Contracting for Groundwater Irrigation: A Principal-Agent Based Approach to Determining Contract Effectiveness

Jeffrey D. Michler
Dept. of Agricultural Economics
Purdue University
West Lafayette, IN
jmichler@purdue.edu

Steven Wu
Dept. of Agricultural Economics
Purdue University
West Lafayette, IN
sywu@purdue.edu

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1 Introduction

In this study we examine the demand for and supply of groundwater for rice irrigation in rural Bangladeshi villages. We use relational contract theory to investigate groundwater market structure and contract design in Bangladesh. By modifying a model by Dixit (2004) we can integrate stylized observations from the field. This model generates useful comparative statics predictions for conducting empirical analyses of ground water contracting. Our research focuses on how exogenous variations in expectations of the future, accuracy of performance measures, and enforcement (both self- and village level enforcement) affect contract structure.

The use of modern varieties of seed now accounts for seventy-five percent of cultivated land and this growth is supported by irrigation of two-thirds of cultivated land (Hossain, 2009). The rapid growth of irrigation has allowed farmers to expand cultivation from two to three seasons a year. The *Boro*, or dry season, rice cultivation now accounts for fifty-six percent of total rice production compared to just nine percent in 1966-7 (Hossain, 2009). Irrigation's role in increasing Bangladesh's food security is widely acknowledged (Shah, 1993; Adnan, 1999; Palmer-Jones, 2002; Mukherji, 2004; Rahman and Parvin, 2009).

However, economists still seek to understand how such a rapid transformation occurred. Groundwater markets are primarily informal, unregulated, and spontaneous. Prices as well as contracts are not uniform across villages. While the emergence of groundwater markets has played a major role in the agricultural development of Bangladesh, economists still disagree on how these markets formed, how they operate, and what will be their long-term impacts on the social welfare of the nation. As Mukherji (2004) noted, "there has so far been no attempt at formulating a general theory of groundwater markets. Thus, the current mode of functioning of groundwater market still leaves a lot of unanswered questions such as 'why do several modes of water contracts coexist under seemingly similar conditions and why do they respond differently to similar sets of incentives and disincentives?' " We hope the research contributes to filling this gap.

2 The Market for Groundwater

In his seminal study, Shah (1993) describes the groundwater market in South Asia as oligopolistic. Capital costs and the physical environment make the case for considering tubewells as natural monopolies. While STWs can be powered by either diesel or electricity, most pumps in Bangladesh are electric. This is because electricity is subsidized, resulting in lower operating costs compared to diesel pumps. Shah (1993) finds that pumping costs tend to be uniform across villages while prices for water delivery vary widely. Waterless farmers engage well owners to provide sufficient water to allow for successful crop cultivation. These water buyers primarily judge well owner performance on two metrics: adequacy and reliability. Adequacy is getting the desired volume of water and reliability is getting water when it is desired.

In his research, Shah (1993) distinguished six types of contracts which to date cover all the types of contracts observed in the literature on groundwater markets.[1]

1. **Fixed charge** - A onetime fee paid at the beginning of the growing season for delivery throughout the season.
2. **Labor charge** - The water buyer provides labor and draft power to the seller throughout the growing season as payment for water. The exchange rate for hours of labor and water is agreed to at the beginning of the season.
3. **Piece rate** - Payment of a fee per application per acre at the conclusion of each application.
4. **Output share** - A onetime fee paid, usually in kind, at the end of the growing season at a rate fixed at the beginning of the growing season.

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[1] Our terminology differs slightly from Shah's. we have attempted to be more explicit as well as bridge the nomenclature of Shah and that in more recent studies like Kajisa and Sakurai (2003, 2005).

5. **Input share** - The same as output share, except that the cost of inputs are shared, at the time of purchase, between contracting parties at a fixed rate determined at the beginning of the growing season.
6. **Fixed rent** - A onetime fee paid to the waterless at the beginning of the growing season for the use of the land by the water seller.

While not all contracts will be observed in a single village, a menu of contracts is almost always available in any given village.

In addition to allowing for all six types of contracts, a comprehensive model of groundwater contracts must account for several stylized facts. First, recall that the task of well owners (providing sufficient water) is multidimensional, consisting of both the adequate and the reliable delivery of water. Farm output is a function of both of these tasks while well owners find both tasks costly. To date, studies of groundwater markets have only acknowledge the multidimensionality of water provision (Shah, 1993) without discussing its implications. A second stylized fact is that parties continue to enter into contracts despite the absence of government institutions to enforce contracts. This phenomenon of contract enforcement in the shadow of the law has been explicitly accounted for in models of land tenure contracts (Hayami and Otsuka, 1993) but only observed and briefly discussed in studies of groundwater markets (Palmer-Jones, 2002).

Recent research has usied the language of contract theory to motivate descriptive empirical analysis of groundwater markets. Examples include bilateral bargaining models (Kajisa and Sakurai, 2003), relational contracting (Kajisa and Sakurai, 2005), and enforcement by social institutions in the shadow of a formal legal system (Rahman et al., 2011). Although principal-agent terminology is used in these studies, few have developed econometric tests based on the comparative static results generated by principal-agent models. So far, Banerji et al. (2012) is the only study to actually attempt at modeling the behavior of buyers and sellers in the marketplace. Yet Banerji et al.'s work is narrowly focused on a rare contract type. Their model seeks to explain behavior in villages where the price of water is set by a council of village elders. This situation is uncommon in South Asia and unobserved in Bangladesh.

To date no one has replicated Hayami and Otsuka's (1993) work on land tenure contracts by developing an explicit model for groundwater contracts. We attempt to accomplish this by using relational contract theory to help understand contract choice and enforcement issues. By better understanding why certain types of contracts are adopted and how contracts are enforced, we hope to provide a clearer picture of the current market structure. Furthermore, by adapting previously developed models to the specifics of the market for groundwater, we hope to provide generalizable comparative static results that can direct future empirical work. We test these comparative static results using a recently collected data set on groundwater irrigation practices in Bangladesh.

3 Theoretical Framework

Reviewing the literature on groundwater markets, a curious occurrence repeats itself – the inversion of the role of principal and agent. While the principal-agent model is often referenced in the groundwater market literature, rarely is a model ever explicitly developed. With what appears to be no reflection regarding possible implications, the water buyer has been cast as the agent while the water seller has been cast as the principal. This inversion appears to have started with early studies focused on issues of power and taken its vocabulary from work on land tenure contracts (Wood and Palmer-Jones, 1991; Palmer-Jones, 2002). These studies identified the water seller, sometimes referred to as the "waterlord," as the principle and the waterless farmer as the agent. Subsequent approaches have maintained this identification without comment. In cases where principal and agent are homogeneous or where bargaining power is explicitly accounted for, the reversal of roles should not matter. However, when considering cases of enforceability, performance measure, and heterogeneous agents, these distinctions can play an important role determining comparative static results.

While identifying the "waterlord" with the principle is an understandable, and maybe even an attractive, approach, it does not conform to the traditional conception of the principal-agent model. Regardless of who proposes the contract, the principal should be identified with the party that pays a fee for a service while the agent is the party that provides the service for a fee. Thus, in groundwater markets, the principal is not the water seller but the water buyer who tenders payment in return for a service. The agent is the water seller who provides the service. Parties contract over the provisioning of sufficient water, which depends on the water seller's effort. Sufficient water is measured by the adequacy and reliability of water provisioning.

3.1 The Agent: The Water Seller

To account for the multiple dimensions of the water seller's task and the absence of legal enforcement, we follow the model developed by Dixit (2004). The water seller undertakes several actions represented by the n-dimensional vector $\mathbf{a}$. This vector includes the agent's actions in delivering adequate and reliable water. The water seller incurs a personal cost $c(\mathbf{a}) = 1/2\mathbf{a}'\mathbf{a}$.

The agent's actions contribute to the outcome y for the principal. In contracting with the agent, the principal is solely interested in the delivery of sufficient water. Therefore, y can only take two values. If the agent delivers sufficient water, $y = 1$. If the agent fails to deliver sufficient water, $y = 0$. The probability of success is

$$\Pr(y = 1|\mathbf{a}) = \mathbf{y}'\mathbf{a} \tag{1}$$

where $\mathbf{y}$ is an n-dimensional vector of the marginal products of agent action with respect to the outcome. Following Dixit (2004), along with Baker et al. (2002), we assume all parameters are such that probabilities fall in the requisite range $(0, 1)$.

The outcome y is internal, meaning it is only observable by the contracting parties and this is common knowledge. Each water buyer (principal) determines his own level of sufficient water based on plot size, seed type, fertilizer use, pesticide use, etc. For a moment, assume a water buyer determines that sufficient water for his plot is y_s. The water buyer and water seller can contract on that level of delivered water. However, such a contract must be informal, meaning it is unenforceable. This is because it is costly for an outside third party to gather all the relevant information to determine what really is sufficient water for a given plot. A water seller could deliver y_s, as agreed, but the water buyer could claim the contract was actually for $\overline{y}_s > y_s$. Since a third party cannot accurately determine y_s for the plot in question that third party cannot rule in a dispute over y.

Similarly, since sufficient water is based on adequate and reliable applications of water throughout the growing season, it is impossible for a third party to determine *ex post* if sufficient water was actually delivered. A water seller could deliver $\underline{y}_s < y_s$ while claiming to have delivered y_s. Since a third party cannot accurately determine if y_s was delivered that third party cannot rule in a dispute on y.

Despite the inability to create a formal contract on y, an external and publicly verifiable performance measure x does exist. In the case of groundwater contracts, this publicly verifiable signal is crop output. While y took a binary value, x can be normalized to take a value between 0 and 1 such that

$$x = \mathbf{x}'\mathbf{a} + u \tag{2}$$

where $\mathbf{x}$ is an n-dimensional vector of the marginal product of action with respect to the performance measure and u is a normally distributed noise term.

The agent's compensation package is based on three components. An unconditional and enforceable salary S, an objective and enforceable bonus ξ, and a subjective and self-enforcing bonus η paid if $y = 1$. we call a contract on y the water contract and a contract on x the crop contract. Such a compensation scheme allows us to represent all six contract types observed by Shah (1993).

1. **Fixed charge** $\eta = 0$, $\xi = 0$, $S > 0$.
2. **Labor charge** $0 < \eta < 1$, $\xi = 0$, $S > 0$.
3. **Piece rate** $0 < \eta < 1$, $\xi = 0$, $S = 0$.
4. **Output share** $\eta = 0$, $0 < \xi < 1$, $S = 0$.
5. **Input share** $\eta = 0$, $0 < \xi < 1$, $S < 0$.
6. **Fixed rent** $\eta = 0$, $\xi = 1$, $S < 0$.

Interpretation of the fixed charge, output share, and fixed rent contracts is intuitive. The remaining three contracts require some comment. For the piece rate contract, Stiglitz (1975) shows that it is formally the same as the output share contract. In the case of groundwater, the rate is based on sufficient water delivery and not on crop output. For the input share contract, Hayami and Otsuka (1993) show that any sharing of input costs can be represented as a *de facto* production loan and therefore can be included in the fixed payment term. In our case, as opposed to the land tenure case, the water selling agent is providing input loans to the water buying principal. Finally, the labor charge contract is what the land tenure literature refers to as the input share contract. This is because the water buying principal provides inputs to assist the water selling agent in his own production. Again, these input provisions can be viewed as *de facto* loans and therefore modeled in the current framework. The difference between labor charge and input share contracts is not only the direction of the *de facto* loan but what signal the bonus is paid on. In the labor charge contract, the principal exchanges labor for water intra-seasonally. In the input share contract the agent is repaid his loans at harvest time with a share of the crop output.

The seller maximizes his expected payoff

$$\max_{\mathbf{a}} U = S + \xi \mathbf{x}'\mathbf{a} + \eta \mathbf{y}'\mathbf{a} - 1/2\mathbf{a}'\mathbf{a} \tag{3}$$

Solving for the optimal action level gives

$$\mathbf{a}^* = \xi \mathbf{x} + \eta \mathbf{y} \tag{4}$$

Substituting the optimal action level back into the agent's objective function yields

$$U = S + \xi \mathbf{x}'(\xi \mathbf{x} + \eta \mathbf{y}) + \eta \mathbf{y}'(\xi \mathbf{x} + \eta \mathbf{y}) - 1/2(\xi \mathbf{x} + \eta \mathbf{y})'(\xi \mathbf{x} + \eta \mathbf{y}) \tag{5}$$

which simplifies to

$$U = S + 1/2(\mathbf{x}'\mathbf{x}\,\xi^2 + 2\mathbf{x}'\mathbf{y}\,\xi\eta + \mathbf{y}'\mathbf{y}\,\eta^2) \tag{6}$$

Following Dixit (2004) we can simplify notation by choosing units such that $\mathbf{x}'\mathbf{x} = 1 = \mathbf{y}'\mathbf{y}$ and $k = \mathbf{x}'\mathbf{y}$. Geometrically, k is the cosine of the angle between vectors $\mathbf{x}$ and $\mathbf{y}$. By the Cauchy-Schwarz inequality $k^2 \leq 1$. Economically, k is the correlation between the marginal effects of $\mathbf{a}$ on x and y, and therefore is a measure of the accuracy of signal x in revealing y.

The agent's maximized utility is

$$U = S + 1/2(\xi^2 + 2k\xi\eta + \eta^2) \tag{7}$$

making the agent's participation constraint

$$S \geq u_0 - 1/2(\xi^2 + 2k\xi\eta + \eta^2) \tag{8}$$

which we assume the principal satisfies with equality.

3.2 The Principal: The Water Buyer

Adapting Dixit (2004) slightly, the benefit to the water buyer is

$$V = \mathbf{y}'\mathbf{a} - (S + \xi\mathbf{x}'\mathbf{a} + \eta\mathbf{y}'\mathbf{a}) - v_0 \tag{9}$$

where V is the value of sufficient water to the water buyer and all other terms are as previously defined and v_0 is the water buyer's outside option. Note that the value to the principal accrues from the sufficient delivery of water and not from rice output. Rice production requires numerous other inputs that are exogenous to the relationship between the water buyer and water seller. If one were to examine the production function for rice, equation (9) would be a factor input equation in that production function.

Substituting the agent's participation constraint, equation (8), into the principals payoff function and simplifying yields,

$$\max_{(\xi,\eta)} V(\xi,\eta) = (k\xi + \eta) - 1/2(\xi^2 + 2k\xi\eta + \eta^2) - u_0 - v_0 \tag{10}$$

For the use of the subjective bonus (η) to be self-enforcing it must be the case that the value to the principal from the water contract exceeds the payoff from the crop contract based on the observable outcome (x). This means the principal must solve the following problem:

$$\max_{(\xi,\eta)} \; V(\xi,\eta) = (k\xi + \eta) - 1/2(\xi^2 + 2k\xi\eta + \eta^2) - u_0 - v_0 \tag{11}$$

$$\text{s.t.} \; V(\xi,\eta) - r\eta - V^{\text{CRP}} \geq 0 \tag{12}$$

where Equation (12) is the water buyer's self enforcement constraint, which must be satisfied to keep him from defecting on payment of the subjective bonus. V^{CRP} is the payoff from the externally verifiable crop contract based solely on a salary S and an objective share payment

ξ.[2] r is the discount rate of the principal. Since the agent's participation constraint holds with equality, the principal gets all of the surplus from the relationship.

3.3 Solutions to the Contracting Problem

Given that Dixit (2004) has worked out a variation of the problem stated in equations (11) and (12) we simply state the results here. The FOCs from the model are

$$k - \xi - k\eta = 0 \tag{13a}$$

$$1 - k\xi - \eta - \mu r = 0 \tag{13b}$$

which yields

$$\xi = \mu r k/(1 - k^2) \tag{14a}$$

$$\eta = (1 - k^2 - \mu r)/(1 - k^2) \tag{14b}$$

where $\mu = \lambda/(1 + \lambda)$ and λ is the Lagrangian multiplier. Assuming for the time being that the agent's self enforcement constraint is aways satisfied, this gives three potential solutions.

The first best is when the purely relational or water contract is self-enforcing. This occurs when $\mu = 0$ meaning the principal's self enforcement constraint (12) is non-binding. In this case $\xi = 0$ and $\eta = 1$. The water buyer forgoes use of the enforceable crop contract for exclusive use of the unenforceable water contract. This is the first best because both parties

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[2] Dixit (2004) uses slightly confused notation and we have tried to rationalize it. He uses both the terms formal and external to signify the purely formal contract, what we have called the crop contract. Yet he also refers to external options that each party defaults to in the case of the agent's participation constraint remaining unmet. Since we are particularly interested in how these outside options affect contracts we use crop (CRP) for the formal, enforceable contract and reserve the term v_0 to exclusively signify external or default payoffs that come into play if parties defect.

care about water delivery and are able to contract on that basis. There is no need to use a noisy signal, such as crop output. Such contracts include fixed charge, labor charge, and piece rate contracts.

The purely enforceable or crop contract is used when $\mu = 1$ and $r \geq 1 - k^2$ meaning the principal's self enforcement constraint is binding and the accuracy of the signal k is relatively strong. In this case $\xi = k$ and $\eta = 0$. The water buyer forgoes use of the unenforceable water contract for exclusive use of the enforceable crop contract. This is for one of two reasons. Either the water seller's outside option is attractive enough that the seller is relatively willing to defect on any relational contract and/or the signal k is relatively strong enough that x is not too noisy of an indicator of y. Such a contract would be the fixed rent contract where the water buyer simply rents his land to the water seller.

The second best contract is a mix of both enforceable and unenforceable payments. For this to occur it must be true that $0 < \mu < 1$ and $r < 1 - k^2 < 2$. If this is the case

$$\xi = k(2r + k^2 - 1)/(1 - k^2) \tag{15a}$$

$$\eta = 2(1 - k^2 - r)/(1 - k^2) \tag{15b}$$

The relative weight of ξ and η in the second best contract depends on the discount rate r and the accuracy of the signal k. ξ is increasing in r and k while η is decreasing in r and k. Thus, as the discount rate increases (the future becomes less important) and/or as the accuracy of the signal k increases the formal contract becomes more attractive. On the other hand, as the discount rate decreases (the future becomes more important) and/or as the signal k becomes less accurate the first best, purely relational, contract becomes more attractive.

3.4 Comparative Static Results

We examine three comparative static predictions from the solution to the contracting model. The first is how η and ξ change as the discount rate (r) changes. Taking derivatives of equations (14a) and (14b) with respect to r gives

$$\frac{\partial \xi}{\partial r} = \frac{\mu k}{(1-k^2)} \tag{16a}$$

$$\frac{\partial \eta}{\partial r} = -\frac{\mu}{(1-k^2)} \tag{16b}$$

ξ is positively related to r while η is negatively related to r. These relations are robust across all types of contracts (i.e., values of μ).

Taking the derivatives of equations (14a) and (14b) with respect to k gives

$$\frac{\partial \xi}{\partial k} = \frac{\mu r(k^2+1)}{(1-k^2)} \tag{17a}$$

$$\frac{\partial \eta}{\partial k} = -\frac{2\mu r k}{(1-k^2)} \tag{17b}$$

The relationship between k and ξ is unambiguous. ξ is at a minimum when $k = 0$. This corresponds to intuition. When k is a very noisy signal (i.e., $k = 0$) the use of x as a performance measure is very inaccurate. All else being equal, contracting parties will prefer not to use ξ when k is near zero.

The relationship between k and η is also unambiguous but it requires more exposition. As $k \rightarrow 1$, $\eta \rightarrow \infty$, and as $k \rightarrow -1$, $\eta \rightarrow -\infty$. At first this seems to contradict the economic intuition that water contracts on y become more likely as the accuracy of x worsens ($k \rightarrow 0$). But, k can be either a signal of good work ($k > 0$) or a signal of bad work ($k < 0$). What matters is not the sign of k but the strength of k. When k is replaced with its absolute value, η is at a maximum when k is at a minimum. Thus, economic intuition is supported by the comparative static analysis. All else being equal, contracting parties will prefer to use η when k is near zero.

A third comparative static result exists regarding how contracts change as the severity of village enacted punishment increases. This third result follows directly from examination of equations (11) and (12) and requires no mathematical exposition. In the shadow of the law, rural villages often develop their own community wide mechanisms for punishment. This punishment can affect the outside options of both principal (v_0) and agent (u_0). When one party defects on an enforceable crop contract that party becomes subject to village level punishment. As the severity of the punishment increases (i.e. v_0 or u_0 decreases), the larger becomes the payoff from V^{CRP}. A larger payoff to the principal on the enforceable crop contract tightens the self enforcement constraint (12), making the unenforceable water contract less likely.

3.5 Testable Hypotheses

This brief exposition provides three important comparative static results: 1) how contracts change as discount rates change, 2) how contracts change as the accuracy of signal k changes, and 3) how contracts change as the severity of village enacted punishment changes.

- **H1**: Purely relational (water) contracts are more likely when discount rates are low (future is relatively important) while purely enforceable (crop) contracts are more likely when discount rates are high (future is relatively unimportant).

- **H2**: Purely relational (water) contracts are more likely when k is close to 0 (x is weakly related to y) while purely enforceable (crop) contracts are more likely when $|k|$ is close to 1 (x is strongly related to y).

- **H3**: Purely relational (water) contracts are more likely when the severity of village enforced punishment decreases while purely formal (crop) contracts are more likely when the severity of village enforced punishment increases.

4 Survey Data

Our analysis utilizes recently collected household and village level survey data from rural Bangladesh. 960 households from 96 villages were surveyed during the 2013 *Boro* season (January-June). Households were randomly selected while villages were selected using a stratified random sampling method to ensure a representative sample of *Boro* rice agriculture in Bangladesh. To our knowledge, this is the first survey specifically designed to gather data on groundwater irrigation practices and contracts in South Asia.

Households were asked a range of baseline questions regarding income, land and asset ownership, and agricultural productivity. Since the survey was specifically designed to study groundwater contracting, it provides us with detailed information on contract history, availability, choice, and price. We also collected data on household experience with or perceptions of enforcement and punishment mechanisms. Since not every household will have experience of contract violation, a series of village level surveys were also conducted to determine village level enforcement and punishment mechanisms.

5 Empirical Strategy

Our empirical analysis attempts to test the significance of potential determinants of groundwater contract choice. To simplify analysis, we combine first and second best contracts together into the group called water contracts. This is because the second best contract relies, in part, on the unenforceable payment η. The crop contract is distinct from the other two types of contract because it is completely enforceable. For estimation we use the standard probit model of the form

$$\Pr(y_i = 1|\mathbf{X}_i) = \Phi(\mathbf{X}_i'\beta_i) \tag{18}$$

where y_i is the type of contract chosen, Φ is the standard normal c.d.f., $\mathbf{X}$ is a matrix of independent variables, and β is a vector of coefficients. The matrix $\mathbf{X}$ includes measures of k, r, and punishment (*PNSH*), along with variables for the standard idiosyncratic household characteristics.

Empirically testing the hypotheses stated in Section 3.5 requires writing out the estimation equation.

$$\Pr(\text{WTR } = 1|\mathbf{X}) = \Phi(\beta_0 + \beta_1 r + \beta_2 k + \beta_3 PNSH + \delta_1 \text{SZ} + \delta_2 \text{BZ}) \tag{19}$$

Terms are as previously defined with SZ and BZ being vectors of seller and buyer characteristics, respectively, and the δ's being the related coefficients. we can use the following tests for support of the previously stated hypotheses.

- **H1: discount rate** - The null hypothesis that discount rates do not affect contract choice is

  $$\mathbf{H1}_0 : \beta_1 = 0 \tag{20}$$

  Rejection of the null supports our hypothesis that different levels of the discount rate contributes to the adoption of different types of contracts. However, the theory says more. The comparative static results say that the water contract is less likely under high discount rates. So, $\beta_1 < 0$ supports the comparative static result.

- **H2: strength of signal** - The null hypothesis that the accuracy of the signal k does not affect contract choice is

  $$\mathbf{H2}_0 : \beta_2 = 0 \tag{21}$$

  Rejection of the null supports our hypothesis that differences in signal accuracy play a significant role in determining the type of contract chosen. Similar to H1, the theory says more than just “different levels of k matter.” A value of k near 0 is more likely to be associated with the water contract while $|k|$ closer to 1 is more likely to be associated with the crop contract. A $\beta_2 < 0$ supports the comparative static result.

- **H3: punishment** - The null hypothesis that the severity of punishment does not affect contract choice is

  $$\mathbf{H3}_0 : \beta_3 = 0 \tag{22}$$

  Rejection of the null supports our hypothesis that the severity of the punishment matters in contract choice. As with the previous two hypotheses, the comparative statics predict a certain sign for the parameter. As severity increases, the enforceable crop contract becomes more likely and the unenforceable water contract becomes less likely. Thus, $\beta_3 < 0$ supports the comparative static result.

6 Conclusion

Survey work in Bangladesh concluded the final week of May and data analysis is ongoing. Preliminary results support all three of our hypotheses. However, these results are based on a truncated data set. Any conclusions must be refrained until a full analysis of the data set is completed in the upcoming month.

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