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Valuing certainty in a consensus-based water allocation mechanism

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[1] We present an interdisciplinary approach to attach economic value to model certainty. The central theme of this paper concerns valuing certainty in water resource management, specifically resource allocation. A conceptual framework is developed to study (1) a hypothetical scenario of three water users attempting to mutually agree on allocation of some fixed amount of water amongst themselves and (2) California water policy negotiations along the lines of Adams et al. (1996). We attempt to answer how uncertainty in a policy variable affects the "allocation solution" in such consensus-based decision-making processes. This study finally evolves into economic valuation of uncertainty reduction and willingness to pay for the same.

1. Introduction

[2] Efficient use of water resources is becoming increasingly important. Globally, many researchers have expressed concerns over depleting freshwater sources or accumulating demands [*Israel et al.*, 1994; *Whittington and McClelland*, 1992; *Parros*, 1999; *Utton*, 1996; *Rogers*, 1993; *Giannias and Lekakis*, 1997] and have called for a cooperation-based framework to ameliorate conflicts. Water is often a scarce and precious resource in semiarid regions [*Tarboton*, 1995; *Supalla*, 2000]. Even when this is the case, water is often allocated economically inefficiently under the doctrine of "appropriative" rights [*Burness and Quirk*, 1979]. Optimal apportionment would follow if the marginal benefit realized by using a certain amount of resource is equal to its marginal value [*Lyon*, 1999]. However, such a rule might be difficult to impose when users are uncertain about the available stock of water resource. It therefore brings forth two specific but interconnected issues: uncertainty in the amount of water to be apportioned, and how this uncertainty influences an otherwise efficient allocation amongst competing users. We therefore focus on how a consensus mechanism is influenced by uncertainty and on the value of reducing uncertainty based on consensus building.

[3] Though an allocation mechanism should be designed to address the problem at hand [*Hurwicz*, 1973], many authors have discussed the applicability of different allocation mechanisms in various water resources management problems. Examples include cost allocation to accommodate environmental externalities [*Frisvold and Caswell*, 2000; *Loehman and Dinar*, 1994; *Dinar and Xepapadaes*, 2002; *Dinar and Howitt*, 1997], cost allocation of multiagency water treatment projects [*Dinar et al.*, 1992; *Lejano and Davos*, 1999], water diversions from the Great Lakes

[*Becker and Easter*, 1995, 1997], etc. While some of these applications included allocation mechanisms based on the social planner problem or dynamic games, cooperative game theory appeared to be a more popular allocation mechanism. However, few researchers have dealt with the effect of uncertainty in policy variables on allocation solutions.

[4] The two most common solutions employed from cooperative game theory are the nucleolus solution [*Schmeidler*, 1969] and the Nash-Harsanyi solution [*Harsanyi*, 1963]. The nucleolus concept provides an equitable solution to the core allocation problem. Given a set of players, the core of the game identifies a solution set that all the players should be willing to accept. While the nucleolus solution is more social equity based [*Lejano and Davos*, 1995], the Nash solution is cooperation to achieve efficiency in allocation [*Nash*, 1953]. Furthermore, empirical tests on the acceptability and stability of various solution concepts to cooperative allocation of environmental control cost [*Dinar and Howitt*, 1997] suggest that the Nash-Harsanyi solution is more stable than the nucleolus when both the solutions were considered acceptable in the sense that solution lies in the core of the game.

[5] The choice of solution concept that is selected here for our case studies depends not just on stability or efficiency issues but also on an explicit framework to accommodate consensus building. We base our analysis of the allocation mechanism on the Rausser-Simon multilateral bargaining model [*Adams et al.*, 1996]. It is an extension of Rubinstein's model [*Rubinstein*, 1982] in which two players take turns in proposing a division of a pie. However, on the basis of the treatment of *Binmore et al.* [1986], it can be shown that the Rausser-Simon model provides a solution similar to the Nash-Harsanyi bargaining solution. The solutions achieved from these approaches are exactly the same when all the players in the game have the same bargaining power. Given that the bargaining solution is Pareto efficient, any solution that is perturbed due to the presence of uncertainty provides an incentive to reduce such uncertainty. We show this in our case studies and derive an economic value for reduction in uncertainty.

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[6] The major contribution of this paper is twofold. First, it studies how uncertainty due to physical processes can be accommodated in a consensus-based decision-making (CBDM) process. Such uncertainties are incorporated through a collection of a player's decision sets (a decision set of a player is defined as a set that contains his "potential" choices), where a collection corresponds to different states of his belief of the underlying processes. The agent then bases his decision via expected utility maximization. Second, the use of a multilateral bargaining model allows for a conceptualization of individual player's behavior in a sequence of subdecisions to finally arrive at a solution that is acceptable to all other players. This conceptualization allows a modeler or a policy maker to picture how uncertainty due to physical processes affects the final solution of a CBDM process via effects on the players involved.

[7] The following section sheds light on the importance of consensus building in decision making and discusses the multilateral bargaining model. Section 3 presents the implementation of the model to a hypothetical case study wherein three farmers negotiate for a share of some surplus amount of water under conditions of uncertainty. Our emphasis is placed on the value of certainty in benefits due to conveyance loss conditions. Section 4 examines another case study based on California water policy negotiations. Here, we analyze how the bargaining solution shifts when all the negotiating parties face uncertainty in a policy variable. Section 5 discusses the applicability of the model in policy making, its strengths and weaknesses. The paper concludes with observations on how the bargaining solutions under conditions of uncertainty distort the preference structure of players and results in a net willingness to pay for a reduction in uncertainty.

2. Multilateral Bargaining Model

[8] In a conflict model of decision making, the strongest player (legally, politically or otherwise) takes as much of an available surplus of water as he or she desires, leaving other players with little or no water. This form of social inequity has been a topic of debate in the environmental movement strategy literature [*Pellow*, 1999]. CBDM provides a new definition of power sharing and policymaking in which all interested parties are given a place at the negotiating table. The framework provides for a sustained negotiation process in which the parties look for cooperative solutions to issues common to them. While conflict cannot be entirely avoided, the attempt to reach consensus, rather than setting negotiations in a winner-take-all framework, can sometimes allow for significant gains for all parties involved.

[9] Before consensus-based decision making can be employed, appropriate legal measures must be in place. As noted by *Lejano and Davos* [1995] and *Adams et al.* [1996], there is often a long bargaining period over the bargaining rules before the substantive bargaining begins. In this paper, we assume that such rules of negotiations have been set a priori. This is reflected in the parameters assumed in the examples we present, as well as the assumed allocation mechanisms that will be followed if the bargaining fails.

2.1. Model Specification and Convergence

[10] We employ the Rausser-Simon [*Rausser and Simon*, 1991] multilateral bargaining approach to model such a CBDM process. The specification of the multilateral bargaining problem includes a finite number of profit-maximizing players, $\{P_1, P_2, \ldots, P_1\}$, who bargain to select a policy vector from some set of possible alternatives, $\aleph$. The set $\aleph$ is assumed to be compact in $\Re^N$. A policy vector $\mathbf{x} \in \aleph$ yields the ith player a payoff of $\pi_i(\mathbf{x})$ (or $u_i(\mathbf{x})$). The incentive for the ith player not to disagree is defined by a disagreement payoff, π_i^o (or u_i^o) (i.e., the payoff the ith player would realize if the negotiations fail). Players obtain ideal payoffs if, individually, they experience no water scarcity. All the players want to achieve payoffs that are as close to their ideal points as possible. It is further assumed that decisions are reached by unanimity under the CBDM framework. That is, all parties must agree to an allocation before it is implemented.

[11] The structure of the Rausser-Simon bargaining model is replicated by first identifying disagreement and ideal payoff points of all the players in the policy space. Then a bargaining game is defined such that all the players want to achieve an agreement unanimously but they have to do so by making proposals in turns. A cycle of proposals is then defined as one round-robin round.

[12] In the context of consensus building, we define "expected" payoff of a player as what he can realize after a cycle of proposals. It is expressed as a weighted sum of payoffs in a cycle of proposals, where the weights represent individual bargaining power. All other players therefore enforce a part of a player's "expected" payoff via their last proposal and emphasize it by their bargaining power. If any consensus is to be built, a player has to accept that a part of his "expected" payoff is being enforced by other players (otherwise he is not considering the wishes of other players). Also, other players have to accept his "expected" payoff as what he will at least accept from future rounds of proposals (if they want their wishes to be considered by this player). These acceptance conditions on "expected" payoffs are therefore important elements of consensus building and cooperation. If we assume that players are rational, they might not want to disagree with such conditions. This is most likely when they face serious consequences if the negotiations fail. In other cases, extra legal instruments can be brought into the game to ensure that these conditions are followed, say by penalizing the players guilty of disobeying the rules. The players can also agree upon such "parameters" and penalties within some legal framework before the start of bargaining.

[13] Therefore if we say that a bargaining game is consensus based, a player in his turn makes a proposal that yields payoffs (from this proposal) to other players that are no less than the "expected" payoffs that they can obtain from the last cycle of proposals. Otherwise some nonproposing player objects to such a proposal and the negotiations break. Note that the game is deterministic once the bargaining weights have been fixed. Each player, in his turn, makes a proposal that gets him the most favorable deal while making sure that other players get at least as much as their "expected" payoffs from the previous cycle of proposals. Thus a player in his first opportunity proposes as close to his ideal point as possible while making sure that others do not fall below their disagreement payoffs. This holds for other players too. The "expected" payoffs of all the players can then be defined as a weighted sum of
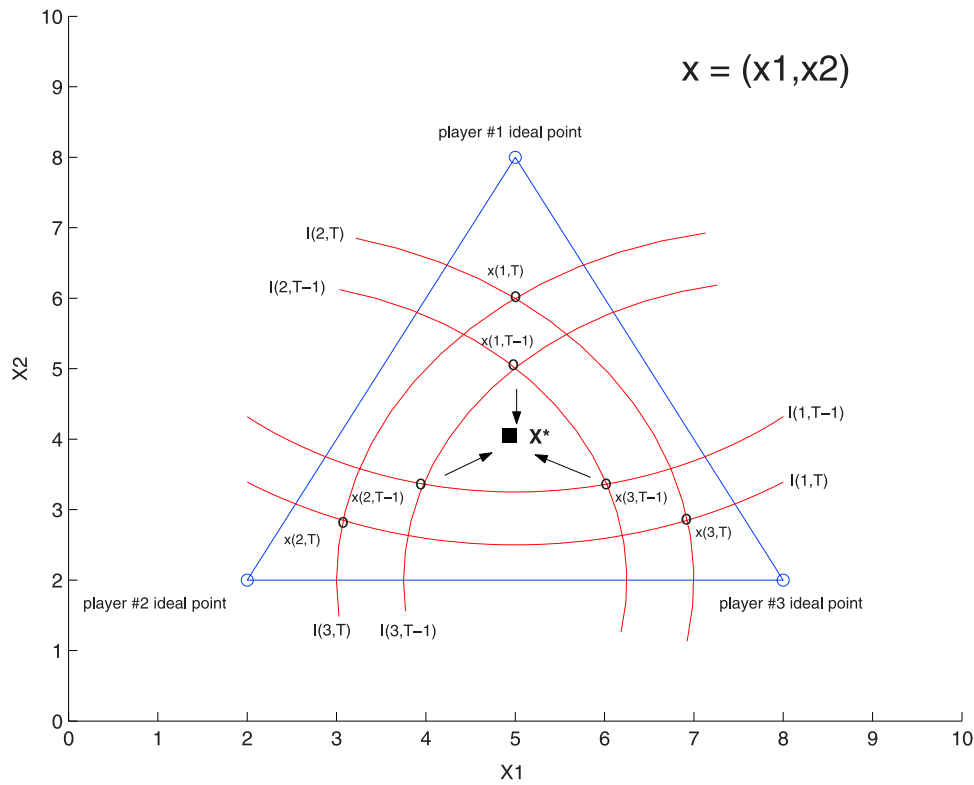
Figure 1. Rausser-Simon multilateral bargaining model, an example.

possible payoffs from the first cycle of proposals. Over successive cycles of proposals, these "expected" payoffs increase for all the players (see Figure 1). This follows from the fact that all the players get an opportunity to make a proposal that is favorable to them in any cycle, while during the turn of others within the same cycle they get at least their "expected" payoff. This makes their "expected" payoffs in the next cycle of proposals greater than their "expected" payoffs in the last cycle, putting a tighter constraint on the proposer's options.

[14] It can be shown that this game converges to a solution under certain rationality assumptions on the players (that they never prefer less of something they like, and the more they have of what they like, the less they like to have more). An assumption of quasi-concave preference structure of the players is sufficient for the convergence of the game. The quasi-concave preference structure of the players leads to a *convex* set (a convex set is a set where any linear combination of any two elements belongs to the same set) of feasible points (a set of feasible points is a set of points that obey a certain "feasibility" condition) such that they don't fall below a certain level of "expected" payoffs (see the definition of level sets of quasi-concave functions by *Avriel* [1976]). We define this set of feasible policy points as a "no-worse-than-expected" set. Since each player's decision problem, when it is his turn to propose, is to maximize his payoff subject to other players' "expected" payoff constraints, he is effectively thinking of a maximizing proposal in the intersection space of other players' "no-worse-than-expected" set (an intersection of sets is a set that contains only those elements that are common to all the sets). Also, an intersection of convex sets is a convex set [see *Avriel*, 1976]. Thus he finds a proposal that uniquely

maximizes his payoff, and uses it to update his "expected" payoff for the next round of proposals. Similarly, others also decide about their proposals and update their "expected" payoffs. Since "expected" payoffs in each cycle of proposals are higher than those in the last cycle, the constraint set for any player's maximization problem shrinks over successive cycles. Finally if the number of cycles is finitely large, the proposals of all the players lie sufficiently close to all others' "expected" payoffs simultaneously, proving convergence of the model.

[15] To formalize the game and closely follow the terminology of the Rausser-Simon bargaining model, we reverse the labels on the rounds of proposals (we call the last round as the first and vice versa). We say that the game ends when the players face disagreement payoffs and begins at a solution point. The intent is to characterize a set of equilibrium strategy profiles of the players, or in simpler terms to identify what (and why) a player will not want to propose in any round and why the players will agree with the solution.

2.2. Characterization of the Set of Equilibrium Strategy Profiles

[16] The proposal made by P_i in the last period, T, is accepted if and only if it yields each player P_j a utility level at least as great as the player's disagreement payoff, π_j^o. In each round $t < T$, a proposal by P_i is accepted if and only if it yields each $P_j \neq P_i$ a payoff level at least as great as P_j's expected utility from playing the subgame starting from round $t + 1$, or his reservation utility in round t ($\pi_j^{o,t}$). Thus P_i maximizes his utility, subject to the constraint that for each $P_j \neq P_i$, the vector x_{p_i} yields P_j no less than π_j^o for $t = T$, or P_j's expected utility conditional on reaching the next

round. If the solution to the proposer's (P_i) constrained maximization problem yields P_i at least the expected utility from proceeding to the next round, he proposes this solution to his maximization problem. Otherwise, he proposes a vector that is rejected by one or more players.

2.3. An Example

[17] Consider a three-player bargaining problem over a two-dimensional policy variable [*Adams et al.*, 1996; *Thoyer et al.*, 2001]. The two-dimensional policy variable plane identifies the space of possible agreement policy vectors. Each player has a most preferred location, called his ideal point. The game is assumed to be long but finite, with a total of T possible rounds of bargaining. At each round $t < T$, nature chooses at random a player P_i with probability w_i (this identifies a player's access probability and is interpreted as the player's bargaining power), such that $\sum_I w_i = 1$. Player P_i, chosen at random, makes a proposal $\mathbf{x}_{Pi} \in \aleph$. If the proposal is acceptable to all, the proposal forms the solution vector. Otherwise, the bargaining moves to the next round. The game continues until period T, where if the proposal propounded is not accepted all the players get their disagreement payoffs. $I^{j,t}$ identifies the reservation payoff in round t of each player P_j. This can also be seen as a player's expected payoff from playing the subgame from the $t + 1$ period onward. P_j's reservation payoff in some round $T \gg t$ is also his disagreement payoff, when the players fail to agree upon a solution if the negotiations go to round T.

[18] For $P_i's$ proposal to be accepted in any arbitrary round t, it has to yield other players a payoff level greater than their expected payoff (obtained by playing the subgame $t + 1$ from then onward). At $t = T$ in Figure 1, P_2 proposes $\mathbf{x}^{2,T}$ with probability w_2, yielding P_1 his disagreement payoff ($\mathbf{x}^{i,T}$ is the solution to P_i's constrained maximization problem in round T). Similarly, P_1 would get his disagreement payoff when P_3 proposes $\mathbf{x}^{3,T}$ with probability w_3. P_1 realizes a strictly higher payoff when he proposes $\mathbf{x}^{1,T}$ with positive probability w_1. Thus the payoff that P_1 expects in the final round when he is in the penultimate round, and hence his reservation payoff in round $T - 1$, is greater than his reservation payoff in the final round (or his disagreement payoff). By backward induction, P_1's reservation utility in round t will then be greater than that in round $t + 1$. Similarly, this can be shown to be the same for all the other players. Accordingly, the distance between the players' proposals will be closer in round t than in round $t + 1$. Thus if T is large enough, the distance between the proposals of players in round 1 will be arbitrarily small, and in the limit as $T \to \infty$, the solution to the game is deterministic and $\mathbf{x}^*$ is implemented with probability one.

2.4. Specific Remarks

[19] From the above example it may appear that only the first round has any meaning. This is true if players implement the game in the same way, but it assumes they are sufficiently smart to calculate all the possible moves of all the other players up to some finitely large number of rounds into the future. The calculation of other players' moves is equivalent to knowing their equilibrium strategies in any round, where a strategy of a player is defined as how he would react to a proposal. The players therefore propose a

solution in first round itself, since they would know (by their own convergence argument) that the solution is the only proposal agreeable to all. However the assumption of sufficient far sightedness and capacity to know others' strategies is too strict. Thus by inverse labeling proposal rounds in the model specification (with the round when a solution is achieved labeled as the last round of proposals and the round when players face their disagreement payoffs as the first round), we have assumed that the game is implemented from a round of disagreement and the players propose onward to a solution. This implicitly assumes that they can only calculate other players' strategies one round at a time.

[20] Note that both the kinds of round labeling have the same set of equilibrium strategies in each round, irrespective of its label. Hence the arguments of convergence to a solution are the same in a mathematical sense and the solution of the game is the same. Thus labeling does not matter if the solution point is of interest, though it is important in defining how the game is implemented. Therefore, by relabeling the proposal rounds as in the subsection of model specification and convergence, we can also follow from the above example why the game converges to a solution.

[21] The following two case studies show how uncertainty influences the equilibrium solution. The first case study is a simple three-farmer problem under uncertainty. It shows how uncertainty due to conveyance loss enters the parameters of a player's profit function. This modification in the preference structure is not due to a change in the player's preference, but to his belief of uncertainty in conveyance loss. It therefore shows, in simple and explicit terms, that the final allocation solution is affected by a change in preference parameters of a player (in addition to second-order effects on other players) due to the presence of uncertainty. This similarly happens in the second case study. Here we consider the effect of uncertainty (at different levels) in the degree of water right transferability on the bargaining solution of California water policy negotiations as studied by *Adams et al.* [1996]. However unlike the first case study, the effect of change in preference parameters (due to uncertainty) of one player on the bargaining solution is not dominant because second-order effects on other players are stronger. Thus these two case studies serve as complimentary examples for clear exposition of the effects of uncertainty on consensus-based decision making and the value that can be derived by reducing such uncertainty.

3. Case Study I: Three-Farmer Problem

[22] In this case study, we consider bargaining between three farmers, $\{F_1, F_2, F_3\}$, over sharing some surplus amount of water, X. Their production functions are assumed to be quadratic in water input [*Chakravorty and Roumasset*, 1991; *Burness and Quirk*, 1979]. There is a surplus of water, X, from which the farmers bargain to obtain a share, and which is available at a constant price k. The farmers sell their products at an exogenously fixed and given price p. The profit function for player i is therefore given by,

$$\pi_i(x_i) = p\left[a_i^1 x_i^2 + b_i^1 x_i + c_i^1\right] - kx_i$$
$$= a_i x_i^2 + b_i x_i + c_i, \text{ and } \sum_{i=1}^{3} x_i = X \qquad (1)$$

Table 1. Results Under No Loss Conditions: Symmetric Case[a]

Allocation	Payoffs	Certainty Equivalent Water Allocation
Ideal	2	1
Disagreement	1.333	0.1835
Equilibrium	1.556	0.3333

[a]Certainty equivalent water allocation to farmer i is $x_i^{o,T-t}$ in round $T-t$ when the expected payoff in round $T-t+1$ is $\pi_i^{o,T-t}$. For $t=1$, the certainty equivalent water allocation is the disagreement certainty water allocation. Here $x_i^{o,T-t} = \arg\{\pi_i(x_i) - \pi^{o,T-t} = 0\}$.

Since the profit functions are concave in water input, $a_i \leq 0$.

[23] One of the three farmers also faces a conveyance loss from the source of the surplus to his point of use. Such a loss in conveyance is stochastic in nature. In a bargaining situation, the farmer facing such a loss then bargains for an amount such that, after the loss of a physical quantity of water in conveyance to his cropland, he receives the profit he expected at the bargaining table. Let γ represent the percentage of water arriving at the farm so that the absolute loss in conveyance is given by $(1 - \gamma)x_i$. Thus, during discussions at the bargaining table the profit (or payoff) function of the loss-facing farmer, F_i, would take the form (along the lines of *Chakravorty and Roumasset* [1991]):

$$\pi_i(x_i, \gamma) = a_i\gamma^2 x_i^2 + \left[pb_i^1\gamma - k\right]x_i + c_i$$

[24] The loss-facing farmer attempts to maximize his expected profit over various values of γ, where the true value of γ is unknown. Therefore the farmer's expected profit function depends solely on his perception of the chances with which various losses can occur. This can further be translated, for simplicity, to a continuous probability density function $\psi_i(\gamma,\alpha)$ as a "model" to predict losses. Here α denotes some abstract parameter set to describe the density function. We further assume that the expectation of loss using $\psi_i(\gamma,\alpha)$ is unbiased, or the true expectation of loss coincides with the predicted expectation. Thus a farmer's expected profit function yields the form:

$$\pi_{i\alpha}(x_i) = E[\pi_i(x_i), \alpha] = \int \pi_i(x_i, \gamma)\psi_i(\gamma,\alpha)\partial\gamma$$
$$= a_i x_i^2 \int \gamma^2\psi_i(\gamma,\alpha)\partial\gamma + \left[pb_i^1 \int \gamma\psi_i(\gamma,\alpha)\partial\gamma - k\right]x_i + c_i$$
$$= a_i\left[\mu_2(\alpha) + \bar{\gamma}^2(\alpha)\right]x_i^2 + \left[pb_i^1\bar{\gamma}(\alpha) - k\right]x_i + c_i \quad (2)$$

Here

$$\mu_2(\alpha) = \int [\gamma - \xi]^2\psi_i(\gamma,\alpha)\partial\gamma \geq 0$$
$$\bar{\gamma}(\alpha) = \int \gamma\psi_i(\gamma,\alpha)\partial\gamma$$

where $\bar{\gamma}(\alpha)$ is the expected loss over the density defined by the parameter α. If the true expected loss is denoted by ξ, then by assumption $\bar{\gamma}(\alpha) = \xi$. $\mu_2(\alpha)$ is the variance of the density function defined by α. The variance describes the spread of the distribution about the expectation, which in turn explains the uncertainty in the modeled loss being close to the expectation. The larger the variance, the greater will

be the uncertainty that the predicted loss is close to the expected. Note that $\gamma = 0$ (α is a null set) for the case when none of the farmers is facing a conveyance loss.

3.1. Payoffs

[25] Ideal payoffs are defined as the payoffs that the farmers receive if there is no scarcity condition. Thus the ideal payoff of any farmer F_i is his maximized profit, the solution to the unconstrained profit maximization problem:

$$\pi_i^{ideal} = \max_{x_i} \pi_i(x_i) : 0 \leq x_i,$$

or

$$\pi_{i,\alpha}^{ideal} = \max_{x_i} \pi_{i\alpha}(x_i) : 0 \leq x_i,$$

for the case with uncertainty in x_i. Their ideal point allocation, x_i^{ideal}, in the set of possible alternatives is defined as the solution to the first-order necessary condition of the above maximization problem. Disagreement payoffs are calculated using an unbiased lottery system to allocate the available surplus.

3.2. Simulations

[26] To investigate and demonstrate the effect of uncertainty in conveyance loss on the bargaining solution for this case study, we choose the coefficient values (in equations (1) and (2)) as $\{a_i^1, b_i^1, c_i, p, k, X\} = \{-1,3,1,1,1,1\}$. It is assumed that each of the three farmers has perfect knowledge about the payoff functions of the other two and that there is in place an enforcement mechanism under the CBDM framework that requires all the farmers to be honest about their payoff functions. All the farmers have equal representation in the sense that they all have equal bargaining power ($w_1 = w_2 = w_3 = 1/3$). If the negotiations fail, they will get their disagreement payoffs. Therefore it is assumed that if the negotiations fail, the surplus is allocated through a lottery system. To simplify matters, we consider the farmers to have the same payoff function coefficients.

3.2.1. Bargaining Under No Loss Conditions

[27] As one would expect, the farmers share the total surplus equally and each receives an equal allocation of water under ideal conditions, disagreement conditions, and equilibrium conditions.

[28] The first row of Table 1 shows the ideal payoffs and ideal allocations. Payoffs in this row are unconstrained maximized profits, and the water allocations are its maximizers. The second row contains the disagreement payoffs and corresponding certainty equivalent water allocation. The third row shows the equilibrium solution. Although the reservation payoffs are not that low (since we have $N = 3$), risk neutral farmers still negotiate because their equilibrium payoffs are higher than their disagreement payoffs. Moreover, due to the limited quantity of surplus water (because, in order to achieve ideal payoffs, they would require a total of three units of surplus), their equilibrium payoffs are less than their ideal payoffs.

3.2.2. Bargaining Under Loss Conditions With No Uncertainty

[29] We now suppose that the first farmer faces an uncertain loss in conveyance. His expectation of the amount

Table 2. Results Under Loss Conditions: No Uncertainty

Allocation	Farmer	Payoffs	Certainty Equivalent Water Allocation
Ideal	1	1.892	1.0494
Ideal	2 (= 3)	2	1
Disagreement	1	1.296	0.1921
Disagreement	2 (= 3)	1.333	0.1835
Equilibrium	1	1.485	0.3403
Equilibrium	2 (= 3)	1.551	0.3299

of water delivered to the cropland is assumed to have a value of $\xi = 0.9$. Characterization of uncertainties in conveyance of water must accommodate the possibility of either seepage losses from a conveyance system or groundwater return flows entering the conveyance system. Therefore the variation in losses is assumed to be greater than 1 to allow for both losses or gains in conveyance. While counterintuitive, in practice gains are occasionally observed in canal flows. $\mu_2(\alpha) = 0$, as we are considering no uncertainty in loss predictions.

[30] The ideal payoff for the first farmer is reduced because of these conveyance losses. The entry of loss in his payoff function changes his expected payoff such that his ideal allocation is greater than when he faces no losses. Moreover, his equilibrium payoff also decreases.

[31] Another interesting observation for this simulation is that the equilibrium payoffs of farmers 2 and 3 are lower than their equilibrium payoffs when farmer 1 does not face a loss condition (Table 1). The loss affects all farmer profits, even though only one of the farmers faces a loss in conveyance. This observation, however, is subject to the choice of parameters identifying the profit functions of the farmers used in the simulations. Table 2 shows that the total social benefit (sum of equilibrium payoffs of all the farmers), which is 4.587 units, is less than the total social benefit under the no-loss condition (4.668 units, from Table 1). This reduction is due to both the reduced equilibrium payoff of farmer 1 and to a reduction in equilibrium payoffs of the other two farmers. It is from this reduction of equilibrium payoffs that we find the economic utility of reducing modeling uncertainty, as the next section explains.

3.2.3. Bargaining Under Loss Conditions With Uncertainty

[32] We now extend the previous section by varying the level of uncertainty in the losses that farmer 1 may face, to show how farmer 1's equilibrium payoff varies with uncertainty. We vary μ_2 from 0.1 to 0.9. Varying μ_2 is equivalent to varying α, which defines a particular probability density of losses. In essence, varying μ_2 provides various perceptions of loss uncertainty and therefore a loss "model" with varying prediction uncertainty. These perceptions mathematically represent the estimated density functions of losses. Estimation in turn is never a reality but only an approximation to it. A better approximation explains reality better, and hence a better estimated density is closer to the "true" density function. Even though the smallest achievable uncertainty would be bounded from below by the actual uncertainty (which exists in nature), we have arbitrarily selected this lower bound to be 0.1. The previous assumption that the expected predicted loss coincides with the actual expectation is maintained for all predictor densi-

ties ($\overline{\gamma}(\alpha) = \xi = 0.9$). This means that the loss expected (in a mathematical sense) under a particular model (defined by α) is the same as the "true" loss expectation.

[33] Not surprisingly, the larger the variance in farmer 1's prediction of his loss, the lower is his equilibrium profit. Both the equilibrium total profit and the marginal profit decline as the variance of predicted losses in conveyance increases. This can be partially attributed to farmer 1's ideal payoff. The greater the uncertainty, the smaller is his ideal payoff. This in turn reduces his disagreement payoff, which causes his equilibrium payoff to fall. Figure 2 illustrates this behavior of equilibrium payoff of farmer 1.

[34] If we assume that a unit increment in the equilibrium payoff for all the farmers increases their indirect utility by the same amount, the increment in farmer 1's equilibrium payoff with some decrement in uncertainty is the maximum that he is willing to pay for that decrement in uncertainty. Thus Figure 2, in a way, plots the willingness to pay off farmer 1 for certainty when in negotiation for a share in the available surplus of water.

3.3. Specific Remarks

[35] Some readers may ponder, Why not have the farmers auction off the surplus water and split the revenues amongst themselves? This may fetch a better price and thus a larger revenue surplus to be shared rather than bargain over the division of surplus at some a priori fixed price. Note that we have not assumed in the paper that the players have a priori partial ownership of the surplus. Thus farmers have to unanimously agree to auction off the surplus first, before splitting the revenues. However, then this collective decision will depend heavily upon a later process of revenue distribution. The players therefore still have to go through a process that "fairly" distributes the revenue, such as a consensus-based decision-making process.

[36] What if the owner of the surplus decides to auction the surplus to a farmer with the highest bid rather than allowing the farmers to bargain for a share at some fair price? Though economically efficient, this option will be in stark contrast to the intent of this paper (which is to provide a modeling framework for consensus-based decision making). Auctions are the purest form of markets. While a bargaining approach leads to a Pareto inferior (option A is Pareto inferior to option B when option A, in comparison to option B, makes at least one party worse off even if all the other parties are better off) solution to auctions, the latter totally ignores the equity dimension of revenue distribution [*Thomas and Wilson*, 2002]. This lack of equity dimension in auctions is evident in its monopolistic nature [*Bulow and Klemperer*, 1996]. Multilateral bargaining at least allows for a platform where possible arrangements for equitable distribution can be discussed [*Krishna and Serrano*, 1996].

4. Case Study II: California Water Policy Negotiations

[37] Here we study a more realistic scenario of California water policy negotiations as considered by *Adams et al.* [1996]. In the early 1990s, representatives from agricultural water agencies, urban water agencies, and environmental groups attempted to forge a consensus-based solution over issues relating to California water policy. The major issues in the negotiations included degree of water right transfer-
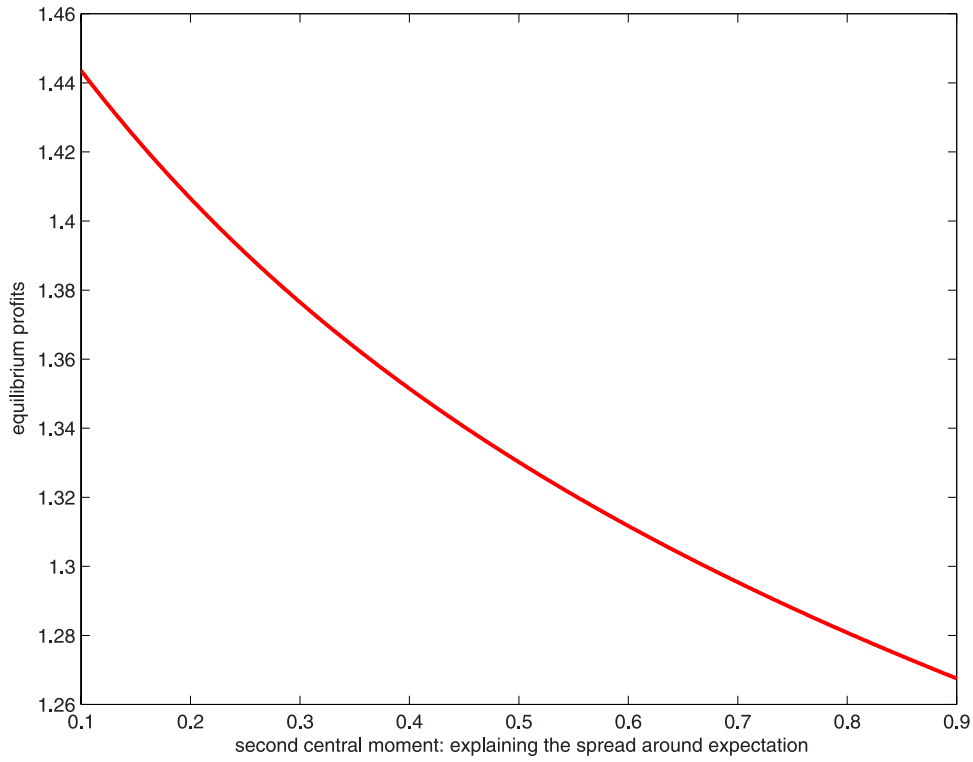
Figure 2. Variation of equilibrium profits of farmer 1 with μ_2 (second central moment).

ability, degree of environmental protection and degree of infrastructure development. A case study by G. Adams (1993, discussed by *Adams et al.* [1996]) indicates that all three groups have distinct preferences over the three issues, with each group strongly in favor of one issue, strongly opposed to a second and moderately opposed to the third. In the following study we consider the effect of uncertainty (at different levels) in the degree of water right transferability (due to uncertainty in understanding the underlying physical processes governing any amount of water transferred after a policy decision has been made), and how it distorts the bargaining solution.

4.1. Payoffs

[38] The bargaining (or policy) space for the three interest groups is three-dimensional. The level of utility that each player receives from any point in this space is defined by a constant elasticity of substitution (CES) utility function of the form [*Adams et al.*, 1996]:

$$u_i(\mathbf{x}) = \left(\sum_{k=1}^{3} \gamma_{i,k} \left[\theta_i - \left(x_k - x_{i,k}^{ideal} \right)^2 \right]^{\xi_i} \right)^{(1-\rho_i)/\xi_i}, \quad (3)$$

$\mathbf{x} = \{x_1, x_2, x_3\}, i = 1, 2, 3.$

[39] Here the utility function forms are risk averse, defined by ρ_i. Again, the players considered are representatives of the farmer group *(i = 1)*, the urban group *(i = 2)*, and the environmentalists *(i = 3)*. The core issues on the negotiation table are degree of infrastructure development (x_1), degree of water right transferability (x_2), and degree of environmental protection (x_3). $\mathbf{x}_i^{ideal}$ is the ideal solution that the *i*th player favors the most, while $\gamma_{i,k}$ is the weight that the *i*th player attaches to the *k*th policy variable. ξ_i is the

substitutability coefficient responsible for substitution between the three policy variables for player *i*, and θ_i ensures that the utility term in the square bracket is always positive.

[40] While *Adams et al.* [1996] consider the effects of variation in policy space and coalition breaking on the negotiation outcomes, we here consider how uncertainty (at various levels) along one of the dimensions of policy space affects the outcome of the negotiations. *Adams et al.* [1996] consider deterministic games. They draw their conclusions by varying the parameters of players' utility functions and then repeating the deterministic game, an approach different from the one that we present here. However, like *Adams et al.* [1996], we consider normalized policy space (feasible policies lying in a unit cube) with the various parameters of the utility functions (equation (3)) given in Table 3.

[41] Additionally, we consider an uninformed prior (represented as a uniform distribution) on uncertainty in x_2. Furthermore, this uncertainty is heteroscedastic such that all players face larger uncertainty in x_2 if any of the players, in any round of bargaining, proposes a higher degree of rights transferability. In effect, we consider a new variable

Table 3. Parameters for CES Utility Form for the Three Players in the California Water Policy Negotiations

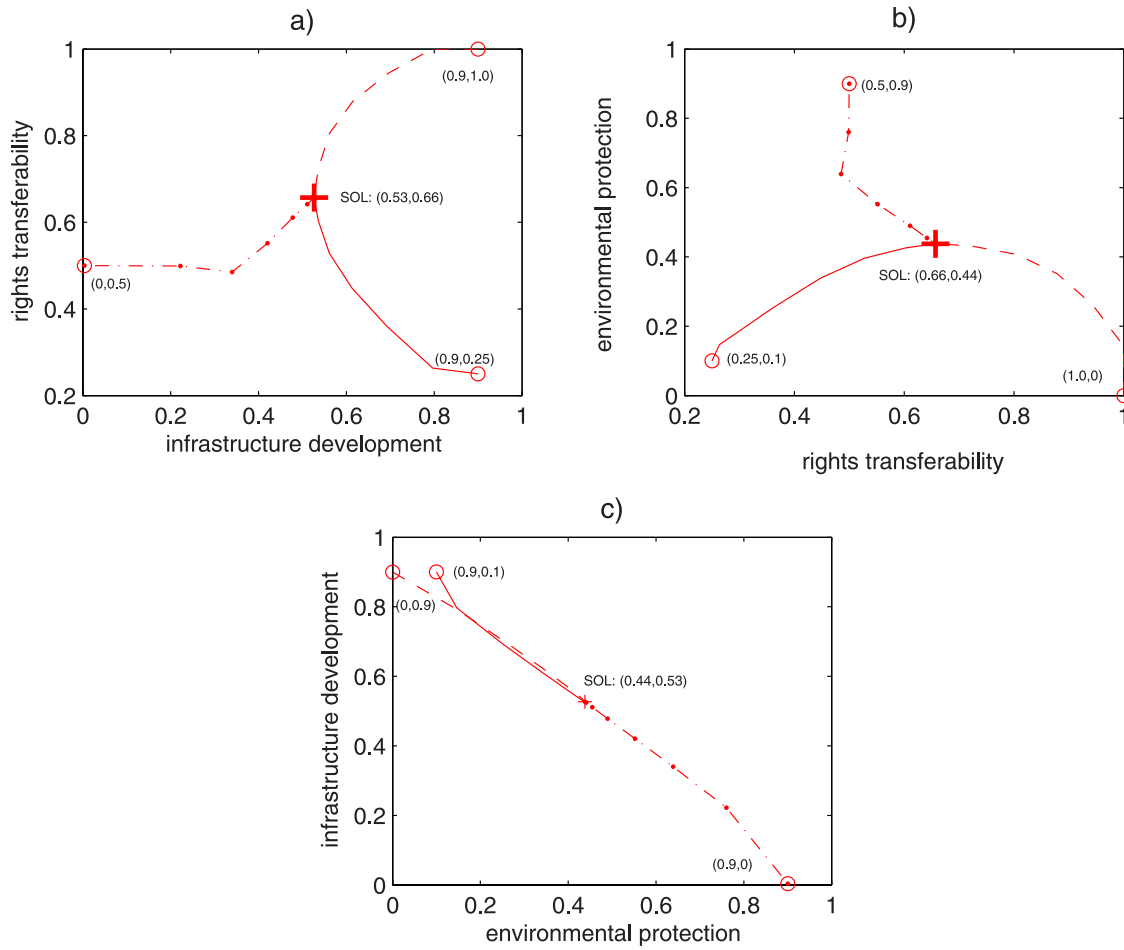| Parameters	P_1	P_2	P_3
$x_{i,1}^{ideal}$	0.9	0.25	0.1
$x_{i,2}^{ideal}$	0.9	1.0	0
$x_{i,3}^{ideal}$	0	0.5	0.9
$\gamma_{i,1}$	0.9	0.9	0.75
$\gamma_{i,2}$	0.25	0.9	0.5
$\gamma_{i,3}$	0.75	0.25	0.9
ξ_i	−6.0	−6.0	−6.0
θ_i	1.0	1.0	1.0

Figure 3. Evolution of the bargaining game under no uncertainty between three players projected in two-dimensional policy space. Solid lines trace the proposals made by the farmer group, dashed lines trace the proposals made by the urban group, and dot-dashed lines trace the proposals made by the environmental group. Circles indicate a player's ideal allocation point, and pluses indicate the bargaining solution reached by all three players.

$x'_2 = x_2 r$, where the random variable $r \sim U[1 - p/2, 1 + p/2]$, which all three players see as effective degree of water right transferability. Assuming all the players are expected utility maximizers, their transformed utility functions are of the form:

$$u'_i(\mathbf{x}, p) = \mathop{\mathbf{E}}_{r \sim U[1-p/2,1+p/2]} \left(\left(\left[\sum_{k=1,3} \gamma_{i,k} \left[\theta_i - \left(x_k - x_{i,k}^{ideal} \right)^2 \right] \right]^{\xi_i} + \gamma_{i,2} \left[\theta_i - \left(r x_2 - x_{i,2}^{ideal} \right)^2 \right]^{\xi_i} \right)^{(1-\rho_i)/\xi_i} \right),$$

$$r x_2 \in [0, 1] \forall x_2$$

(4)

Here p identifies a level of uncertainty in exact knowledge of the attainable degree of water rights transferability, x_2. For $p = 0$, we have our base case, i.e., a case with no uncertainty. In order to obtain disagreement utility levels for all the players, we assume that under the bargaining breakdown condition, all three players receive their least feasible utility levels $u_i^o(\mathbf{x}_i^o, p)$, where

$$u_i^o\left(\mathbf{x}_i^o, p\right) = \min_{\mathbf{x} \in [0,1]^3} u'_i(\mathbf{x}, p)$$

[42] Since the ideal policy solution for each player is considered as a parameter (given in Table 3), it is straightforward to note that $u_i^{ideal}(\mathbf{x}_i^{ideal}, p)$ is the ideal utility level for each of the players.

4.2. Simulations

[43] We first demonstrate the convergence of the bargaining game for the base case ($p = 0$). In all the simulations that follow, we assume equal bargaining power for all the players ($w_1 = w_2 = w_3 = 1/3$). Figure 3 shows the evolution of the game in pairwise two-dimensional projection of the policy space. In the policy space showing the degree of infrastructure development versus the degree of water right transferability (Figure 3a) and the degree of water right transferability versus degree of environment protection (Figure 3b), the proposals of all the players converge from their ideal points (indicated by circles). In Figures 3a and 3b the players' ideal points are located far apart from each other. Also, their ideal points form their proposals in the last round. The players are able to propose their ideal points in the last round, as their disagreement utility levels are the minimum utility levels that they can achieve within the feasible policy space. It shows that the policy pairs that each player proposes are not in good agreement with other
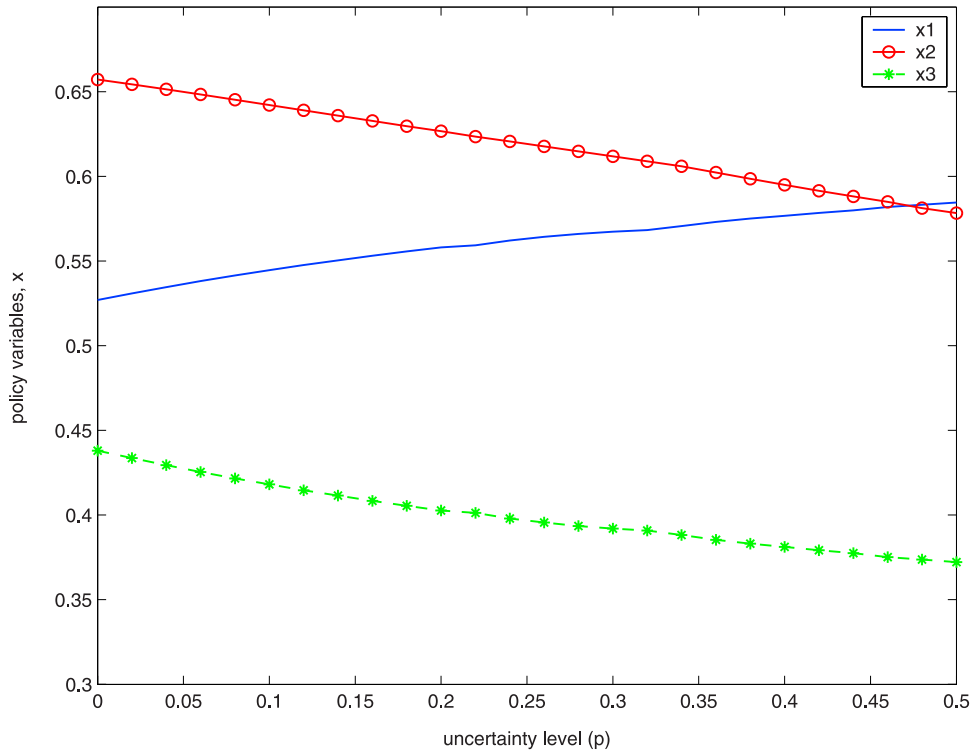
Figure 4. Bargaining solution sets (policy set solutions) under varying uncertainty levels.

players' proposals. However, in the policy pair space of degree of environmental protection versus degree of infrastructure development (Figure 3c), the policy pairs proposed by the farmer and urban groups almost coincide. However, those are in disagreement with proposals made by the environmental group.

[44] Such behavior is due to the preference structure of all the players over the issues. Farmer and urban groups are identical in their preference for degree of infrastructure development, moderately differ over degree of environment protection, and strongly differ over water right transferability. On the other hand, the environmental group's preference over all of the three issues disagrees with both the farmer group and the urban group. This is the reason why the proposals of the farmer and urban group closely agree with each other in Figure 3c and disagree in Figures 3a and 3b, while proposals of the environmental group never agree with the other two groups.

[45] We now simulate the bargaining game under varying uncertainty levels, $p > 0$. Uncertainty levels considered range from $p = 0.02$ to $p = 0.5$, with increments of 0.02. The expected utility level for each player is numerically calculated by uniformly sampling r from the interval $[1 - p/2, 1 + p/2]$ 10,000 times and then evaluating the mean of $u_i''(\mathbf{x}, p)$ as an estimate, $\hat{u}_i'(\mathbf{x}, p)$, of $u_i'(\mathbf{x}, p)$ (equation (4)). Here

$$u_i''(\mathbf{x}, p, r_j) = \left(\left(\left[\sum_{k=1,3} \gamma_{i,k} \left[\theta_i - \left(x_k - x_{i,k}^{ideal} \right)^2 \right] \right]^{\xi_i} \right. \right.$$
$$\left. \left. + \gamma_{i,2} \left[\theta_i - \left(r_j x_2 - x_{i,2}^{ideal} \right)^2 \right]^{\xi_i} \right)^{(1-\rho_i)/\xi_i} \right)$$

$$\hat{u}_i'(\mathbf{x}, p) = \frac{1}{10000} \sum_{j=1}^{10000} u_i''(\mathbf{x}, p, r_j)$$

$$r_j \sim U[1 - p/2, 1 + p/2], r_j x_2 \in [0, 1]$$

[46] Figure 4 shows the trace of each element of the policy solution of the bargaining game under varying uncertainty. Figure 5 shows the trace of the equilibrium utility levels that the three players thus achieve. With an increasing level of uncertainty, players agree to a higher degree of infrastructure development but to lower degrees of water rights transferability and environmental protection. The urban group has the highest preference for the degree of water right transferability, followed by the environmental group and then the farmer group. However, the farmer and urban groups have identical preferences for the degree of infrastructure development in contrast to the preference of the environmental group for the same policy variable. Observing increasing uncertainty in the degree of water right transferability, the urban group attempts to compensate the loss in its utility by substituting it with a higher degree of infrastructure development than when not facing any uncertainty. This makes the farmer group stronger in bargaining for a higher degree of infrastructure development (due to the implicit coalition with the urban group over the issue). While on one hand this leads to a higher degree of infrastructure development as an accepted policy, on the other hand it makes the environmental group weaker and therefore leads to a lower degree of environmental protection as an accepted policy.

[47] Figure 5 further supports such an argument. At lower levels of uncertainty, the urban group is able to increase its level of equilibrium utility, from the equilibrium utility level for the base case ($p = 0$), by substituting it with a higher degree of infrastructure development. However, at higher levels of uncertainty it receives lower equilibrium utility levels, as a higher degree of infrastructure development is not able to completely compensate for loss in utility levels due to a lower degree of water right transferability. Also, the equilibrium utility level of the farmer group increases with
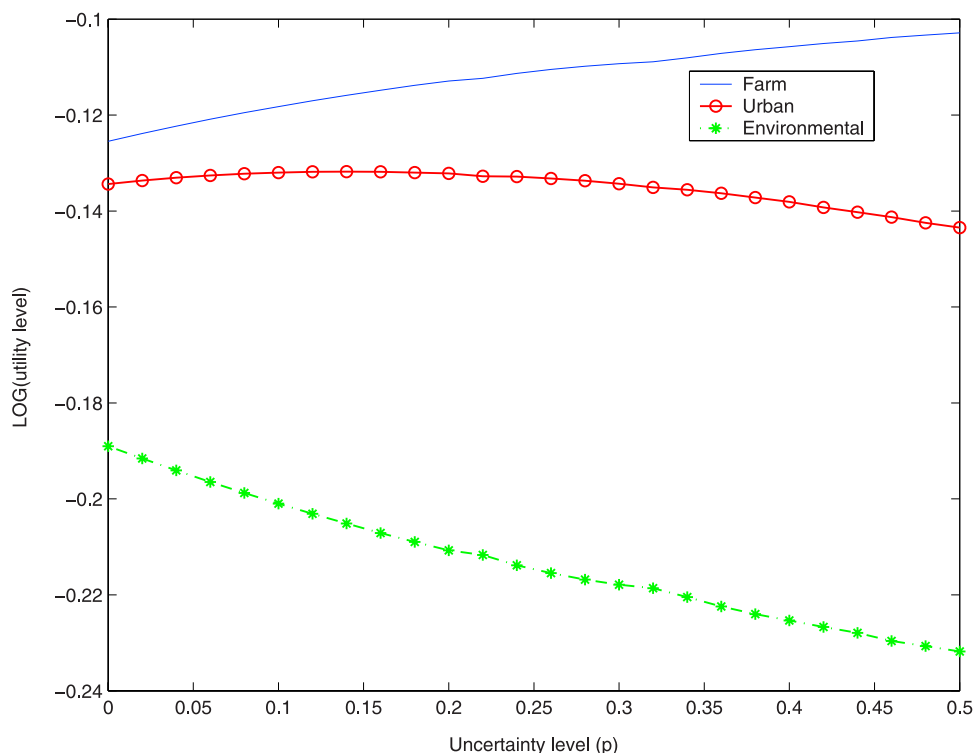
Figure 5. Log of equilibrium utility levels for all the players under varying uncertainty levels.

increasing uncertainty level, while the equilibrium utility level realized by the environmental group decreases.

[48] Therefore, under increasing uncertainty over the realizable degree of water rights transferability, the biggest loser is the environmental group and the biggest gainer is the farmer group; further, the urban group is responsible for such an observation. Since the preferences of the farmer group are more closely aligned with the urban group than the environmental group, it implicitly supports the cause of the former rather than the latter.

[49] Figures 6a–6c shows how the solution of the bargaining game distorts with increasing level of uncertainty. It shows, in pairwise projected policy space, that the solutions get further away from the base case ($p = 0$) as p increases, with solution at $p = 0.5$ (indicated by crosses) at a maximum distance from the base case solution ($p = 0$, indicated by pluses). This distortion leads to an increasing loss in total equilibrium utility levels (the sum of all three players' equilibrium utility levels) with increasing uncertainty level. From Figure 5, we then obtain net willingness to pay for a reduction in uncertainty level as shown in Figure 6d. Thus as emphasized earlier, uncertainty adds a form of cost on the players depending upon their preference structure and how uncertainty enters into the policy space.

[50] Figures 5 and 6 provide some insight into implications for water resource management and policy making. Under a given negotiation structure, the farmer and the urban groups are, knowingly or unknowingly, collaborators against the environmentalist group. Just because the first two groups are more like-minded than the last group, the environmental group has a weaker say in seeking a higher degree of environmental protection and against more infrastructure development. Also, this situation worsens with increasing uncertainty, in spite of the fact that all three

groups were allowed the same bargaining power in proposing their agendas. Such a situation can lead to unintended underrepresentation of the environmental group and policies that lead to higher environmental degradation when lesser may have been more socially desirable. In such a situation, additional players such as some government agencies can weigh in to support the underrepresented group. Another alternative can be the willingness of the environmental group to pay for better understanding on water transferability. Additional policy variables can also be added to dilute the tradeoff between infrastructure development and environmental protection.

5. Discussion

[51] Cooperative game theory has been used frequently in various water resource management problems, especially cost allocation problems. *Giglio and Wrightington* [1972] were among the first authors to employ cooperative game theory in a cost allocation problem. On the basis of the treatment of *Binmore et al.* [1986], it can be shown that the Rausser-Simon model presented in this paper provides a solution similar to the Nash-Harsanyi solution concept. This solution concept, in addition to other concepts, has been important in cooperative game theory applications in cost allocation problems. For example, *Frisvold and Caswell* [2000] discuss these possible mechanisms to allocate costs of constructing pollution control projects between cities. *Lejano and Davos* [1995] compare variants of the nucleolus concept as a mechanism for cooperative cost allocation of a joint multiagency water project. One should note, however, that the use of cooperative game theory (and various solution concepts within) is not only restricted to cost allocation problems. After all, cost allocation problems are
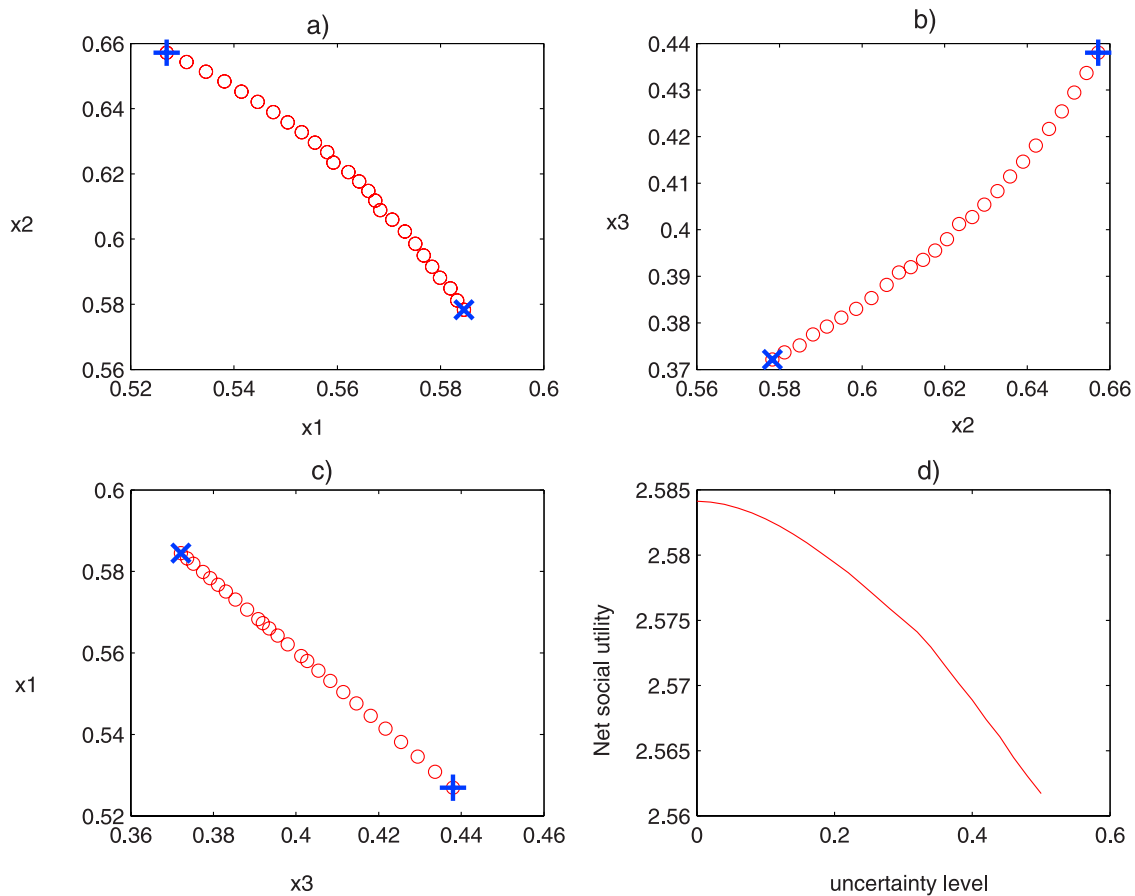
Figure 6. (a−c) Distortion in the equilibrium policy solution with varying uncertainty levels. Pluses indicate the solution for the base case ($p = 0$), and crosses indicate the solution for $p = 0.5$. (d) Total equilibrium utility levels, sum of utility levels for all three players, for $p = [0,0.5]$.

equivalent to benefit allocation problems (with benefits accrued by the players defined as the negative of costs incurred). Thus the same solution concepts can be carried over to cooperative surplus allocation problems. For example, *Dinar et al.* [1992] explores the same solution concepts for cooperative allocation of benefits from an irrigation project.

[52] In a similar spirit, this paper employs a variant of the Nash-Harsanyi solution concept for a general class of decision problems. The players are modeled to decide collectively and the dimension of cooperation comes via consensus building. It subsumes the problems of cost as well as benefit allocation problems (where a decision problem is how to divide costs or benefits amongst the players). It is general because it also allows for hybrid decision problems such as situations when any decision harms one party while others benefit and the players want to arrive at a consensus-based solution. The Rausser-Simon bargaining model can also "conceptualize" real-world negotiations where the parties involved may have to accrue intangible costs or benefits, or even negotiations wherein a player is a silent observer to negotiations (that is when he cannot propose a solution but can disagree to others' proposals).

[53] The richness in the Rausser-Simon bargaining model is due to its dynamic conceptualization of a consensus-based decision-making process and its notion of "power".

Any player with a voice in negotiations has nonzero power and by definition this power partially affects what others realize (since no one should disagree). This implicitly models a player's consideration of other players' needs in his proposal. Decomposition of an entire game (negotiation) into subgames, or rounds, then provides a possible conceptualization of negotiations in "slow motion." This brings out interaction between the players, their preferences and powers. Utility maximizing proposals of the players can be traced over different rounds or subgames, further allowing for flexibility in representing time as another factor in negotiations, representing various rounds. Overall, it is thus possible to understand how and why various players behave under different settings via their proposals in different rounds.

[54] For example, when a player has much more to lose than others if the negotiations fail and is quite different from others in his preferences, it can be expected that he will receive a worse deal from any consensus-based decision making. The paper specifically studies this effect via the Rausser-Simon multilateral bargaining model. Common to both the case studies is how uncertainty, which does not have any explicit associated cost, can make a player weaker in negotiations than otherwise. One important implication is that negotiating parties should attempt to reduce such uncertainties by technological innovations before entering negotiations. This point has already been discussed in the

case studies. Another point is the degree to which it affects the players and who else (among the players) may benefit from their investments in uncertainty reduction. This is where the study of game dynamics becomes important. Both the case studies show that there are some second-order effects on the payoffs of other parties that are not experiencing uncertainties. This is attributable to implicit coalition formations due to correlated preference structures. Some parties have a preference structure similar to the affected party or some parties have correlated preferences but different from the affected party. While the former set of parties loses, the latter set collectively gains due to implicit cooperation against the former. Therefore a cost-sharing mechanism for uncertainty reduction in negotiations for water resource policy making can be devised on the basis of this model dynamics. Then we can infer uncertainty costs (or implicit benefits) afflicted upon the players and justify cooperation (at least partially for the correlated set of affected parties) for cost sharing. For example, unaffected farmers may want to partially finance canal lining for reducing conveyance loss for the first farmer, when they realize it leads to a win-win situation for all. They can even approximate how much they should invest to be net gainers.

[55] Uncertainty, especially in decision making in water resource management, can easily occur due to natural causes. In both our case studies, it can enter due to losses, insufficient measurement information or approximate model estimation that disallows exact quantification of water resource. These case studies additionally show that it can reduce the overall (total) benefits that can be accrued. Thus if no party, especially the affected one, is fully capable of financing uncertainty reduction measures, some government agency may want to weigh in for overall benefit. Then this model can help those government agencies to ascertain the appropriate level of involvement. It also provides some insight into other roles that such agencies can play. For example, in the second case study the environmental group is the party most affected by uncertainty in water rights transferability, when it is not the party that is directly facing uncertainty. Further the farmers' group gains with increasing uncertainty levels. It is obvious that the gaining party will not have any interest in reducing uncertainty and this may lead to undesirable consequences for the environment under increasing uncertainty (in spite of the presence of an environmental group in negotiations). A government agency may then want to enter the game dynamics to avoid such consequences. It can do so (1) by entering the game as a player, (2) by supporting uncertainty reduction measures, or (3) indirectly by making other players aware of the negative consequences on the environment and attempt to change their attitudes toward the environmental dimension of policy making. Specific interests within a consensus-based decision-making process can also be promoted by better representation of interests at the bargaining table. Uncertainty can also be incorporated as an additional policy issue in decision making. A player or an interest group cannot be held responsible for uncertainty when it is due to natural causes. Thus, if uncertainty (faced by some due to natural causes) is incorporated as another dimension of decision making, its isolated effects on specific parties can be partially removed via the game dynamics. However, such

an arrangement is highly unlikely as those players who are not directly affected by uncertainty (and they know it) will be reluctant to include it as one of the topics of bargaining.

[56] It has to be stressed that the dynamics of the Rausser-Simon model is of use in modeling consensus-based decision making (with or without uncertainty) when the players are rational and honest, can be represented as utility maximizers, and follow the rules (which are set a priori) of bargaining. The notion of rationality and honesty cannot always be ensured, since they are hard to quantify. Related to the same point is the interpretation of model results. It is limited by the level of accuracy with which its parameters, such as default power, bargaining power, ideal points, perception of uncertainty by various players, each player's level of information about other players' preference, etc. can be quantified. Bargaining solutions via a multilateral bargaining model are sensitive to these parameters in varying degree. These sensitivities further depend on the allocation problems in hand. Thus solutions can be highly uncertain due to uncertainty in the estimation of model parameters. Also, improvements in the model need to be made by including temporal dynamics over successive rounds in players' behavior [*Thoyer et al.*, 2001]. This additional structure may help accommodate the pace at which real-world negotiations take place. Finally, bargaining itself cannot always be recommended as the most appropriate institution to facilitate consensus-based decision making. In real-world situations, bargaining may not start if all the players do not agree upon the terms and conditions of bargaining ("the parameters"). Even if bargaining starts, it can take significant time before any solution is reached, or it may not even converge. To allay such disadvantages of bargaining, hybrid institutions can be formulated [*Milgrom*, 1989; *Elyakime et al.*, 1997]. For example, the players may collectively decide to auction off the surplus in the three-farmer case study, provided they have already negotiated on how to share future revenues from the sell-off. The players then have an additional incentive to reach an agreement on the shares if they do not want to miss high market prices due to scarcity.

6. Conclusions

[57] Rausser and Simon's multilateral bargaining model was utilized to simulate the CBDM processes. Two case studies were analyzed under this framework. Though the success of such a framework crucially depends on the institutional structure of the negotiations, it was assumed that a sufficient legal and institutional framework was in place to address this requirement. In both case studies, we observed that the bargaining solution under uncertainty deviates from the solution under no uncertainty. Moreover, the deviation increases with higher levels of uncertainty. This increasing deviation with uncertainty also quantified the willingness to pay for a reduction in uncertainty.

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