study due to its significant groundwater depletion issues, exacerbated by intensive agricultural practices, particularly rice farming.
The study area is a 191,330 square kilometer Upazila (upazila is a sub-district, which includes some villeges) called Tanore in the Rajshahi District of the Barind Tract. In this upazila, there are 191000 residents, and 81% of them are engaged in agriculture. Ground water extraction through deep and shallow tube wells accounts for the majority (more than 90%) of the irrigation needs of this region. The existence of both BMDA-operated and privately owned deep tube wells, various classes of farmer groups, ground water shortage, and other common features of the Barind Tract have led to the selection of Tanore upazila as the study area.

Data Collection

The study is based on primary data to find out farmer's water use behaviour and preference for groundwater pricing systems, and responses to some plausible alternative pricing models in the Barind Tract. Primary data were collected with the help of a detailed questionnaire survey constructed to elicit in-depth information on farmers' water use behavior, socio-economic characteristics, pricing preferences, and responses to varying groundwater pricing structures. Questions included irrigation practices, awareness of water conservation techniques, income levels, farm sizes, and willingness to pay for improved groundwater management. Another section acquired demographic information and information regarding crop types, existing water costs, and perceptions about effects of current pricing on income and productivity.
A total of 273 farmers were purposely sampled, with a 90% confidence level and a 5% margin of error. The sample represented three key farmer categories: Smallholders (households operating less than 0.2 hectares), Medium (households operating between 0.2 and 1.0 hectares), and Large (households operating above 1.0 hectares). Quota sampling was applied to balance these categories, ensuring diverse perspectives on groundwater pricing..
The respondents in this study were diverse in terms of both demographic and socioeconomic factors. The majority of respondents were male, with ages ranging from 25 to 60 years. In terms of socioeconomic status, smallholders had lower annual incomes compared to medium and large farmers, with income levels influencing their access to resources and willingness to adopt new irrigation practices. Education levels varied, with many respondents having completed primary or secondary education.
In addition to collecting the qualitative data through completion of the questionnaire, Participatory Rural Appraisal (PRA) tools- Focus Group Discussions (FGD)s and Key Informant Interviews (KII)s and a Seasonal Calendar were employed to obtain further qualitative insights into community-specific issues, preferences, and seasonal variations of water use. To ensure data validity and reliability, the survey instrument was pre-tested through a pilot survey with a small sample of farmers. Feedback from the pilot was used to refine the questionnaire. Additionally, internal consistency was assessed using Cronbach’s alpha to ensure that the survey items consistently measured the intended constructs. The final sample size of 273 respondents was deemed sufficient for reliable statistical analysis, providing a 90% confidence level with a 5% margin of error.
Informed consent was obtained from all participants, ensuring they were aware of the study’s purpose and their right to confidentiality and voluntary participation. Anonymity was maintained, and all data were handled confidentially. The study adhered to ethical guidelines and was approved by the Ethics Review Board.

Data Analysis

The analysis proceeded through four main stages:

Descriptive Statistics

Using descriptive statistics, an overview of farmers' demographic and socio-economic characteristics were analyzed, segregating into three landholding categories: Smallholders, Medium, and Large. Information concerning age, income, education, farm size, present irrigation practices, and water conservation awareness is portrayed. Statistics such as mean and median, standard deviation, and frequency distributions were calculated to provide a wide range of profiles of the study population, detailed analysis.

Analyzing Water Usage Behavior forming the basis for more with Tobit Regression Model

The Tobit regression model was employed to analyze the price sensitivity of groundwater users, as the data were censored. Some farmers reported not using any water due to the high cost of groundwater, and these censored responses were accounted for in the model. The model used the following equation:

Dependent Variable (y_i) denotes Water use-cubic meters

$$y_i = X_i\beta + \varepsilon_i, \text{ where } y_i = \max(0, y_i)$$

per acre. Independent Variables are groundwater price in BDT per m³, farm size category as small, medium, large, annual income expressed in BDT, and adoption of water-saving methods, preferably alternate wetting and drying. Therefore, the model equation:

$$y_i = \alpha + \beta 1(\text{Price}) + \beta 2(\text{Farm Size}) + \beta 3\ (\text{Income}) + \beta 4\ (\text{Technology Adoption}) + \epsilon_{i0}$$

The Tobit model enabled achieving quantifiable relationships among water usage and key factors such as pricing and farm characteristics. This analysis helped make inferences on how price sensitivity, size of the farm, and income levels influenced water use and the likelihood of adopting conservation practices across the farmer categories.

Assessing Preferences for Pricing Models

The Choice Experiment was carried out to understand farmers' preferences for different groundwater pricing models. Farmers were presented with 12 choice sets and asked to select between three alternatives: Tiered Pricing, Volumetric Pricing, and Block Pricing, each with different water allocation volumes and costs per unit. The experiment identified overall preferences and the extent to which farmers were willing to change pricing schemes based on their needs.

Choice Experiment Model

In the Choice Experiment, each farmer i was entailed to numerous sets of choice, where in each one they selected one option from three alternatives. Assuming the random utility model, utility:

$$U_{ij} = X_{ij}\beta + \varepsilon_{ij}$$

X_{ij} is a vector of attributes (e.g., price per unit, water allocation) of alternative j as perceived by farmer i, β is a vector of parameters to be estimated, and ε_{ij} is the error term representing unobserved factors.

Multinomial logit models were used to analyze farmers' preferences among the three pricing models with the probabilities given by:

$$Pij = \exp(X_{ij}\beta) / \sum_{k} \exp(X_{ik}\beta)$$

This model estimates the probability that a farmer chooses a pricing model given its attributes.

Latent Class Analysis (LCA)

A Latent Class Analysis (LCA) was applied to cluster farmers based on their individual responses to the Choice Experiment. This would allow researchers to determine unobserved subgroups, where each class would represent a set of farmers with similar preferences for groundwater pricing models.

$$P_{ij}|_{\mathcal{G}} = \exp(X_{ij}\beta_c) / \sum_{k} \exp(X_{ik}\beta_c)$$

The overall probability of individual i choosing alternative j, accounting for c class, is:

$$P_{ijl} = \sum_{c} \pi c \cdot P_{ijl}$$

Where, πc is the probability of membership in class c, $P_{ij}|_c$ is the conditional probability of choosing j given class c.

One to four latent classes were explored, and the suitable model was chosen in view of the Bayesian Information Criterion (BIC) versus Akaike Information Criterion (AIC) that takes into account the fit and complexity of the model. The latent classes uncovered preference groups and guided to socioeconomic and farm factors responsible for different pricing attitudes.

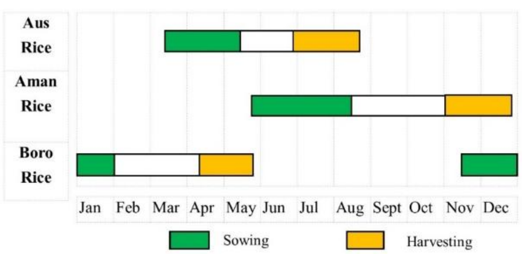
Incorporating Qualitative Insights from PRA Instruments

Qualitative information which has been collected through the use of PRA tools, such as Focus Group Discussions (FGDs), Key Informant Interviews (KIIs), and the Seasonal Calendar, was also thematically analyzed in order to provide additional insights to the quantitative results. Content analysis served to extract themes on perceived equity, price acceptability, uptake challenges and the use of water over time. These qualitative insights added an understanding of the social and economic dynamics that govern farmer's behaviors and choices, and bolstered the quantitative results from the survey as well as the Choice Experiment.

3. Results and Discussion

Cropping pattern and Groundwater Pricing Practice

The Barind Tract, the largest rice producer region in Bangladesh, is home to two-time intensive rice production and one-time winter vegetable production. The three major types of rice produced in the study area are Aus, Aman, and Boro. These crops are grown throughout the year, with Aus being planted during the rainy season from May to September, followed by Aman rice in November-December (Fig.1).

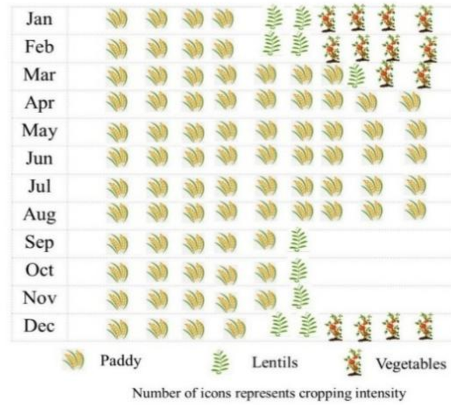


Source: Author's preparation

Fig.1: Rice Production Calendar

The Boro-Aus cropping pattern is also practiced during the dry season, with Boro rice planted in November-December and harvested in March-April. This pattern allows farmers to cultivate two high-yielding rice crops in the same field during the same season. The Boro-Aman cropping pattern is also popular in the Barind Tract because it allows farmers to cultivate two high-yielding rice crops in the same field during the same season. Winter vegetable production, such as tomato, different types of lentils, potato, and coli flower, is mainly cropped between December and March (Fig. 2).

However, advance research and government attention have made it possible to triple rice production in Bangladesh. This practice involves growing three successive crops of rice on the same plot of land within a single calendar year. The three crops are usually Boro, Aman, and Aus.



Source: Author's preparation

Fig.2: Seasonal Cropping Calendar

Current irrigation pricing in the Barind Tract relies on shallow tube wells and man-made canals, which are typically bought by farmers alone or in groups for private use on their lands. Four types of deep tube well (DTW) ownerships are found (Table 1) private deep tube wells (9%), "Somobai Somity" unions (27%), NGOs managing the distribution system (3%), and deep tube wells provided by BMDA (63%). The payment system for DTW irrigation operated by BMDA is maintained by pre-paid meters and smart cards, with farmers needing to purchase the smart cards from the agents of BMDA before using the wells.

BMDA provided DTWs covers around 50 to 55% of the cultivated area. The users of the BMDA-operated DTWs are considerably luckier than those of the other types of DTWs since they provide better technical support with contemporary technology, prepaid billing, a digital maintenance system, and skilled officials. However, the pricing structure is where there is the most prejudice. According to a field survey, farmers that use BMDA wells for irrigation pay Tk 120 (USD 1.13) per hour. They have to get prepaid cards with a time limit of several hours from local merchants. A BMDA official oversees the well, however, it is regularly maintained by some chosen members among the regular users. The study found that 60% of the money farmers pay for the use of deep tube wells goes toward energy consumption, where the cost of electricity is subsidized, 10% goes toward deep tube well operation costs, 2.5% goes to dealers of smart cards, 15-20% goes toward maintenance costs, and the remaining money is used to pay BMDA employees. No profit is made by BMDA in this irrigation system. The NGO provided DTWs also run in the same way, although, they do not have the prepaid card payment system.

Table 1: Deep Tube Well Ownership and Costing showing unequal costing among different groups

DTW Ownership Type	Share among all DTWs	Fuel Used	Per hour Irrigation Charge Tk. (USD)	Increased cost per irrigation per hectare Tk. (USD)
BMDA	61%	Electricity	120 (1)	-
NGO	3%	Electricity	120 (1) to 130 (1.08)	-
Private (Individual)	9%	Electricity and Diesel	450 (3.75) to 500 (4.16)	At least 5280 (44)
Farmer's Union	27%	Electricity and Diesel	450 (3.75) to 500 (4.16)	At least 5280 (44)

Source: Author's preparation

However, the DTWs for private individuals and the Farmer's union show significantly increasing costs for the users whose lands are not covered by the BMDA service (Table 1). For purchasers and owners, there are two separate price tiers. The majority of the pumps are powered by electricity, which is equivalent to the cost of BMDA pumps. (Electricity for irrigation is subsidized for everyone). Other pumps use diesel, which is a more expensive fuel source. According to the size of their parcels, the owners divide the usage hours and just cover the cost of fuel. But they charge other farmers buy water from them a far higher price.

According to the availability of neighboring DTWs and the fuel type used, the farmers are to pay the owners Tk. 7200–8000 (USD 60–66.67) for every hectare of land. The cost is Tk. 1800–2000 (USD 15–16.67), per hour which is four–five times higher than what the BMDA or an NGO provided DTWs would charge. It demonstrates unequal payment for water use, with small and marginal farmers suffering the most.

Farmers' Water Usage Behavior in Response to Pricing

The Tobit regression model was employed to analyze the behavior of farmers regarding groundwater price response since data was censored. This analysis has morphed into an elucidation of how the pricing, sensitivity, socio-economic considerations, and farm characteristics affect farmers' water use in Barind Tract.

Summarized descriptive statistics regarding water usage and key independent variables are given in Table 2:

Table 2: water usage and key independent variables statistics

Variable	Mean	St. Deviation	Min	Max
Water Usage (m^3/ha)	70.25	25.80	0.00	150.00
Groundwater Price (BDT/m^3)	4.50	1.25	2.50	7.50
Farm Size (ha)	1.15	0.75	0.10	4.0
Income (BDT/year)	250000	100000	100000	700000
Technology Adoption (%)	12.50	32.00	0.00	1.00

Source: Author's preparation

Water use had an average of 70.25 m^3/ha and a standard deviation of 25.80, displaying differences in irrigation practices. Irrigation did not occur for 12% of respondents due to escalated water costs. Prices ranged from 2.50 to 7.50 BDT/m^3, with an average of 4.50 BDT/m^3, underscoring variation across localities. The adoption rate of technologies for water saving among the respondents was extremely low, only 12.5% having utilized technologies such as Alternate Wetting and Drying (AWD) and Drip Irrigation.

The impact of groundwater pricing and other factors on water usage. The results are summarized in Figure 3:

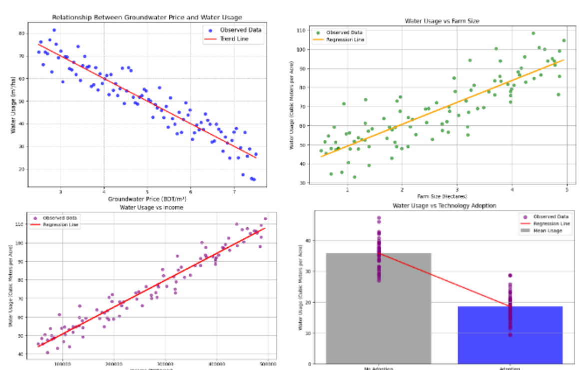


Figure 3: Relation between water usage and price, income, farm size, and technology adoption

Table 3: Tobit Regression Results on Factors Influencing Water Usage

Variable	Coefficient (β)	Standard Error	t-Statistic	p-Value
Groundwater Price (BDT/m³)	-0.85	0.20	-4.25	<0.001
Farm Size (ha)	12.50	3.00	4.17	<0.001
Income (BDT/year)	0.00015	0.00005	3.00	0.003
Technology Adoption	-15.75	6.25	-2.52	0.012
Constant	35.00	8.50	4.12	<0.001

Source: Author's preparation

The price coefficient ($\beta=-0.85$) was significant at whereas $p<0.001$. This denotes a strong and negative relationship between price and water usage. Each increase of 1 BDT/m³ in groundwater price translated into a reduction of 0.85 m³/ha of actual water usage. This finding strengthens the argument that raising groundwater prices brings down excessive use of water while encouraging conservationism for farming.

The positive farm size coefficient ($\beta=12.50$) as statistically significant ($p<0.001$), and the much larger farms utilized more water per hectare than smaller ones. For every additional hectare bought, water usage rose an average of about 12.50 m³/ha. Such results were expected because larger farms use more irrigation as a function of the scale effect, but inefficiencies in their usage must be emphasized.

The income coefficient ($\beta=0.00015$) was positive and was statistically significant at ($p=0.003$) which indicates that larger farmers tend to use more water because of high income. Each increase of 100,000 BDT in annual income would result in, on the average, an additional 15 m³/ha of water usage. Levels of income can make price sensitivity into a faulty deal; farmers may consume more water, even as prices increase.

Adoption of water-saving technologies was negatively related to water usage ($\beta=-15.75$, $p=0.012$) Application of technology such as AWD allowed it to conserve an average of 15.75 m³/ha of water. This indicates the way technology of this kind can assist in promoting water conservation, especially when combined with good pricing policies.

The constant term ($\beta=35.00$) was significant ($p<0.001$) which embodies the actual water usage of farmers with average characteristics if the values of the other factors are held constant.

Farmer's Preferences of Potential Pricing Strategy

The third objective was to evaluate farmers' preferences for and reacts to different groundwater pricing models: volumetric pricing, marginal cost pricing, tiered pricing, block pricing, and operational cost pricing. Data on preference were collected by means of a choice experiment, which were then analyzed using Latent Class Analysis (LCA) and multinomial logistic regression to locate key drivers of preferences.

Table 4: Farmers' responses to different pricing techniques

Pricing Model	Overall (%)	Total	Small (%)	Medium (%)	Large (%)
Volumetric	28	76	25	30	35
Marginal Cost	18	49	15	20	25
Tiered	32	87	40	35	25
Block	15	41	10	10	20
Operational Cost	7	20	10	5	15

Source: Author's preparation

Table 4 indicated that out of all the pricing models available to farmers, Tiered Pricing was the most common amongst 32%. This is perhaps because people consider it to be fair and straightforward. Volumetric Pricing was also favored, more so especially with medium scale and large scale farmers due to its transparency and correlation with the usage. The most disliked model was Operational Cost Pricing especially because it neither encourages conservation nor efficiently allocates costs.

LCA categorized farmers into different classes according to their responses. The three-class model was chosen based on the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC), as illustrated in Table 5:

Table 5: Farmers' categorization based on AIC and BIC

Model	AIC	BIC
1-Class	3450.12	3485.67
2-Class	3201.45	3248.29
3-Class	3100.32	3165.20
4-Class	3150.15	3225.38

Source: Author's preparation

The outcomes from the AIC and BIC analysis strongly point that the three-class model is the most specific for grouping the farmers in relation to the preference for various systems of groundwater pricing. This classification takes into account the difference in socio-economic behavioral attributes of the farming population and helps in better understanding the concerns and priorities of the farmers. The next table illustrates these three classes and their distinguishing dominant features which are very crucial in formulating fair and efficient groundwater pricing strategies.

Table 6: Distribution of Farmer Segments by Pricing Preferences

Class	**Segment Size (%)**	**Dominant Preference**	**Characteristics**
1	40	Tiered Pricing	Small-scale farmers; price-sensitive; equity-focused
2	35	Volumetric & Marginal Cost	Medium-scale farmers; efficiency-driven; conservationists
3	25	Block Pricing	Large-scale farmers; resource-intensive; income-resilient

Source: Author's preparation

The analysis of irrigation pricing model preference for farmers clearly suggested their firm segmentation (Table *6*). Equity and predictability were priority features for whatever smallholder they could have, thus favoring Tiered Pricing. Some median farmers sought cost-effective methods that would also favor conservation and, therefore, favored Volumetric and Marginal Cost Pricing. Large farmers, burdened with heavy irrigation requirements, emphasized flexibility, bringing them to opt instead for Block Pricing in order to both maximize the efficiency of water usage and reduce costs.

Table 7: Correlation between Key Variables and Pricing Preferences

Variable	**Volumetric**	**Marginal Cost**	**Tiered**	**Block**	**Operational Cost**
Farm Size (ha)	0.45 (p=0.01)	0.40 (p=0.02)	-0.20 (p=0.05)	0.75 (p=0.01)	-0.10 (p=0.10)
Income (BDT/year)	0.30 (p=0.01)	0.15 (p=0.05)	-0.25 (p=0.02)	0.50 (p=0.01)	-0.20 (p=0.10)
Education (years)	0.35 (p=0.01)	0.20 (p=0.05)	0.15 (p=0.05)	-0.10 (p=0.10)	0.10 (p=0.15)
Access to Water-Saving Tech	0.50 (p=0.01)	0.45 (p=0.01)	-0.10 (p=0.10)	-0.15 (p=0.10)	-0.50 (p=0.01)

Source: Author's preparation

The study also discloses the effects of selected factors on pricing preferences of farmers; namely, farm size, income, education and adoption of water-saving technologies (Table 7). Larger and high-income farmers favored block and volumetric pricing models due to their high water demands and flexibility requirements. Lower-income farmers may have considered tiered pricing favorable due to its predictability. The increase in education levels was associated with the choice of conservation-oriented models such as volumetric and marginal cost pricing. Moreover, farmers utilizing water-saving technologies were more likely to favor volumetric-style and marginal cost pricing models since they kept in line with conservation efforts.

A balanced approach to water pricing has been recommended in the study. Tiered pricing, being ideal, is not fully able to promote conservation. Volumetric and marginal cost pricing being efficient do incur vast infrastructure and monitoring costs. Block pricing, generally appropriate for big farms, can suffer from over-extraction if not very careful in its regulation. The imperfect nature of operational cost pricing has therefore further prompted the need for reform. Context-specific institutional innovations can strengthen implementation efficiency significantly. It, thus, becomes indispensable for policymakers to figure out some hybrid models combining some aspects of tiered pricing with the volumetric price to promote sustainable and equitable groundwater management in the Barind Tract.

4. Conclusion

This research assessed groundwater use and pricing among farmers in the Barind Tract, Bangladesh, identifying issues such as groundwater depletion, inequitable pricing, and unsustainable extraction. The study found that high irrigation water prices promote conservation through reduced consumption, but current pricing schemes, especially those controlled by private tube well owners, disproportionately affect small and marginal farmers. Among the pricing models evaluated, tiered pricing was favored by smallholders for its fairness, while larger and conservation-oriented farmers preferred volumetric and marginal cost pricing for efficiency.

A hybrid pricing model combining tiered and volumetric features is recommended to balance equity and sustainability. Investments in infrastructure, such as advanced water metering systems, are essential to ensure the pricing scheme's viability and enable better monitoring and enforcement. Offering incentives or subsidies for water-saving technologies like AWD could further reduce water use without harming productivity. Educational initiatives are also necessary to raise awareness among farmers about the environmental and economic benefits of sustainable groundwater management.

Regulatory reforms are needed to address gender inequalities and ensure fair access to groundwater resources. Improved governance structures will help prevent exploitative practices by tube well owners. Further research should explore the evolution of hybrid pricing models, aligned with the socioeconomic realities of the Barind Tract, and assess their long-term impact on agricultural productivity and groundwater sustainability. Integrating gender-sensitive data systems and community participation mechanisms could foster inclusive decision-making and enhance adaptive groundwater management outcomes.

This study is limited by its cross-sectional design, which prevents assessing long-term impacts of pricing changes. Additionally, the low adoption rate of water-saving technologies like AWD among farmers requires further investigation into the barriers to technology uptake.

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