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Role of price and enforcement in water allocation: Insights from Game Theory

Francisco Assis Souza Filho,[1,2] Upmanu Lall,[2,3] and Rubem La Laina Porto[4]

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[1] As many countries are moving toward water sector reforms, practical issues of how water management institutions can better effect allocation, regulation, and enforcement of water rights have emerged. The problem of nonavailability of water to tailenders on an irrigation system in developing countries, due to unlicensed upstream diversions is well documented. The reliability of access or equivalently the uncertainty associated with water availability at their diversion point becomes a parameter that is likely to influence the application by users for water licenses, as well as their willingness to pay for licensed use. The ability of a water agency to reduce this uncertainty through effective water rights enforcement is related to the fiscal ability of the agency to monitor and enforce licensed use. In this paper, this interplay across the users and the agency is explored, considering the hydraulic structure or sequence of water use and parameters that define the users and the agency's economics. The potential for free rider behavior by the users, as well as their proposals for licensed use are derived conditional on this setting. The analyses presented are developed in the framework of the theory of "Law and Economics," with user interactions modeled as a game theoretic enterprise. The state of Ceara, Brazil, is used loosely as an example setting, with parameter values for the experiments indexed to be approximately those relevant for current decisions. The potential for using the ideas in participatory decision making is discussed. This paper is an initial attempt to develop a conceptual framework for analyzing such situations but with a focus on the reservoir-canal system water rights enforcement.

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1. Introduction

[2] Much of water resources systems analysis technology used today was initiated by the Harvard Water Project [*Mass et al.*, 1966] and was motivated by institutional needs for tools for water resources infrastructure project evaluation and operation. As many countries have recently tried to adopt water sector reforms it has become clear that there is a need for integrated mechanisms to (1) develop consensus to address conflicts and define the administrative goals of waters policy and (2) promote desirable behavior of water users through *regulation*. This social and political challenge needs technical tools to project the outcomes of proposed institutional actions and investments toward the goals and of the potential effectiveness of the regulation system. This is a current challenge for water resource systems management, particularly in developing countries where issues related to water governance routinely emerge. This is the context of the work presented here. We explore some issues in the implementation of water rights enforcement and water pricing that could help a water institution analyze potential progress toward water allocation and regulation in terms of definable goals for efficiency, equity and effectiveness. We use a setting in Brazil to provide the context and motivation for our analysis.

[3] A cornerstone of the regulatory process is an equitable, effective and reliable system of water permits. The reliability of the right to use a granted amount of water is fundamental to the resulting behavior of the water users. If reliability cannot be guaranteed, then the system quickly degenerates into an open access system marked by free rider behavior. Two types of mechanisms are usually important for the functioning of a water system. The first are economic measures, such as pricing for water quantity, quality and reliability, market mechanisms and trading, insurance against climate or other risks. The second is an enforcement system that includes inspection/monitoring (*probability of identifying the offender*); rules that define penalties for each infraction (*punishment*); and administrative or judicial arbitration of the punishment (*application of the punishment*). This enforcement system will have a financial cost. An objective of the institution is to assess what and how to best

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[1] Department of Hydraulics and Environmental Engineering, Center of Technology, Federal University of Ceara, Fortaleza, Brazil.

[2] International Research Institute for Climate and Society, Columbia University, Palisades, New York, USA.

[3] Department of Earth and Environmental Engineering, Columbia University, New York, New York, USA.

[4] Department of Hydraulics, University of Sao Paulo, Sao Paulo, Brazil.

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invest in such measures to achieve desirable programmatic outcomes.

[4] In 1996, Brazil promulgated Law 9433–97 that defined new institutional landmarks of water policy. This law initiated water sector reform in Brazil. One of the basic characteristics of this law is the establishment of an administrative mechanism for the resolution of water conflicts (Article 32 Paragraph II). State and National councils and basin committees with the participation of water users, civil society and government were created to develop consensus through negotiation in a public setting. This reform dramatically enlarges the action space of water resources policy from one primarily focused on infrastructure to one that is normative and regulatory. The public law (Brazilian Law 9984) that created the national water agency, ANA, in 2000, reinforces the regulatory dimension of the reform proposed by Law 9433–97.

[5] Brazil's Water Resources Plan identifies water allocation through the right to use water. A goal is to achieve sustainable development of water resources, while seeking some measure of financial self-sustenance in system operation through appropriate pricing of the allocated water. Economically efficient water use is tied to the capacity to pay. Large users who can pay can be given preferential allocations with some longer-term security. The planning process, allocation, and revenue collection for operation are consequently linked in the Brazilian water allocation system. Negotiated macro allocation of water resources to large users or sectors, for instance in the state of Ceara, is part of a formal tactical planning process. These allocations can be for various terms ranging from a year to a few decades.

[6] The water allocation process faces two important challenges. The first is the allocation of the climatic risk between the state and the private agents. This is a well known problem, and reflects the inability of the State to guarantee the allocation to all users over a period of contract performance given that the long-term average historical water availability cannot be secured with 100% probability over any fixed future period. The concerns with the variations in the base long-term flow estimates of the Colorado River (United States), and the associated uncertainties with the long-term allocation of the Colorado River water are an example of this risk. The second is the social risk of regulatory failure due to free-rider behavior. This is manifest from a combination of the water pricing structure, the efficacy of monitoring and enforcement and the severity of the punishment. A large investor may be willing to pay a high price for industrial water use provided that the access can be guaranteed. However, if the water price is high and enforcement is weak, free rider activities will effectively negate the industrialist's water right and guarantee. This may prevent the industrialist from joining the allocation or water market, and hence jeopardize the financial viability of the entire system. A similar problem may occur during extreme drought when scarcity (need) rather than price motivates free rider behavior. These behaviors can then become endemic, as is the case now in Ceara where irrigators often withdraw water and do not pay the water use administration bodies (ANA/Bulk Water Company of Ceará State in Brazil (COGERH)), in turn limiting regional development in water sensitive industries. The climate risk can be better identified through stochastic and climate modeling and then mitigated through structural (e.g., storage) and nonstructural (e.g., insurance) means. The social risk needs to be addressed directly by policy and administrative action toward efficient regulation, and can be better characterized through behavioral modeling. This is the focus of this paper.

[7] Specifically, we analyze how the free rider behavior may emerge in a command and control (classical administrative allocation through a system of permits) style of enforcement conditional on the efficacy of use monitoring, offender's punishment and water price. This analysis is conducted using (1) the theories of Rational Crime and of Public Law Enforcement and (2) Game Theory to model users' strategic behavior.

[8] The article is developed in five sections. The next section introduces some details of the problem as well as the context. The third section introduces the structure of administrative water allocation (command and control), and the analysis of the water user and agency behavior. The fourth adds a pricing system for licensed use. Finally, the fifth section discusses and summarizes the results.

2. Problem Context

[9] Water rights systems have evolved over time to facilitate river basin development. In the absence of water rights, a "free for all" could ensue, such that upstream users could preferentially divert water, thus reducing the incentive for infrastructure development. The need to resolve such potential conflicts has led to a variety of allocation, licensing or water rights systems that designate the terms of allowable water withdrawal from different locations along a river to a suite of clearly identified users. However, unless there is monitoring and enforcement of these rights, the system can degenerate into a free for all. Thus, regulatory mechanisms need to be considered as part of the design of such a system. In western societies, such as the United States, an effective legal system in combination with a state or user supported monitoring and metering system provides such a capability. In developing countries where governance is not as effective, the water system operator needs to consider how much to invest in monitoring and regulation to ensure the fiscal stability of the system, and to ensure equity across use and reliability of supply to each user as prescribed by existing contracts or licenses. This situation is discussed and developed in this paper in the context of an operational situation in the state of Ceara in northeast Brazil.

[10] The general case may be considered as such. There are multiple users who can draw water from a river or canal system. There is a licensing authority that derives some revenue from licensed water use, and is charged with ensuring that the use attributes are consistent with the licenses. The users may include several "free riders" who divert more than their allocation (which could be zero). Such a user's response to regulation or enforcement may depend on the penalty for a violation, the value of the water, and the probability of being caught violating the license terms. At the same time, the regulator incurs costs for effective enforcement, i.e., increasing the probability of catching free riders by metering, hiring inspectors and through incentives for reporting theft. The regulator may be concerned about recovering the investment in enforce-

ment through the penalties or fines levied, or may consider other goals such as the reduction of free rider use to a desired target level. Thus, cost effectiveness or perception creation may drive the regulator's investment in enforcement. In either case, the regulator would like to understand or predict the behavior of free riders to two key parameters of enforcement, the probability of being caught and the associated penalty. These are useful system design elements or decision variables for the regulator.

[11] Here, we consider a game theoretic approach for the analysis of the design of an enforcement system. Two main conditions of application are considered. The first case considers a single reservoir that supplies a homogeneous set of users, with similar water use and financial attributes, such as farmers with roughly similar land holdings and irrigation needs. The second case considers two reservoirs in parallel that supply a heterogeneous mix of users, some of whom may ascribe considerably higher value to the use of water, and its reliability. For instance, some of the farmers may have greater land holdings devoted to high cash value perennial crops or to shrimp. In either case, the response of the users to a particular penalty and the associated probability of being caught are of interest, so that investments in enforcement can be improved. The user response is assumed to be rational and responsive to the two enforcement measures prescribed. In the current version of the model, reinforcement learning of the probability of enforcement through social interaction among users or media reporting is not considered. However, the transfer of such information downstream through the system is considered through a direct estimation of the water available at different locations on the river/canal system relative to what should be available there on the basis of the allocated licenses. Thus, users are informed of the progressive failure of or success of the enforcement action. This information influences their decision to invest in infrastructure for diversion from the canal to their point of use. Equilibrium solutions for the free rider use contingent on an enforcement strategy, the diversion investment and the value of water are derived and explored further through simulation considering that the initial configurations of users and their free rider attributes may vary with position on the delivery system.

[12] The Ceara setting that motivated the developments discussed here is described in the next section. The background on the framework is then introduced and discussed.

2.1. Application Site

[13] Ceara, in Northeast Brazil is a semiarid region with dramatic interannual and multidecadal climate variability. The history of Ceara is marked by recurrent, catastrophic drought (like in the years 1777, 1887, 1915, 1950, 1970, 1983, and 1993) that spurred major water resources infrastructure projects in the 20th century. These reservoir and canal systems have significantly increased resilience to drought and promoted economic development in the region. The provision of reliable water supplies has led to urban and rural growth as well as a transition from primarily rain fed, subsistence agriculture to irrigation and higher cash value agriculture.

[14] The design of an appropriate water governance and allocation system emerged as an important goal during this evolution of water infrastructure. Brazil as a whole, and Ceara, have moved toward a system of water licenses ("outorga") (1) in Brazil, a water code was introduced in 1937 and reformed through Water Law 9433 in 1997 with the creation of a National Water Agency (ANA) from 2000 and (2) in Ceara, through the creation of the Water Resources Secretary in 1986. The license may be free or have a fixed or variable (linked to quantity used) price structure. Given the high interannual variability in rainfall and hence in streamflow and reservoir contracts, the quantity of water available to each user during a drought or dry year may be substantially lower than their allocation under the license.

[15] Agricultural or others large users who have licenses to divert water from canal or rivers systems must still invest private capital to build diversion structures and local storage facilities for their water allocation. These users need to consider the marginal cost of the size of the diversion, the value of the water to the user, and the probability with which the user expects to be able to receive or divert a certain quantity of water. This probability is related in part to the variability of climate as filtered by the reservoir system and in part to the behavior of users upstream on the canal or river. Further, in a given year, the availability may be markedly different, and the user may invest some resources at the beginning of the irrigation season to prepare a certain amount of land for cropping, on the basis of the anticipated water that could be diverted. Some estimate of the water that may be available that year is usually available from a policy decision by the State Water Agency as to their proposed reservoir releases during the season. These releases do not guarantee delivery of water to the users. They merely establish what will be released, and hence availability downstream will depend on the seasonally variable free rider behavior of the users and any losses/gains along the network. The user then has two investment decisions – a long-term decision on infrastructure investment for diversion, and an annual cropping land use decision with direct water diversion implications.

[16] In Ceara, political intervention was necessary in the 1993 drought to ensure that water could reach the capital city of Fortaleza. The official priority structure is to provide water for human use first and to then use the residual water for agriculture. However, during the drought that year, significant diversion by upstream farmers threatened the supply of Fortaleza. The government of the state supported by paramilitary forces visited various locations to plead for and to order restoration flow.

[17] As Brazil moves toward full implementation of license system; the issue of the performance of the license system has come to the fore. Specifically, in Ceara, the head of the water agency, COGERH, is now pursuing a direction that makes the fiscal well being and revenue generation key priorities for her agency. In this context, the problem at hand can be posed thus:

[18] How much effort and what kind of effort should COGERH expend on license enforcement such that free rider use can be reduced to desired levels, particularly during the drought years or other constrained or overallocated situation? Since COGERH is emphasizing an economic objective for its operation, it is natural to ask if such an enforcement effort can be economically self-sustaining, i.e., can the revenue from enforcement action offset the cost of enforcement (inspection and penalty)? In 2002–6, COGERH considered net revenue maximization as a goal

for licensing and enforcement, and proposed tying staff promotions and renumeration to the degree to which this objective was achieved.

[19] At present, COGERH does not have extensive metering of users or system flows or estimates of losses such as infiltration or evaporation due to nonhuman factors in rivers. A monitoring program that addresses these would be needed to provide benchmark data to constrain future estimates of theft and natural loss. A real time telemetry system would also help identify and flag the spatial distribution of legal and illegal use. However, such a system requires significant investments for installation and maintenance for which an economic analyses of cost and benefit is needed. COGERH currently randomly dispatches inspectors to patrol the system and detect and address theft. It also has intentions of implementing an effective pricing system for water use. Increased investments in monitoring, theft detection and enforcement will need to accompany such attempts at revenue generation.

[20] These types of questions are relevant not just to COGERH, but also for operation of other systems concerned with reducing water loss. Similar water rights enforcement issues emerge in the context of groundwater rights management. For instance, groundwater is over appropriated in many parts of the United States, and investments in water rights enforcement are a concern for agencies such as the Utah Division of Water Rights. The physical situation differs in that the groundwater system does not have the sequential use structure of a reservoir-canal system, and institutional enforcement measures are different.

2.2. Background on the Framework

2.2.1. Law and Economics

[21] The economic theory of "Law and Economics" born out of the ideas of *Coase* [1960] provides a starting point for the analysis. The general context of economic regulation is detailed, for instance, by *Viscusi et al.* [2000]. The first concept is the assumption that the individual water users behavior, or free rider behavior can be understood as a "rational crime" [*Cooter and Ulen*, 2000, p. 439]. A rational crime is defined as an illegal act that is performed by an individual if and only if the person derives a benefit that is perceived as larger than the punishment (fine) for the crime. Given this concept, various aspects of regulation and enforcement can be considered. The legal literature in this area dates back to the 18th century. More recently, *Becker*'s [1968] work was particularly influential, and extensive discussions of the topic are documented by *Polinsky* [1980], *Shavell* [1993], and *Polinsky and Shavell* [1992, 2001, 2005], who develop and present a "Theory of Public Enforcement of Law."

[22] Some basic questions of interest are outlined by *Polinsky and Shavell* [2005, p.3] such as the following: (1) If the crime can be detected only with some probability, then what is an appropriate level of sanction to be levied on the offender? (2) How much of the social resources should be invested for the offender's capture, i.e., to increase the probability of detection?

[23] *Polinsky and Shavell* [2005] argue that the general problem of public law enforcement can be viewed as a problem of the maximization of social well-being. In this regard the state has the following four choices to make: (1) the definition of an offense, e.g., if the offender causes damage to another individual and needs to compensate that individual or if the offense is directly the violation of a state standard or norm, in which case the state needs to sanction the offender; (2) the form of the sanction, i.e., monetary versus nonmonetary; (3) the magnitude or severity of the sanction; and (4) the target probability of detecting offenders.

[24] *Polinsky and Shavell* [1992] argue that a key aspect of the design of the regulatory system is the assessment of enforcement cost as a function of the probability of crime detection, and the associated penalties. This cost can be divided into two components, a fixed cost that does not depend on the number of persons who commit infractions and other variables associated with the process cost and offenders' punishment. This fixed cost is associated directly with the scale of the system regulated and with the maintenance of a target detection probability of offenses. The variable cost is the cost of processing each enforcement action. This is a primarily a cost associated with the legal process of prosecution of the offenses. Given the probability of detection, the fixed and the variable costs, Polinsky and Shavell suggest that the optimum fine or sanction could be calculated by maximizing the net social benefits defined by the aggregate benefits of the expected value of the reduction of damage to harm to individuals from enforcement actions, reduced by the expected value of the residual damage, and by the costs associated with enforcement. *Polinsky and Shavell* [2001] extend these ideas to consider the social cost of corruption in the surveillance and prosecution system. An application of the idea of enforcement for water regulation is given by *Kilgour* [1998].

2.2.2. Game Theory

[25] The rational crime regulation framework introduced above does not consider the interaction of those regulated or of the asymmetries between individual costs and benefits and social costs and benefits. The private costs of water users or agents do not coincide with the social costs (e.g., the cost of polluting for the industry is smaller than the social cost of the pollution). Further, in a setting where there are many competing users, larger factors driven by competition or cooperation dynamics can contribute to the rationale of the crime, as perceived benefits and costs for each agent can be shaped by their experience.

[26] The economic and social agents in a river basin who are regulated by an authority such as COGERH interact frequently in a strategic and competitive setting. From this competitive interaction new behavior can emerge which may not be hegemonic in an isolated action. The mathematical representation of this strategic behavior may be accomplished using the theory of the competitive games [*Nash*, 1950b]. The Nash Equilibrium does not necessarily coincide with Pareto's economic efficiency or with some utilitarian or equity based criterion of justice [*Rawls*, 2002, 2003] applied to an individual with multiple objectives or to a common welfare metric applied to a group. Game Theory has been applied extensively to the common pool resource management problem, including water and irrigation management following *Ostrom*'s [1990] seminal work. Key references include *Ostrom et al.* [1994] and *Weissing and Ostrom* [2000].

[27] The competitive equilibrium models of Nash are described, for example, by *Nash* [1950a, 1950b, 1953],

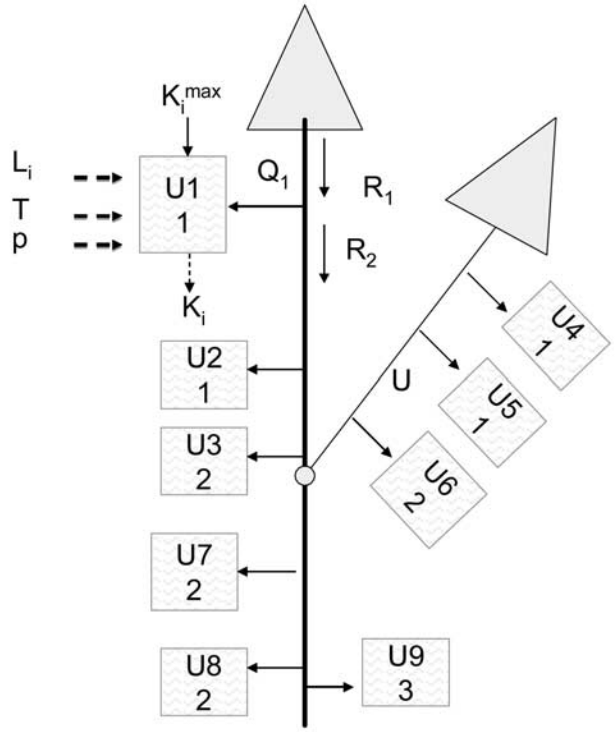

Figure 1. Conceptual network diagram.

Gibbons [1992], *Osborne and Rubinstein* [1994], and *Myerson* [1997]. Application of the theory of the games in water resources are given by *Rogers* [1969], *Loehman* [1995], *Rausser* [2000], and *Getirana et al.* [2006] for cooperative games and by *Young et al.* [1982], *Martinez Junior* [1991], and *Parrachino et al.* [2006] for cost allocation. Here we jointly develop these ideas in conjunction with the framework for Public Enforcement of Law outlined in the previous section.

3. Administrative Allocation (Command and Control)

[28] The free rider dynamics of rational crime in a regulatory setting with competition and interaction among users is developed in this section considering a regulatory agency that functions under the "command and control" paradigm, and can set the water price by user type, define water allocations, invest in a monitoring system to regulate use and theft, and can also set the penalties for infractions of the allocation. The ideas are developed through idealized settings.

3.1. Water System Structure and Users

[29] The generic setting addressed is illustrated in Figure 1. The users are arranged along the canal or river system. The user i has a license or water right in the amount of L_i, and an installed capacity to divert water $K_i^{\max}$ that may be larger than their license L_i. The water available in the canal or river at the point of the user's diversion depends on the release R from the upstream reservoir and the cumulative net withdrawals (canal/river losses and gains, and the withdrawals by the users) above that point. For the sake of simplicity we will ignore the river/canal losses and gains due to environmental factors in this presentation and focus only on the original flow available and the water withdrawn by the upstream users. Further, for now we will consider that the release R from the upstream reservoir is the designated release by the regulatory agency for the time period (e.g., month or season) of interest. This release may be larger or smaller than the total water rights (or licenses) allocated downstream. In the formulations that follow we consider the analysis for a representative season, for a fixed value of R, rather than over a time series of releases that may incorporate stochastic factors or climate variability. A limited, parametric analysis of the influence of varying R relative to the total allocation is pursued.

[30] In this idealized setting, we now consider the role of free riders on water availability along the river/canal network. If there are no free riders in the system, the water available at every point of diversion ℓ can be written explicitly as

$$R'_\ell = R'_{\ell-1} - Q_i = R'_{\ell-1} - \min\left(L_i, R'_{\ell-1}\right), \qquad (1)$$

where Q_i is the amount withdrawn by the ith user, the ith user is located between the diversion points $\ell - 1$ and ℓ, and R'_ℓ is the water available downstream of diversion ℓ. If the water available at the point of diversion by the user exceeds the license, then the user draws a quantity equal to the license, else the diversion is limited to the available water. Here, a priority water rights structure, i.e., based on seniority or preference, is not considered.

[31] To motivate the enforcement perspective, the next step is to consider how this mass balance equation is modified in the presence of free riders. Here, we shall assume that the location of the point of diversion of each free rider is known a priori. Thus, a nonlicensed free rider can be considered in the same way as a licensed free rider who draws in excess of their license, since we can nominally set the license L_i of such a user to 0. The free riders behavior will be determined by the probability that they will be caught p, the magnitude of the fine on being caught M_i, and their potential net revenue $\pi_{\rm i}$ from water use. Here, K_i refers to the proposed withdrawal by the user, whereas Q_i is the withdrawal achieved. If we consider a single user, and a known upstream reservoir release R or availability of water $R'_{\ell-1}$ above the diversion point, then there is no difference between Q_i and K_i. However, in a multiuser system, a user may or may not be aware of the diversion plans and free rider behavior of upstream users, and hence the water $R'_{\ell-1}$ that is potentially available to the user is unknown a priori. In this case, the user may plan to divert K_i on the basis of an anticipated availability $AR'_{\ell-1}$, but may only achieve Q_i. In this setting, the amount of water diverted, Q_i will be determined such that $\pi_{\rm i}$ is maximized conditional on the actual availability $R'_{\ell-1}$. Figure 2 presents the structure of this model. This process can be represented as

$$\max_{K_i} \pi_i,$$

subject to an availability constraint

$$Q_i \leq R'_{\ell-1},$$

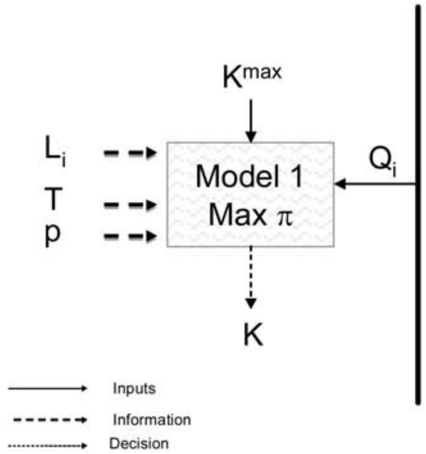

Figure 2. Schematic of user model under command and control.

a utilization constraint

$$Q_i \leq K_i,$$

and a capacity constraint

$$K_i \leq K_{\rm i}^{\max}, \tag{2}$$

where the expected net revenue for the user is

$$\pi_i = \beta_i\alpha_{0i} + (1-p)\beta_i\alpha_{1i} - CF_iK_i - pM_i, \tag{3}$$

the penalty for illegal use is

$$M_i = T\beta_i\alpha_{1i},$$

the legal withdrawal is

$$\alpha_{0i} = \min(Q_i, L_i),$$

the illegal withdrawal is

$$\alpha_{1i} = \max(0; Q_i - L_i),$$

and the maximum diversion capacity is $K_i^{\max}$, β_i is the net unit revenue or benefit from water considering variable costs only, CF_i is a unit fixed cost for creating a diversion capacity K_i, and T is a unit penalty for illegal use.

[32] In equation (3), the first term represents the net revenue contributed by legal use. The legal use α_{0i} is limited by the license L_i and the available water $R'_{\ell-1}$. The second term represents the expected net revenue from the excess illegal use α_{1i}. If the excess use is detected by inspection, then the water is cut off and the associated irrigated area loses its production. The third term refers to the fixed cost of developing the irrigated area corresponding to a proposed diversion level K_i. The last term reflects the expected value of the penalty for illegal use. The penalty M_i is considered proportional to (1) the amount of the excess withdrawal α_{1i}, (2) the net revenue β_i per unit of water for the agent, and (3) a factor T which determines the severity of the fine. Here, the idea is that the penalty for illegal use may need to recognize the relative affluence of the user or the marginal utility of water to that user. Otherwise, a richer user may not be responsive to the fines, or a poorer user may have no capacity to pay the fine. Of course, other ways to address equity in fines in could be considered.

[33] Now the mass balance along the river/canal structure considering free rider behavior can be computed by moving sequentially through the diversion points one user at a time, and solving the optimization model defined by equations (2) and (3) for each of these users. Each downstream user may be fully aware of all upstream decisions and hence of the available flow $R'_{\ell-1}$, or they may have full or partial ignorance as to these decisions and hence the available flow. In this case they may proceed with their analysis using either a probability distribution of $R'_{\ell-1}$, or its expected value. Thus, a number of issues can be explored.

3.2. Single User: Rational Crime Paradigm

[34] We first consider how the rational crime paradigm can be invoked to model the decision of an individual user on the water network. The extension to group dynamics is pursued in the next section.

[35] The basic model for the behavior of a single user is as described in the preceding section (equations (2) and (3)). The reader may note that the choice presented to the user by the model is that of a lottery where the user gets a different reward depending on whether or not the illegal use is detected, which in turn depends on the probability of detection. This is consistent with the concepts of rational crime as presented by *Cooter and Ulen* [2000]. In this section, since there is only one user, we develop the solutions to the decision model without indexing the variables by the subscript *i* or *l*.

[36] For the user to steal, i.e., $\alpha_1 > 0$, a necessary condition is that the user's marginal net revenue with respect to the quantity illegally abstracted is positive

$$\frac{\partial\pi}{\partial\alpha 1} = (1-p)\beta - CF - pT\beta > 0. \tag{4}$$

This assumes that the water available, R, is greater than the proposed diversion K. In this case, $K = \alpha_{0+}\alpha_{1,}$ leading to the derivative above. We can now express the limiting probability of detection that leads to free rider behavior or water theft as

$$p \leq \frac{1 - CF/\beta}{1+T}. \tag{5}$$

The numerator in (5) represents endogenous variables for the user, while the denominator represents the parameter related to the penalty for theft. Henceforth, this limiting probability is denoted as $P_{\rm CR}$. If the probability of detection p is less than or equal to $P_{\rm CR}$ then theft occurs, else not. An application of this equation for representative user classes in Ceara, Brazil is shown in Figure 3. We note that as expected $P_{\rm CR}$ decreases as T increases. Further, if the cost of preparing additional area to use with illegal water is high, relative to the net unit revenue for water, then there is a lower need for effective enforcement at the same penalty level, T. The estimated unit benefits and consumption for selected groups in the Jaguaribe valley in Ceara are presented in Table 1. On the basis of this data, and assuming T is 1 (fine fully proportional to the value derived from water), the shrimp farmers require lower enforcement

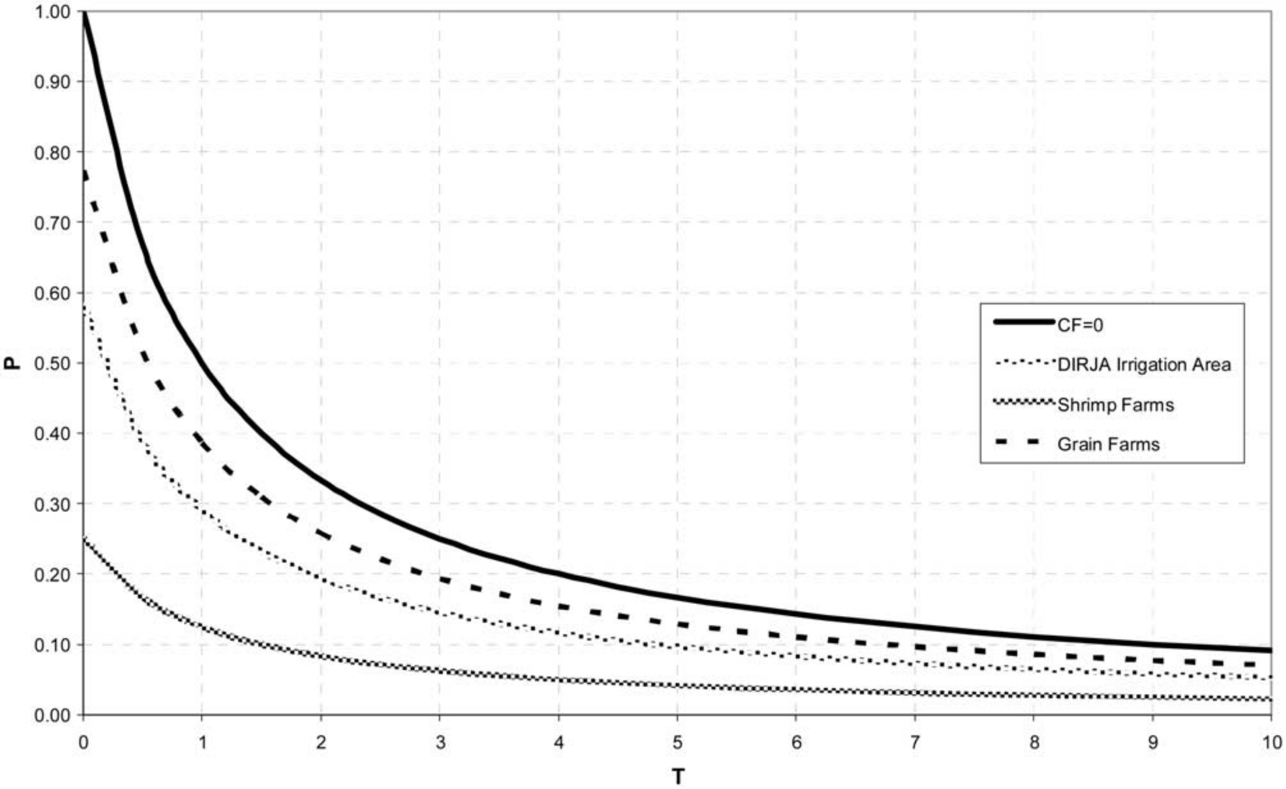

Figure 3. Relation between T and P_{CR} for users in Ceara, Brazil. Each curve represents a different case as listed in the legend.

(in terms of either p or T) to conform to their license than the corn or bean farmers.

[37] The second question to ask is whether it is useful for the user to try to increase the licensed quantity or to steal at the current penalty structure. This can be assessed by comparing $\frac{\partial\pi}{\partial\alpha 1}$ to $\frac{\partial\pi}{\partial L}$

$$\frac{\partial\pi}{\partial L} = \beta - CF = \beta(1 - CF/\beta) \quad (6)$$

$$\frac{\partial\pi}{\partial\alpha 1} > \frac{\partial\pi}{\partial L} \Rightarrow (1-p)\beta - CF - pT\beta > \beta - CF$$
$$\text{or} \quad p(\beta + T) < 0 \text{ or } p < 0. \quad (7)$$

Since the condition identified in (7) is physically unrealizable, where possible the ser would prefer to increase their license relative to stealing.

3.3. Regulation in a Strategic Game: Multiple Uses

[38] The single user case is now extended to consider multiple users on the network, but on the assumption that all the users are aware of their position on the network, and of the potential diversions by users upstream of them, and hence each user knows the applicable available water $R'_{\ell-1}$ for his or her own diversion. A reinforcement learning process is considered to justify this assumption as illustrated in Figure 4. Each year or each cycle through the simulation, users make decisions as to the amount of water they will withdraw. These decisions are propagated downstream through the network as the amount of water available at each diversion point, as show in equation (1). The water available to the user, $R'_{\ell-1}$, at cycle (t + 1) through the simulation is set equal to the quantity that was computed through the simulation at cycle t. In other words, the user has a memory of what he or she expects to receive, given past experience with the behavior of other users, and of the upstream release from the agency, R_1. The iterative cycle of simulations converges (in our experience) to a stable solution that reflects this "knowledge." Hence, this is a direct generalization of the situation developed in the preceding section; the same equations apply at the level of a user, but system performance needs to be assessed across N users. The situation is illustrated in Figure 4.

Table 1. User Information: Estimate Demand, Gross Benefit, Variable, and Fix Cost[a]

Users	Demand (hm3/a)	Gross Benefit, β (10^6 R\$/(hm^3/a))	Variable Cost, C_v (10^6 R\$/(hm^3/a))	Fix Cost, CF (10^6 R\$/(hm^3/a))
1, grain farms, Icó	55.81	0.150	0.056	0.081
2, DIJA irrigation area	22.10	0.276	0.209	0.028
3, shrimp farm (low Jaguaribe Valery)	–	1.209	0.689	0.130

[a] This was constructed using the *COGERH* [1999] and *SRH-Ce* [2002] study on capacity to pay. R$ is the Brazilian currency.

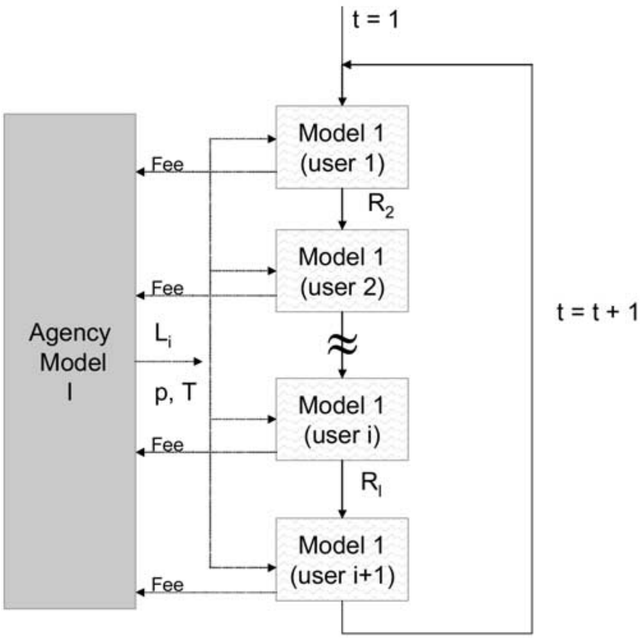

Figure 4. Simulation structure under command and control.

[39] First let us consider that the group of users is homogeneous, i.e., each user has the same demand and net unit benefit from the use of the water (the setting corresponds to that in the Jaguaribe-Apodi Irrigation District (DIJA) irrigation area, for which data was presented in Table 1). As an example consider a single reservoir, and 9 users, each licensed to take 5 units, located serially on the stream section below the reservoir. Gains or losses to natural factors on the stream section are assumed to be insignificant. Consider a total release of 45 units, consistent with the total licenses allocated. Following the logic developed in the previous section, we can see that if the probability of enforcement $p< P_{\mathrm{CR}}$ for the economic situation of the users, then the upstream users will be free riders (drawing water up to $K^i_{\max}$ or $R'_{\ell-1}$), and the downstream users will not receive any water. Thus, the aggregate social benefit will be the same as for the case without free riders since the unit benefit derived from the use of the water is the same for all use. However, this situation leads to inequity across users, which in turn may stimulate a demand for increased enforcement to render the system stable. Here, unlike *Polinsky and Shavell* [2005] we do not seek to maximize net social benefit. Rather, the competitive behavior of agents under uncertainty is analyzed under the game theoretic paradigm.

[40] The second case we can consider is that the users are heterogeneous, e.g., they have different net unit benefits from water use, and different fixed costs to bring the land under irrigation in the season of interest. All other parameters are kept the same. In this case, the solution proceeds in exactly the same way, except that the value of P_{CR} is different for each user. In this case the relative location of the free riders on the stream network depends on their economic attributes. Table 2 illustrates the type of solution that results from a sequential application of the basic optimization model described by equations (2) and (3) for each user along the network. The situation in Table 2 considers three types of users (see Table 1) on a reservoir system illustrated in Figure 3. Three main demand centers are considered. Each demand center has three users. The user type mix varies across demand centers. Three levels of enforcement probability p are considered, and in each case the behavior of the system is simulated. Consistent with the situation in Ceara, the user with the highest net unit benefits from water use is at the end of the system. In Ceara, this is the capital city of Fortaleza. The maximum diversion capacity of each user, $K^i_{\max}$ is taken to be the same for illustrative purposes, and $T = 3$. The results illustrate that in this setting all users end up with a diversion equal to their license, if $p = 0.16$, which is higher than the P_{CR} of the upstream users, but lower than the P_{CR} of the last user who gets water. As the effort on enforcement decreases, users with P_{CR} values higher than p, become free riders, and their illegal abstraction is limited only by $K^i_{\max}$ or $R'_{\ell-1}$. The only recourse the downstream users will have is to push for an increase in p and/or T.

3.4. Regulatory Agency Model

[41] The regulatory agency may use economic incentives or fines to condition user behavior. The key variables considered here are the fine (T) and the inspection effectiveness (p) for detecting water theft. The agency is considered to be auto interested with the goal of maximizing its net revenue associated with enforcement actions. This is not likely to be true in general, since public agencies will typically only try to recover costs (i.e., seek net revenue is zero). However, COGERH, the water supply and regulatory agency in Ceara, chose to use maximization of net revenue as its objective during 2002–2006, motivating the choice here. The net revenue of the agency in this context can be defined as

$$\pi_{ag} = \sum_i \left(pT\beta_i\alpha_{1i}\right) - ap^b. \tag{8}$$

Here, ap^b denotes the cost of regulation. This cost covers satellite monitoring, hydrometering of the water courses and users, inspection teams in the field, data analysis and judicial or administrative action. Using only satellite monitoring may be a low-cost strategy, but the ability to detect illegal usage is related to the satellite resolution, and also to the effectiveness of the proxy used for detecting use. Installing and maintaining in field telemetery could be much more effective (higher p) but at substantially higher cost. The cost function is expected to be convex ($b > 1$), and the parameters a and b can be estimated using cost information for each component of the enforcement strategy. In the previous section the inspection effectiveness, p, was varied till all users were brought under compliance. Here, we

Table 2. Users' Demand and Benefit Histogram for Nash Equilibrium for the Command and Control System With Homogeneous Users[a]

Demand (water units)	Benefit (monetary unit)	Relative Frequency	
		Regulated	Free Rider
0	0.00	0	0.44
5	1.95	1	0.11
10	3.90	0	0.44

[a]The total license equals the total supply (45 water units).

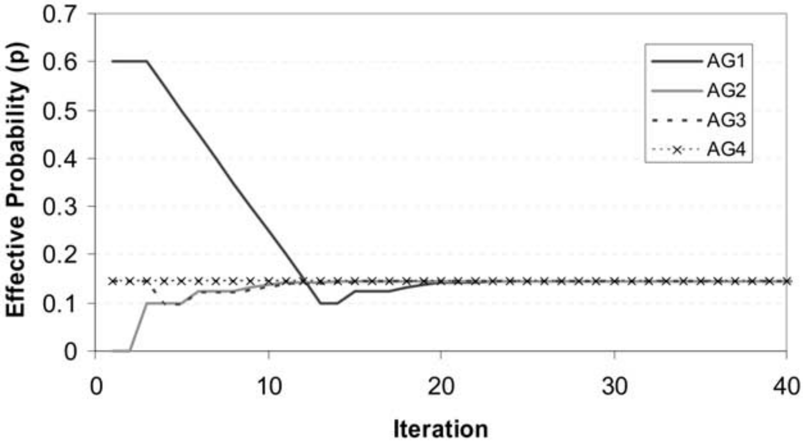

Figure 5. Trajectory of simulations of command and control using the same penalty factor for illegal use ($T = 3$) and different initial inspection effectiveness (p).

explore an optimal value of p given the maximization of equation (8) considering that the fine, T, is fixed by a state law. This is not a single step problem since the users will react to the inspection effectiveness and modify their behavior. To account for these factors, a game is considered, where the agency proposes a p on the basis of the maximization of equation (8), assuming that the use structure (i.e., the α_{1i}, and β_i) is known. This p is then "transmitted" to the users. Each user then solves their optimization problem as in the previous section. This solution is then transmitted back to the agency, and the two step iterative process is repeated till convergence, i.e., the Nash equilibrium is derived via simulation. Figure 4 present the simulation structure.

[42] The Nash equilibria for p derived for $T = 3$, with different a and b, for the case of homogeneous users, are illustrated in Figure 5 and Table 3. Four different initial conditions and the convergence to the optimal value of $p = 0.146$ are illustrated, following the iterative solution procedure described in the preceding paragraph and illustrated in Figure 4. As would be expected given the tendency for free rider behavior, the convergence toward the final solution comes from the inferior limit, i.e., users behave as free riders until they are brought into compliance. The solutions for four other values of T are illustrated in Figure 6. This value of p is the same as given by equation (5) for this class of users. The primary difference from the solution in the previous section is that the trajectory toward this equilibrium contains free riders, whereas the full compliance solution based on only the user's decision could be approached from either direction.

[43] As T increases, the numbers of free riders decreases, and the revenue of the agency may increase, but the income lost by the water users also increases. This non-obvious solution results under the assumption that the upstream user (1) behaves as a free rider and draws more than its allocation and (2) is caught upon inspection some time into the growing season, at which point its water is turned off, leading to a loss in revenue associated with acreage planted to use the unlicensed water, while at the same time, the downstream user could not use this water since they may not have planted as large an acreage given their expectation of receiving a certain flow.

4. Water Pricing and Allocation

4.1. User Under a Water Price System

[44] So far, the price charged for water was not considered as a determinant of user behavior. This important factor is now introduced as part of a water allocation mechanism. We consider that the regulatory agency and the water supply agency are the same (e.g., COGERH in Ceara). Here, a three step allocation process may be used as follows: (1) the agency defines a price of water (w_p) and the likely amount of reservoir release R_1; (2) users submit requests for their desired quantity of water (PO_i) at this price; and (3) the agency allocates the licenses to each user in proportion to the total demand, establishing the licenses, L_i as in equation (9)

$$L_i = \begin{cases} \dfrac{R_1}{\sum\limits_i \mathrm{PO}_i}(\mathrm{PO}_i) & \text{if } \dfrac{R_1}{\sum\limits_i \mathrm{PO}_i} < 1 \\ \mathrm{PO}_i & \text{else} \end{cases}. \tag{9}$$

In this equation R_1 is water availability at the first point of diversion, PO_i is the license requested by the ith user, and L_i is the license granted by the agency. The generic situation is

Table 3. Results From Command and Control Simulations With Homogenous Users, With Reinforcement Learning Through Recursion[a]

Simulation	T	p (initial)	p (final)
AG1	3	0.600	0.146
AG2	3	0.000	0.146
AG3	3	0.150	0.146
AG4	3	0.140	0.146
AG5	5	0.140	0.097
AG7	10	0.140	0.053
AG8	20	0.140	0.028

[a] The simulations (AGx) refer to different combinations of T and p. The resulting final p after simulation to Nash Equilibrium is in the last column.

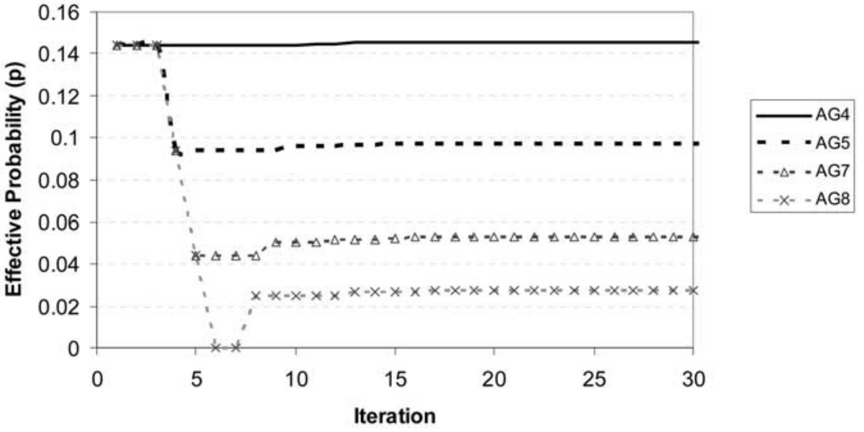

Figure 6. Trajectory of simulations of command and control using different penalties for illegal use (T) but the same initial inspection effectiveness (p).

illustrated in Figure 7, and, the corresponding water user's decision tree is illustrated in Figure 8. Given the price proposed by the water agency, the user decides to propose an allocation PO_i, and also the irrigation diversion he will make, K_i corresponding to the area he wants to plant. The difference $r_i = (K1_\mathrm{i} - PO_i)$, is the amount the user intends to draw as a free rider at this stage. The decision on PO_i and $K1_i$ is made using the model presented in equations (10) and (11), through a sequential simulation of the multiple users on the system, as before in section 3, but with the difference that the decision variables for each user now include the PO_i, and the cost of the licensed water needs to be accounted for.

$$\max_{K1_i, PO_i} \pi_i,$$

subject to an availability constraint

$$Q_i \leq R'_{\ell-1},$$

a utilization constraint

$$Q_i \leq K1_i,$$

a capacity constraint

$$K1_i \leq K_i^{\max}, \tag{10}$$

where the expected net revenue

$$\pi_i = \beta_i \alpha_{0i} + (1-p)\beta_i \alpha_{1i} - CF_i K1_i - pT\beta_i \alpha_{1i} - w_p PO_i \tag{11}$$

with all these terms as defined earlier in equation (2) and (3).

[45] Once the licenses are announced, each user faces a new decision. The decision at this stage is to choose the diversion capacity, K_i, given the license and all the other parameters. This is similar to the multiuser/agency interaction problem described in the previous section.

$$\max_{K_i} \pi_i,$$

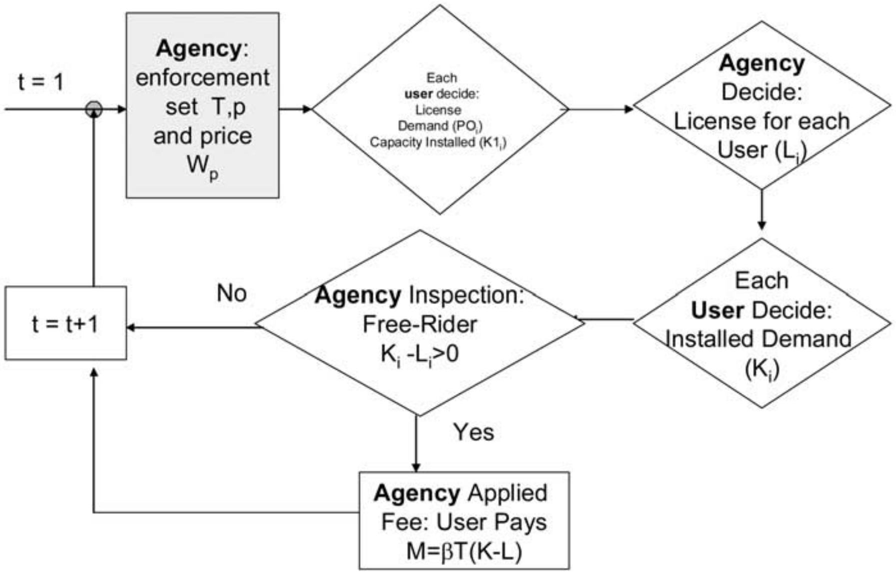

Figure 7. Schematic of decision process with a pricing system.

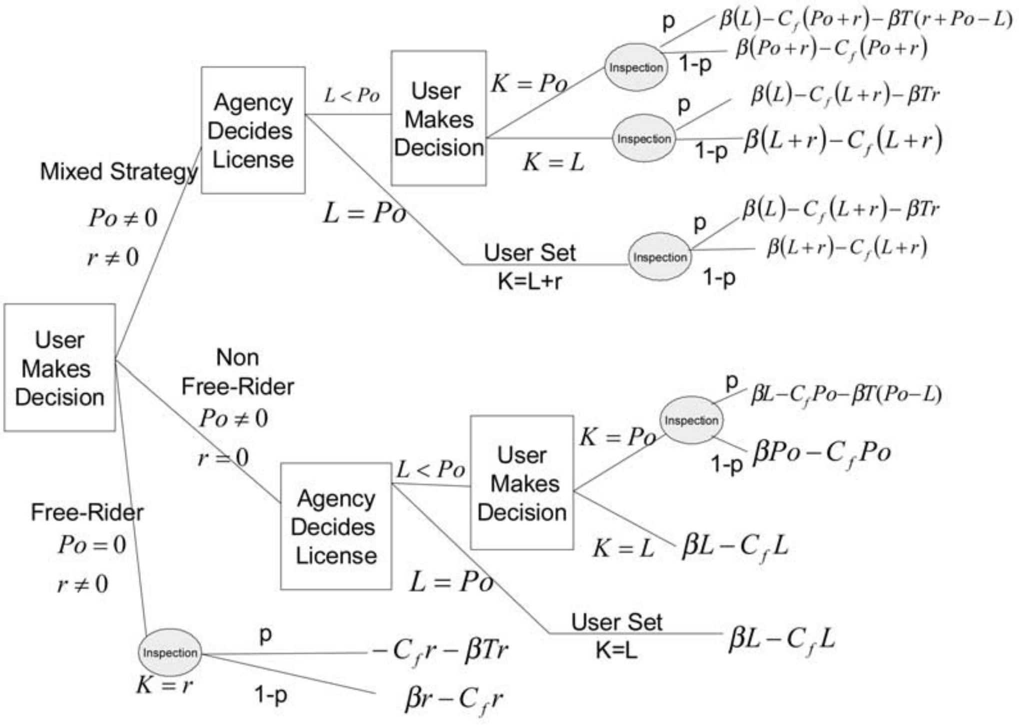

Figure 8. User's decision tree under price-based water allocation ($K1$ = PO + r).

subject to an availability constraint

$$Q_i \leq R'_{\ell-1},$$

a utilization constraint

$$Q_i \leq K_i,$$

a capacity constraint

$$K_i \leq K_i^{\max}, \qquad (10')$$

where the expected net revenue

$$\pi_i = \beta_i\alpha_{0i} + (1-p)\beta_i\alpha_{1i} - \mathrm{CF}_i K_i - pT\beta_i\alpha_{1i} - w_p L_i, \qquad (11')$$

with all these terms as defined earlier in equation (2) and (3). This model is illustrated by Figures 9 and 10.

[46] We can now revisit the question as to the minimum inspection effectiveness needed to move the ith user from free rider behavior to a license given that there is a water price. This can be assessed by identifying the effectiveness probability p such that $\dfrac{\partial\pi}{\partial\alpha 1} \geq \dfrac{\partial\pi}{\partial L}$. This leads to the critical probability P_{CRLR}

$$p_{\mathrm{CRLR}} = \frac{w_p}{\beta_i(1+T)}. \qquad (12)$$

[47] The following outcomes are now possible if we consider only a single user: (1) $P_{\mathrm{CRLR}} > P_{\mathrm{CR}} > p$ user is a free rider since the enforcement effectiveness is too low and the price for the license is very high; (2) $P_{\mathrm{CRLR}} > p > P_{\mathrm{CR}}$ the user does not participate since the enforcement effectiveness is higher than the critical level determined by the user's threshold in the absence of water price and the license price is too high; (3) $p > P_{\mathrm{CRLR}} > P_{\mathrm{CR}}$ leads to the

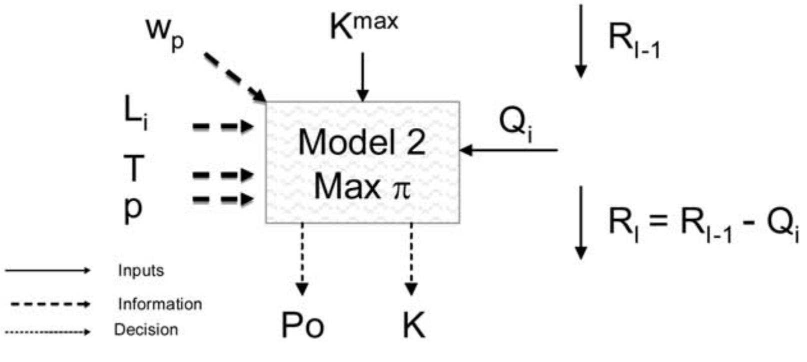

Figure 9. Schematic of user's model under price-based water allocation.

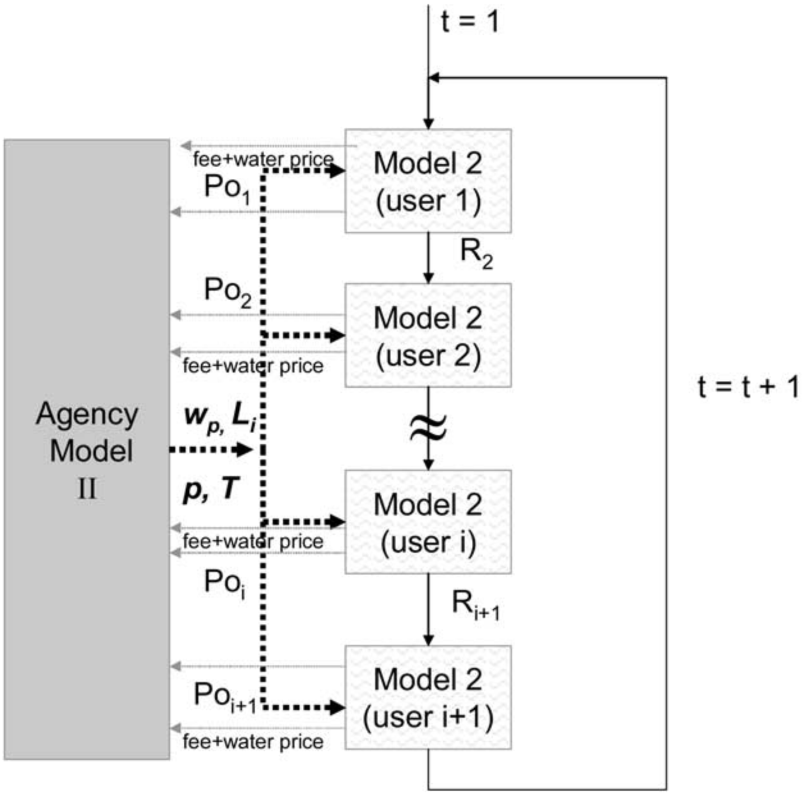

Figure 10. Schematic of user-agency interaction under the price-based water allocation.

same outcome as in case 2; (4) $p > P_{\mathrm{CR}} > P_{\mathrm{CRLR}}$ results in licensed use only; (5) $P_{\mathrm{CR}} > p > P_{\mathrm{CRLR}}$ a mixed strategy with some license and some free-rider behavior; and (6) $P_{\mathrm{CR}} > P_{\mathrm{CRLR}} > p$ leads to free rider behavior as in case 1.

[48] Since cases 1 and 6, and 2 and 3 lead to similar behavior, there are four typologies of possible user behavior. Given the above categorization of a single user's behavior under a pricing and enforcement structure, we can now examine the collective behavior of a set of users and the agency using a sequential simulation as in the previous section.

4.1.1. Homogeneous Users

[49] First, we consider a set of homogeneous users, arranged in sequence along a release stem of the hydraulic network. Recall that the water available to a user is determined by the original release by the agency and the choices of all the upstream users.

[50] In this setting, given the four potential outcomes itemized for each user, the system solution can take the following trajectories. First, we do not need to consider case 2 or 3 since the users will not operate under these conditions. Second, consider that condition 1 or 6 is satisfied. In this case, the price is high, and effectiveness is low. All users are potentially free riders, and will try to allocate and use the maximum capacity $K_i^{\max}$. This translates into free rider behavior such that the first $(k - 1)$ users such that $k * K_i^{\max} > R_1$, are able to utilize the full capacity as free riders, the kth user receives $(R_1 - k * K_i^{\max})$ and the users downstream of the kth user do not receive any water. Next, suppose that condition 4 is satisfied (i.e., $p > P_{\mathrm{CR}} > P_{\mathrm{CRLR}}$). In this case, all users have the capacity to pay, and the effectiveness is high enough so all use is licensed use as identified by equation (9). Finally, consider case 5 ($P_{\mathrm{CRLR}} < p < P_{\mathrm{CR}}$). In this case, effectiveness is weak, but the cost of licensing the water is also relatively low, and hence, it is attractive to license the water. In this case, in the early stages of the simulation all users apply for a license. However, the free-rider action of upstream users leads the downstream user to reduce their request for a license. Once the simulation reaches equilibrium only the upstream users apply for a license and the downstream users do not operate.

[51] It is interesting to consider one special case in this situation. Each user makes an a priori decision to install a capacity $K = K1$, and does not plan to change this decision postlicensing. Example results from such a simulation for different water license prices are shown in Table 4 and in Figure 11, for the case $p > P_{\mathrm{CR}}$. We note that the evolution of system response to equilibrium now depends on the price. As the price increases, all use goes toward licensed use, until condition 3 is satisfied when no user operates because the price and the enforcement are too high. At low prices, condition 4 is satisfied, but initially the upstream users capture all the release leading to 0 usage by the downstream users whose license is not honored as a result of the behavior of the upstream users. As the price increases, the upstream users reduce their offer, $P0$, for the license, and correspondingly reduce $K1$. This translates into a higher rate of license satisfaction for the downstream users, and the increase in licensed use throughout the network. Thus, if the belief is that the users are likely to stay with their a priori

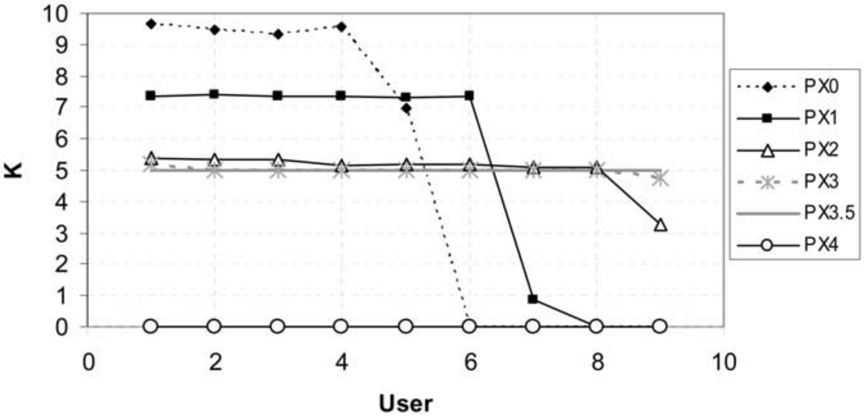

Figure 11. Change in equilibrium as a function of the price. In this simulation, K = PO independent of the state position.

choice for diversion capacity installation even after the license is granted, then the price charged becomes an effective measure of regulation of equity in the system. Note that these observations apply to the equilibrium solution. In all simulations, initially, each user proposes to follow licensed use given that condition 4 is satisfied.

4.1.2. Heterogeneous Users

[52] Now we consider a situation analogous to the one described in the Command and Control section with heterogeneous users, as in Figure 1 and Table 5. We consider 4 simulations with 2 price levels, and 2 enforcement effectiveness levels. The parameters associated with these simulations are listed for each user type in Tables 5 and 6. We note from Tables 5 and 6 that these combinations imply different conditions (as per the list above) for each of the user types, and given this information we can anticipate the solution from the simulation.

[53] The capacity installed by each user under each scenario defined in Tables 5 and 6 is shown in Figure 12. These solutions correspond to what we expect from the individual user profiles. We see that as the price is increased, for the low-enforcement effectiveness case, the type 2 user goes from a mixed strategy to a free rider, while for the higher effectiveness the user goes from licensed use to being screened out of operation. User type 1 never enters the solution. Hence, low value use is either screened out, or promotes a free rider behavior depending on the relative magnitudes of price and enforcement effectiveness. On the other hand, higher value uses will tend to licensed use and are then screened out as price and effectiveness increase.

4.2. Agency

[54] Finally, we consider the agency-user integrated model, where the agency aims to maximize its net revenue, with heterogeneous users and a price structure described in the previous section. The water price is now a decision variable for the agency instead of a fixed scenario. The agency's income could be described as:

$$\pi_{ag} = \sum_i \left(pT\beta_i r_i + w_p L_i\right) - ap^b. \qquad (13)$$

[55] Equation (13) differs from equation (8) in that the revenue now includes the component contributed by the price w_p. As in the previous section, for any value of w_p, we can classify the condition of each user type and anticipate the solution. The difference is that now w_p is a decision variable. The results from the simulation using the same parameters for user attributes as in the previous section are shown in Tables 5 and 6, and Figure 12. Under the net revenue maximization goal, the optimal w_p is much higher than the price in the scenarios considered earlier that were more in line with prevalent prices.

[56] We note that under the conditions of this simulation, all users except those with the highest value use are effectively screened out from the solution. Of course, this

Table 4. Simulations Using the Price System With Homogeneous Users[a]

Simulations	p	w_p (R\$/10 m^3)	P_{CRLR}	Range of Installed Demand	Standard Deviation of Installed Demand
PX0	0.6	0.00	0.000	9.7	4.810
PX1	0.6	0.10	0.037	7.4	3.539
PX2	0.6	0.20	0.075	2.1	0.661
PX3	0.6	0.30	0.112	0.4	0.108
PX3.5	0.6	0.35	0.131	0.0	0.000
PX4	0.6	0.40	0.149	0.0	0.000
PX2-B1	0.1	0.20	0.075	10.0	5.000

[a] The simulations are indexed by PXx reflecting different combinations of p and w_p. In all cases T = 3.

Table 5. Simulations for the Price-Based System With Heterogenous Users[a]

User Type	β	CF	P_{CR}	P_{CRLR} (w_p = 0.2)	P_{CRLR} (w_p = 0.4)	P_{CRLR} (w_p = 3.9)
1	0.94	0.81	0.035	0.053	0.106	1*
2	0.67	0.28	0.146	0.075	0.149	1*
3	5.20	1.30	0.188	0.010	0.019	0.188

[a] The P_{CR} value is now different for each user. Three price levels (w_p = 0.2, 0.4, 3.9) are considered. The third price corresponds to the optimal price when the agency-user model in section 5 is considered. The P_{CRLR} values corresponding to each of these prices for each agent are shown. A P_{CRLR} probability of 1* refers to a case where the price is high enough to force the user out of the market. In all cases T = 3.

Table 6. Simulations for the Price System With Heterogeneous Users[a]

Simulation Index	p	w_p	User 1	User 2	User 3
p010wp02	0.10	0.2	3	5	5
p010wp04	0.10	0.4	2	1	5
p016wp02	0.16	0.2	3	4	5
p016wp04	0.16	0.4	2	3	5
Optimum Equilibrium from agency-user model	0.20	3.9	2	3	4

[a] The simulation index pxxwpyy refers to p and w_p combinations as shown in the table. The numbers shown for each user correspond to one of the six conditions or outcomes listed in section 4.1.

is the usual concern with water supply allocation, and the reason regulatory and allocation measures in a public goods framework, and not rvenue maximization are advocated and used.

5. Summary and Discussion

[57] Many water allocation plans often lapse into disuse or are ineffective when the allocated water is not delivered with any reliability. As indicated at the beginning, climate risk is a factor that affects the water available at the macrolevel, and hence to the users. This factor is usually understood by the users, and by itself does not promote free rider behavior. Rather, the inability or uncertainty to get licensed water at the agreed upon contract price can be a driving factor for free-rider behavior. The other factor is of course the water price. Social equity and efficiency issues consequently arise at the system level, and need to be considered by the operator. The water system operator can set water prices, and fines for illegal use to influence this user behavior. However, the degree of effectiveness in enforcing the licenses that are allocated emerges as a significant concern, since it may require large investments on part of the operator, and only a subset of the users may see the value of paying for this enforcement activity. The work presented here focused on identifying some simple conditions under which the user-agency interactions could be managed toward the goals of either a targeted level of compliance, or equity across users, or to focus on the agency's revenue. Given the conceptual nature of the analyses, a variety of simplifying assumptions were made and applicable conditions derived. Some observations for institution design are summarized below.

[58] 1. If a user's benefit from water use can be assessed, then given the fine structure, and the water price, a selective inspection strategy (per user class and based on their position in the hydraulic network) could be designed, given the P_{CR} or P_{CRLR} value that is estimated for each user. The agency could thus improve enforcement effectiveness with the same budget.

[59] 2. In practice there is information asymmetry between the regulatory agency and the users. This complicates the identification of the optimum inspection level. The maintenance of a users' survey and of background socioeconomic information of the water users is necessary to estimate parameters related to P_{CR} and to help design the monitoring program. COGERH and Water Resources State Department (SRH), the relevant water agencies in Ceara already collect such information. Generally, this is another expense that needs to be accounted for.

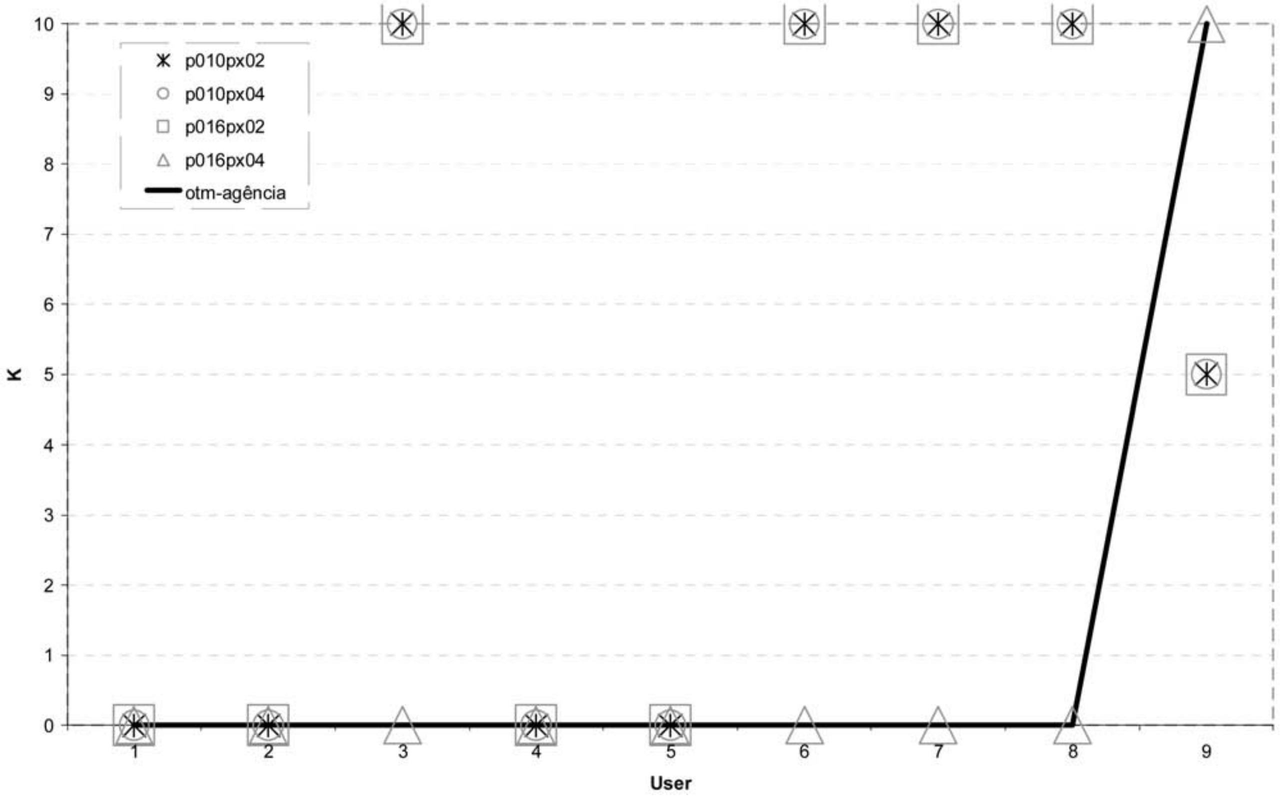

Figure 12. Demand installed (K) by user and as a function of price and effectiveness in the heterogeneous price system.

[60] 3. For a homogeneous user group, the main problem that emerges is inequity due to position on the hydraulic network. The aggregate social benefit derived from water use is unchanged, and the allocation-enforcement process is not primarily impacting the macroscale economic outcome. For a heterogeneous user group, in addition to this positional inequity issue, the overall economics can be impacted if higher value uses fail to get water.

[61] 4. Significant inequities in allocation can result, particularly to high value users, if the water agency does not selectively target upstream users who are potential free riders. This (1) translates into pressure from high value users for enforcement and (2) requires a selective inspection strategy with appropriate investment in enforcement effectiveness. Note that we used p the probability of effectiveness as a general measure in the preceding analyses, and did not separate the effectiveness of inspection from that of prosecution. In many developing countries, the latter is a more significant factor, and may be beyond the control of a water agency.

[62] 5. When water price is not set or considered, the hydraulic position on the network becomes a primary carrier of the information for a user to make a decision as to free rider behavior. Price changes this situation by offering a second signal that needs to be considered passing through the hydraulic network. The joint effect of both pieces of information is assessed in an iterative fashion in reality and in the simulation, conditional on past experience. The additional uncertainty induced by climate, through changing reservoir content and upstream release each year, makes the cognitive assessment of these signals more complex for the users. Hence, the idealized results developed here will actually be “softer” where data is being collected and interpreted by the users in a real situation.

[63] 6. An agency with the goal of revenue maximization through price and enforcement will, as may be anticipated, end up with a water allocation where many uses will be screened out of the system, leading to social inequities, and also a reduced aggregate social benefit. This situation can be and is usually addressed through some social control of the goals of the agency. This is consistent with the public sector regulation of even a privately organized water company.

[64] 7. Given limited budgets, agencies often consider a high fine (T), but are constrained to a low p. As a result, system enforcement is weak and performance poor. In the context of the analyses presented here, combinations of T and p are best interpreted through the applicable P_{CR} and P_{CRLR}, at the individual user level. At the system level, the selection of T and p to maximize the net revenue from enforcement (at a fixed water price) could be pursued by the agency. Decisions on moving to a lower T and higher p, both in system performance and in the economics of enforcement could be formally evaluated. Of course this is only possible if the enforcement budget increases. In this scenario, the user faces a stiff penalty due to the loss of use of excess area irrigated with stolen water if free rider behavior is detected.

[65] 8. The analyses presented assume rational behavior driven by a few economic parameters by both the agency and the users. This assumption may not hold, and actual behavior metrics may need to be elicited through experimentation in a participatory setting that is close to the real transactions.

[66] 9. Enforcement costs can be reduced by involving private individuals in the process. As was noted earlier, downstream users as well as high value users who are likely to be impacted by free rider behavior have incentives to see better enforcement. These groups could be identified and mobilized at relatively low cost to report illegal use.

[67] 10. The use structures and the aggregate water use or demand revealed by the agency-user interaction models is in general different from the traditional macro level price demand models. The inclusion of the externalities caused by free rider behavior as a function of position on the hydraulic network is a major factor in this difference. This is a good reason to explore such models.

[68] 11. The practical application of the ideas presented here requires the estimation of a number of parameters, and tests as to the validity of the assumptions made as to risk preference, utility and user attributes. These relate in a sense to the scenarios presented in the previous sections, and specifically to the parametric evaluations of outcomes as key regulatory parameters are changed. These parametric evaluations prior to implementation can inform the regulator as to the sensitivity of the outcomes to each of the parameters. Then, as the regulatory system is enforced, data can be collected on regulatory effectiveness (e.g., the probability p) conditional on the budget, and the results of the sensitivity analysis with respect to each parameter used to judge whether the outcomes are consistent with expectation given the range of uncertainty assessed or anticipated with respect to the key parameters. If the results are outside the expected range, then the parameter values could be iteratively updated to reflect field conditions. Of course, this suggests additional expenses for information collection to support the regulatory process that need to be accounted for in the budget.

[69] 12. Attitudes toward risk preference were not explicitly considered in what we presented earlier. Risk aversion to being caught could be explicitly modeled. If the user is risk averse, then the user’s utility function will be concave with respect to its expected net revenue, as opposed to linear for the risk neutral case analyzed in this paper. We formally analyzed this situation to show that as expected the likelihood of free rider behavior is reduced with respect to the risk neutral case, for the same parameters as to the probability of detection, the fine and the water price. Conversely, if the user has a convex utility function, i.e., exhibits risk preferred behavior, the likelihood of free rider behavior increases.

[70] Our current work is exploring the use of economic experimentation to understand how departures from the rational crime model used here can be characterized and modeled. An inspection system for water rights enforcement is currently being designed for the state of Ceara, and we are integrating ideas for continuous data collection, analysis and model refinement into the design of this system. Finally, this work interfaces with our recent work [*Souza Filho and Lall*, 2003] on long-range streamflow forecasting using climate information, and the use of this information for the design of market driven and participatory water allocation and risk management tools. The idea here is that using the forecasts we can declare the amount of water that could be allocated

at the reservoir outlet with a specified reliability level. Then an allocation process that could consider multiple price structures related to use, and some prior water rights can be explored using annual and longer-term contracts with reliability terms that could be backed by insurance instruments. The enforcement system design would then adapt to this system of dynamic risk management for water resource allocation, and support both system performance and the assessment of inequities that result because of climate risk or institutional risk.

[71] Our goal in this paper was to expose some basic ideas and consider directions for future integration with management systems. It is our hope that joint consideration of climate and institutional risk in water resource management will be of considerable practical value. Several simplifying assumptions were made in order to constrain the communication. These include a limited specification of the risk attitudes of the participants. In reality users may exhibit varying degrees of risk aversion and these heterogeneous aspects may need to be modeled. Similarly, a strong assumption was made that each user makes rational decisions as to illegal acts in a self interested way, maximizing his or her net monetary benefits, There is evidence from experimental economics that this is often not the case. Given a punishment structure people may choose to cooperate rather than free ride [*Fehr and Gächter*, 2002; *Hagel and Roth*, 1995]. Similarly, the theory of rational crime under utilitarian ethics as considered here is not the only possible paradigm. Others possible considerations include theological factors, ethics, social justice and property rights as discussed by *Des Jardins* [2000].

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F. A. Souza Filho, Department of Hydraulics and Environmental Engineering, Center of Technology, Federal University of Ceará, Campus do Pici, Bloco 713, Fortaleza, Ceará 60451-970, Brazil. (assisfilho@secrel.com.br)

U. Lall, International Research Institute for Climate and Society, Columbia University, Lamont Campus, 61 Route 9W, Monell Building, Palisades, NY 10964, USA.

R. L. L. Porto, Department of Hydraulics, University of São Paulo, Avenue Prof. Almeida Prado, 83 Trav. 2, São Paulo 05508-900, Brazil. (sao41566@terra.com.br)