INSTITUTIONAL ANALYSIS, PUBLIC POLICY, AND THE POSSIBILITY OF COLLECTIVE ACTION IN COMMON POOL RESOURCES: A DYNAMIC GAME THEORETIC APPROACH

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Dedicated to my lovely wife, Eunmee,

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Contemporary policy analyses are frequently based on a presumption that those jointly using a common-pool resource (CPR) cannot themselves resolve collective action problems related to the CPR since individual rationality conflicts with social rationality. CPR situations are frequently portrayed as a Prisoner's Dilemma game, whose unique outcome is mutual defection. Individuals who seek to maximize their individual payoffs, according to this argument, fail to manage CPRs as effectively as they could if they could coordinate their actions.

Empirical studies, however, show that some CPR users have been able to overcome problems of collective action. This anomaly of the standard theory of collective action applied to CPR situations stems from the fact that the incentive structures of individuals facing CPR situations are not well explained by standard theories. Standard theories: (i) lack detailed specification and justification of payoffs (ii) are usually static; and (iii) consider only one of the two main collective action problems in CPR situations -- appropriation problems and provision problems.

Drawing on the Institutional Analysis and Development framework and dynamic game theory, this study develops a new model of the incentive structure of CPR situations that clearly specifies and justifies payoffs, is dynamic, and considers both appropriation and provision problems at the same time. Due to the complexity of this game, a computer simulation using Mathematical program is used in solving this game. This new model enables us to explore the possibility of self-governing solutions to collective action problems in CPRs. The findings of this study demonstrate that appropriators can, under specified conditions, manage CPRs more effectively than predicted by

earlier theories. Further, how key factors affect the possibility of self-governing solutions to collective action problems in CPRs is analyzed.

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Chapter 1

Introduction

Common Pool Resources and Collective Action Problems

Common pool resources include a wide variety of resources, such as irrigation systems, fisheries, wildlife, surface and ground water, range land. Common pool resources (hereafter, CPRs). CPRs are defined as a class of natural or man-made facilities that produce a flow of use units per unit of time that may potentially be utilized by more than one individual or agent simultaneously or sequentially where exclusion from the resource is difficult or costly to achieve (non-excludability) and joint use reduces the amount available to each individual (subtractability) (E. Ostrom, Gardner and Walker 1992). Thus, CPRs share two important common characteristics: Non-excludability and Subtractability (Ostrom and Ostrom 1977; Feeny et. al. 1990; E. Ostrom 1986b; Oakerson 1986).

Non-excludability refers to the technical and economic feasibility of controlling access by potential users. Exclusion is technically infeasible where no practical technique exists for excluding potential users from enjoying the resources. Exclusion is economically infeasible if the costs of exclusion are higher than the benefits of exclusion.

Subtractability means that the consumption by each user subtracts from the value obtained by other users. In other words, the level of consumption or exploitation by one user affects the ability of another user to consume or exploit the resource. If, for example, one irrigator appropriates water from an irrigation canal that is shared by several irrigators, there is less water per unit of irrigating effort for other irrigators.

Characteristics of non-excludability and subtractability present serious problems in human organization. Since it is difficult to exclude users, rational users will maximize their own interests by trying to get as much as possible from the resource while paying as little as possible. But, since the good is subtractable, the availability of that good decreases, as individuals appropriate it. Therefore, a group of rational users will not reach a Pareto-optimal outcome. Outcomes are Pareto-optimal when one cannot increase one person's welfare without reducing someone else's. In CPRs, every user benefits if all refrain from a level of use that exceeds some threshold. Yet, by definition, it is technically or economically difficult to control use of the resource. As a result, users acting independently may not achieve the Pareto-optimal outcome, that they could attain if they behaved in a collectively rational way. Because of the likelihood of suboptimal outcomes, CPR situations are often called "the tragedy of the commons" (Hardin 1968) or "the commons dilemma" (Gardner, E. Ostrom, and Walker 1989).

Situations where individual rationality conflicts with socially optimal choices, such as the CPR case, are Social Dilemmas. A social dilemma refers to a situation where individuals have an individually rational choice that, when made by all members of the group, provides a poorer outcome than that which the members would have reached if members made collectively rational choices (Messick and Brewer 1983). Public good provision problems and CPR problems are typically the two examples given for social dilemmas. Conceptually, these problems have been treated as two separate ones. Public good provision problems have been formalized as "social fences" (Sell 1988; Messick and Brewer 1983) or [11] give-some-games" (Hamburger 1973) . In a social fence or a give-some-game situation, individuals face incentives *to not do* something; when too few do that thing a suboptimal state of affairs results. CPR problems, on the other hand, have been formalized as "social traps" (Sell 1988; Messick and Brewer 1983) or "take-some-games" (Hamburger 1973). This denotes a situation where the individually rational choice *to do* something leads to individual and collective disaster.

In CPR situations, two major kinds of collective action problems --appropriation problems and provision problems -- are frequent sources of sub-optimality (Gardner, Ostrom, and Walker 1990; E. Ostrom 1990). To escape from a social dilemma, we must resolve both problems. Solving appropriation problems focuses on the allocation of the flow of a resource. Solving provision problems focuses on the creation or maintenance of the stock of a resources (Gardner, Ostrom, and Walker 1990; E. Ostrom 1990). In other words, CPRs have two aspects -- flow and stock. Appropriation problems focus on the <u>flow</u> aspect of the CPR, whereas provision problems concentrate on the <u>stock</u> aspect of the CPR. Provision problems have been ignored while appropriation problems have been treated as the major problems for CPRs problems. Provision problems are more important in the cases of man-made resources than in the cases of natural resources. Provision problems, however, can also be of great importance even in the cases of natural resources when maintenance becomes necessary.

The provision and appropriation problems are highly inter-dependent. The incentive structure of the action situation of the appropriation problem is affected by the outcomes of the action situation of the provision problem, and vice versa. This implies that CPR problems should be formalized as "social fences" and "social traps" at the same time, rather than solely as "social traps".

<u>CPR Dilemma and Public Policy</u>

The collective action problems in CPR situations are frequently used as a justification for governmental intervention or regulation (E. Ostrom 1990). Policy recommendations based on this line of logic have been supported and enforced by the logic of the Prisoner's Dilemma (PD) game (Wade 1988a; E. Ostrom 1990; Gardner, Ostrom, and Walker 1990).

cause of its unique and suboptimal outcome (mutual defection), the PD rame has been used to portray the tragic situation of a CPR dilemma in which individual rationality leads to an outcome that is not rational from the perspective of the group. Other games, such as a Chicken game or an Assurance game, also depict some CPR dilemmas well (Runge 1984; Taylor 1987; Isaac, Schmidtz, and Walker 1989; Gardner, Ostrom, and Walker 1990). If no one person's contribution is sufficient to gain a collective benefit but both persons' contribution will produce the joint benefit, the incentive structure of this CPR dilemma can be best described by an Assurance game rather than by a PD game. The incentive structure of this CPR dilemma can be best portrayed by a Chicken game rather than a PD game when: (1) there is a minimum amount of work which must be done; (2) either individual alone can do it all; and (3) each person prefers that the other do all the work.

The recognition that suboptimal outcomes of CPR dilemmas may result from Chicken or Assurance structure instead of PD game incentives does not change the direction of policy recommendation to a great extent. Analysts still often propose to resolve the CPR dilemma through an "externally imposed solution by Leviathan" (Ophuls 1973). The frequent proposal of externally imposed solutions stem from the failure to recognize the difference between "CPR situations" and "CPR dilemmas". According to Gardner, Ostrom and Walker (1990), both CPR situations and CPR dilemmas satisfy the conditions of resource unit subtractability, non-excludability and multiple appropriators (pp. 336-337). However, CPR situations do not satisfy the conditions of suboptimal outcomes and constitutionally feasible alternatives, while CPR dilemmas satisfy both of these conditions. That is:

> if suboptimal outcomes are not produced for at least one combination of the physical system, technology, rules, market conditions, and attributes of the appropriators, there is nothing problematic in the situation. If no alternative set of constitutional feasible strategies (given discounted benefits and costs) would produce both a better outcome for the appropriators or for the group of current and potential appropriators, there is no dilemma (Gardner, Ostrom, and Walker 1990, 337).

Many policy analysts improperly presume that most CPR situations **are** CPR dilemmas and thus must be resolved by external actors. This presumption is not completely wrong. As a matter of fact, we can observe many CPR situations that are CPR dilemmas (for examples, see, E. Ostrom 1990). Yet we can also observe many CPR situations that are not CPR dilemmas because appropriators themselves successfully resolve the potential dilemmas (Dahlman 1980; National Research Council 1987; Wade 1988b; E. Ostrom 1990; Netting 1981; Feeny 1990; Tang 1991). CPRs managed by appropriators without external help can even achieve higher levels of performance than CPRs managed by external agencies (Ostrom, Lam, and Lee 1994).

Theories based upon game theoretic models and the logic of collective action can explain why CPR situations become CPR dilemmas, but they cannot explain how some individuals who jointly use a CPR can achieve an effective form of governing and managing their own commons, while others cannot. Instead of simply presuming that the individuals who share a CPR are inevitably caught in a trap from which they cannot escape by themselves, we should admit that individuals can possibly extricate themselves from various types of dilemma situations at least to some extent. Therefore, we need an adequate theory of CPR situations that can explain differences between various types of dilemma situations and that can explain the resulting differences in the incentive structures of individuals.

There exist many approaches for explaining the possibility of self-organizing solutions to CPR problems. However, no **formal theory** or **model** exists that can satisfactorily explain the success of self-organizing management of CPR, even though many **empirical studies** illustrate the possibility of self-organizing solutions to CPR problems. Formal theories fail to explain successes because they cannot capture the true incentive structure of individuals facing CPR situations. This lack of a proper- model of the incentive structure of individuals in CPR situations leads to the misplaced belief that every CPR situation is problematic; and this incorrect belief consequently leads to the wrong policy recommendations.

Public Policy and Formal Models

Public policy is inevitably based upon some theories about the social problems which the particular policy is designed to tackle (Pressman and Wildavsky 1973). If the theory upon which the public policy is based is wrong, then the policy is likely to fail. To make a precise and detailed prediction of human behavior in a problematic situation and to find a way to alter human behavior to a more desirable state, policy analysts need to know the incentive structures of individuals in that situation. Without knowing and changing the incentive structures that individuals face, policy analysts cannot achieve the desired state or outcome even though they can propose changes to formal rules or formal laws. It is not persuasion or fiat but changes in the incentive structure of individuals that can make changes in the pattern of interaction among them (Chambers 1988; E. Ostrom 1992). By focusing on incentive structures and action arenas,[1] we can see the impacts of various factors which are invisible upon direct observation. An important research problem is, therefore, whether or not an alternative formal theory can be proposed with which we can satisfactorily explain the incentive structure of individuals in CPR situations, the possibility of self-organizing solutions to CPR problems, and the effects of important variables on them. This study will attempt to address this important problem.

This attempt is of great importance to policy studies for two reasons. First, most policy recommendations and development plans on

[1] It is a conceptual unit which is composed of an action situation and an actor. This concept will be explained in detail in Chapter 4.

CPR problems focus on the physical variables and ignore organizational, social, and institutional dimensions (USAID 1983). In the irrigation case, for example, policy analysts are likely to assume that, after new physical works are designed and constructed,

> the farmers in each turnout would, on their own, organize themselves for the equitable distribution of the water allocated to them,...[and] the farmers would maintain their field channels and irrigation structures on their own (Jayawardene 1986, 79).

This misplaced optimistic belief that spontaneous self organization follows the design and construction of physical works by outsiders (without involving the farmers in the process) stems from a lack of understanding of the potential commons problems associated with irrigation systems management. This likely leads to a "natural determinism" (Tamaki 1977, 1), or a dogmatic way of thinking that supposes that natural factors alone determine the success of an irrigation system. My approach pays proper attention to social and institutional variables in addition to physical ones.

Secondly, policy recommendations that do not neglect the potential commons problems associated with irrigation system management may be problematic because they are based on a overly pessimistic theory of collective action. These recommendations treat appropriators as incapable of organizing themselves to tackle commons problems. Hence they impose institutions on appropriators from outside in order to solve commons problems. Only by building proper models of incentive structures facing individual appropriators, can we overcome these pessimistic policy recommendations and solve commons problems more effectively.

To recapitulate, simply giving individuals a fiat or a blueprint cannot guarantee changes in their incentives and behaviors. Changes in public policy or formal rules are not equivalent to changes in the behaviors of individuals (Ostrom and Gardner 1989). We need public policy that can change the incentive structure and generate "PROD change".[2] That kind of public policy requires knowledge of action arenas. Using formal models, we can logically deduce the expected outcomes of the hypothetical situations that follow changes in public policy. Thus, this study attempts to build a new formal model of CPRs to examine the incentive structures of individual appropriators, and to analyze the impacts of important variables, such as institutional arrangements and physical attributes, on incentive structures in action situations and their impacts on the patterns of interaction and outcomes.

Collective Action Problems in Irrigation Systems

A variety of CPRs differ from each other to a great extent. A single formal model, therefore, cannot successfully explain the incentive structures of individuals using these different CPRs. Similarly, there can hardly be a single policy prescription for all commons problems. For this reason, we need to restrict our focus to one specific CPR at a time to avoid the mistake of relying on metaphors as the foundation for policy advice, which "can lead to results substantially different from those presumed to be likely" (E.Ostrom 1990; 23) / In this study, I pick an irrigation system and explore the incentive structure of appropriators in irrigation systems.

An irrigation system is a facility that provides a finite flow of water for multiple appropriators. Irrigation systems share two features. First, once an irrigation system is constructed it is costly (not necessarily impossible) to exclude potential beneficiaries from using the system (non-excludability). Second, the flow of water available at any time in an irrigation system is limited

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[2] Wildavsky (1979) proposed this as a criteria of successful policy. It refers to "Personal Relationships whose Outcomes Differ", which means that we need to alter the pattern of relationships between participants in order to change the outcomes. For more information, see Wildavsky 1979, pp.264-70.

(subtractability). Because of non-excludability, individuals have little incentive to contribute to the provision of the irrigation canal. The problem of subtractability necessitates regulating the use of the limited amount of flow units available in order to ensure a productive and equitable use of the units. Water allocation and investment are two major sources of collective action problems (Tang 1992).

Individually rational farmers might appropriate as much irrigation water as possible even though they would <u>not</u> get the socially optimal outcome; this is the "appropriation problem". Farmers also must cooperate to build and maintain the facilities (e.g., canals, ditches, etc.) essential for effective retention and transportation of irrigation water. For example, they must remove the silt in the canal in order for the irrigation system to work properly. This task requires cooperation among farmers. But, it is difficult to prevent those who do not participate in maintenance work from enjoying the benefit of work done by others; this is the "provision problem" (E. Ostrom 1986b; Gardner, Ostrom, and Walker 1990; E. Ostrom 1990; Ostrom, Gardner and Walker 1992). In short, two major kinds of collective action problems -- water allocation and investment -- frequently contribute to sub-optimal performances in irrigation systems. Despite these collective action problems, however, empirical studies show that low-tech farmer-managed irrigation systems tend to achieve average performance levels above the high-tech systems operated by the State (Tang 1992; Ostrom, Lam, and Lee 1994). This is one of the central puzzles that this study addresses.

Focus of the Research

In this study, I develop a formal game theoretic model to explore the incentive structures facing individuals in CPR situations, especially in the canal irrigation situation. This model allows us to explain the anomalies of previous formal models. With this model, I show that it could be individually rational and possible for appropriators to resolve CPR dilemmas by themselves to some extent under some conditions. Next, I examine the impacts of institutional arrangements, physical attributes, and community attributes on the incentive structure of individuals in CPR situations and on the possibility of a self-governing solution to the collective action problems in CPRs. Due to the complexity of this model, a computer simulation using a Mathematica program solves this game.

In Chapter 2, I discuss several formal models that try to explain the incentive structure of individuals using CPRs and how they can resolve collective action problems without external help. I then propose a new approach to model the incentive structure of CPRs.

Chapter 2

Formal Models of Collective Action Problems and Possibility of Cooperation

The incentive structure of individuals in CPR dilemmas has been portrayed by models such as "the tragedy of the commons," "the collective action problem," and "the PD game." These three models generate the same prediction: appropriators of CPRs cannot resolve the collective action problems without external help. Often, formal models generate more optimistic predictions. "Meta-game theory," "repeated game theory," "correlated game theory" for general collective action problems in CPRs, and "the irrigation game" by Weissing and Ostrom (1991) for collective action problems in irrigation systems all predict that appropriators could possibly escape from the traps of collective action problems without external help to some extent under some conditions.

All of these formal models are, however, "diverse representations of a broader and still-evolving theory of collective action... [and m]uch more work will be needed to develop the theory of collective action into a reliable and useful foundation for policy analysis" (E. Ostrom 1990, 7). In this Chapter, I discuss formal models of collective action and their limitations, then in Chapter three I develop a model of collective action problems in irrigation systems.

Models of Collective Action Problems

The Tragedy of the Commons

Garret Hardin (1968) portrays collective action problems in using CPRs with the case of a rational herder in an open pasture. In his famous example, a rational herder raises animals in a pasture. Each herder receives a payoff from his/her own animals and suffers costs from the deterioration of the pasture when his/her or others' animals overgraze. It is individually rational for each herder to add more and more animals because each herder receives the benefit of his/her own animals yet each bears only a fraction of the costs of overgrazing. Hardin concludes:

> Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit - in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. (Hardin 1968, 1244).

This story portrays a verbal model of "the tragedy of the commons", which has symbolized the expected degradation of resources whenever many self-interested, rational individuals use them in common. This model illustrates well the possibility of the destruction of CPRs in the absence of no external regulation. Although Hardin captures the basic similarities of CPRs, his model cannot explain why and how some appropriators effectively manage their CPR without external regulation. Moreover, this model deals only with "the appropriation problems", neglecting "the provision problems" of CPR situations.

The Logic of Collective Action

Mancur Olson (1965) also points out the difficulties of collective action. He contests the optimistic thesis of group theory that individuals would voluntarily try to further common interests. He asserts that "rational, self-interested individuals will not act to achieve their common or group interests" (Olson 1965, 2) because they have little incentive to contribute voluntarily to the provision of a collective good when non-contributors obtain the benefits of that good. Olson concludes that a large group cannot successfully provide collective goods through voluntary contributions.

Olson also argues that a privileged group can successfully provide a collective good. A privileged group contains at least on individual whose net benefits from their own contribution to a collective good (Aj) exceed zero ($A_i>0$). The net benefit is the difference between the cost (C) and the gross benefit to the individual from the good (V_j).

(!) $A_i \quad - V_i - C$.

If $A_i < 0$ for all individuals in a group, the group is latent and will fail to provide the collective good in the absence of other selective incentives that induce contribution (Olson 1965, Ch. 1). Olson applies this analysis to interest groups and concludes that the latent nature of most of these groups ensures that they cannot effectively provide collective goods without selective incentives.

This model is less pessimistic than "the tragedy of the commons". It offers an explanation of when collective goods cannot be provided voluntarily and when collective goods can be successfully provided without external help. Olson's model, however, only focuses on one of the collective action problems in a CPR situation; it deals only with "provision problems."

Prisoner's Dilemma Game

Harding's model and Olson's model can also be formalized as a PD game (Dawes 1973; E. Ostrom 1990). A 2-person, one-shot prisoner's dilemma game (hereafter, PD game) has been the formal model most frequently used for collective action problems in CPR dilemmas, probably because the PD game formalizes both social traps and social fences. Two characteristics define a PD game.[1] First, defection is the dominant strategy for each player; regardless of whether the other player chooses "Defect" or "Cooperate". Second, if both players follow the dominant strategy, then the final outcome (Defect, Defect) is Pareto-inferior; both players can find some other outcome (i.e., Cooperate, Cooperate) that they jointly and unanimously prefer (Ordeshook 1986; Tsebellis

[1] For more strict and formal properties of a PD game, see Hamburger 1973.

1990).[2] This discrepancy between individual rationality and collective rationality enables a PD game to depict a situation in which everyone may suffer loss even though each individual acts rationally.

This PD game has been the basic model upon which most game theoretic literature on social dilemmas is based, even though some modify it. For example, there exist continuous choice version of PD games (Taylor 1987); graduated choice version of PD games (Snidal 1985; To 1988); n-person version of PD games (Hardin 1971; Hamburger 1973; Schelling 1973); and CPR games (Dawes 1975; Umino 1989), which are modified versions of n-person PD games. All variants of PD game offer two incentives to defect: the desire to avoid being a sucker (fear), and the desire to capture the free-rider payoff (greed). Coombs (1973) asserts that these two incentives are redundant, since either is sufficient to induce defection.

Some argue that "Chicken games" and "Assurance games" represent collective action problems in social dilemmas better than the PD game. Collective action is less problematic in either of these games than in the PD game. Neither game has a dominant strategy and neither always lead to a Pareto-inferior outcome (Tsebellis 1990). Thus, both Chicken and Assurance games portray **CPR situations** (Gardner, Ostrom, and Walker 1990; Ostrom, Gardner, and Walker 1992, Ch.1).[3] For this reason, the

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[2] The original story of a PD game describes a situation in which two accomplices to a murder are arrested and kept separately so that they are unable to talk to one another. During interrogation, each is promised that if he is the only confessor, he will receive a financial reward in addition to acquittal but his partner will receive **a** death sentence. If both confess, they may get life imprisonment instead of a death sentence. They also know that if both refuse to confess, they cannot be convicted for murder due to an absence of witness. In this situation, if they choose to act rationally, each of them will confess to indict the other. Each prisoner can do better by confessing when the other confesses. By confessing, he can get a life imprisonment instead of a death sentence. He also can do better by confessing when the other does not confess; he can get both financial reward and acquittal instead of acquittal alone.

[3] Notice that, however, there also exists equilibrium selection problem in these two games, which is not to be easily solved.

PD game has been the most widely-used presentation of collective action problems in a CPR situation.

Possibility of Cooperation in PD Game

Despite its frequent use and its capability to portray both types of collective action problems, the PD game can only deal with one type of collective action problem at a time. More importantly, empirical evidence indicates that collective action problems are sometimes resolved without external intervention even though the incentive structure matches that of a PD game. In order to explain these anomalies in the prediction of the PD game, several scholars have tried to show that voluntary cooperation (i.e., the solution of social dilemmas without external help) can be obtainable even in the PD game. Most of the efforts to show that mutual cooperation is possible fall into one of three approaches: the meta-game approach; the repeated game approach; or the correlated game approach.

Meta-Game Approach

Nigel Howard offers the meta-game approach. According to him, a meta-game "is "the game that would exist if one of the players choose his strategy after the others, in knowledge of their choices" (Howard 1971, 23).[4] That is, for player 2, there would be four possible contingent strategies: unconditional cooperation (choose C no matter what player 1 does), unconditional defection, match player 1, and do the opposite of Player l. Table 2.1 shows such a meta-game, which is based on a PD game where payoffs for temptation, reward, punishment, and sucker are 7, 4, °' -3, respectively. Table 2.1 denotes the strategies as C/C, C/D, D/C,

[4] Notice that, however, two players are still assumed to choose simultaneously, even though the strategies available to each player look like those of sequential move game. The seemingly sequential movement of this game occurs only in the mind of each player.

Table 2.1: 2-Meta-Game with PD as a "Basic" Game

	C/C	D/D	C/D	D/C
C	4 4	4 4	-3 7	-3 7
D	7 -3	0 0	7 -3	0 0

Table 2.2: The 1-2-Metacrame of PD.

	C/C	D/D	C/D	D/C
C/C/C/C	4 4	-3 7	4 4	-3 7
D/D/D/D	7 -3	0 * 0	0 0	7 -3
D/D/D/C	7 -3	0 0	0 0	-3 7
D/D/C/D	7 -3	0 0	4 * 4	7 -3
D/D/C/C	7 -3	0 0	4 4	-3 7
D/C/D/D	7 -3	-3 7	0 0	7 -3
D/C/D/C	7 -3	-3 7	0 0	-3 7
D/C/C/D	7 -3	-3 7	4 4	7 -3
D/C/C/C	7 -3	-3 7	4 4	-3 7
C/D/D/D	4 4	0 0	0 0	7 -3
C/D/D/C	4 4	0 0	0 0	-3 7
C/D/C/D	4 4	0 0	4 * 4	7 -3
C/D/C/C	4 4	0 0	4 4	-3 7
C/C/D/D	4 4	-3 7	0 0	7 -3
C/C/D/C	4 4	-3 7	0 0	-3 7
C/C/C/D	4 4	-3 7	4 4	7 -3

and D/D, respectively. We call this particular meta-game the "2-metagame", and the PD game a "base game". If we now take the game in Figure 2.1 as the base game and form a l-metagame from it, we obtain a matrix with 16 (=2^4) rows, which correspond to all the ways of assigning C or D in response to player 2's four alternatives. Figure 2.2 shows this game. In Table 2.2, the expression, say, "W/X/Y/Z" represents the meta-strategy "W against C/C, X against D/C, Y against C/D and Z against D/C". Moving to this 16x4 1-2-metagame resolves the Prisoner's Dilemma. Among three equilibria (represented by *) , two have the payoff (4, 4). They result as the outcome of rational choices for the players (i.e., the ones that are the best attainable given some joint strategy of the other players).

A <u>meta-rational</u> outcome for player i may be defined as an outcome yielded by rational action by player i in the metagame. The cooperative outcome (4,4) becomes both individually and collectively rational in 1-2-metagame (Howard 1971, 57) . Howard has proven that (i) every metagame has an equilibrium (Howard 1971, 27); (ii) each Pareto optimum is a meta-game equilibrium in every complete metagame[5] (Howard 1971, 154); and (iii) no equilibrium is introduced or lost by ascending to still higher meta-levels (Howard 1971, 100). Thus, according to the meta-games, we do not need external authority in order to secure voluntary cooperation. Cooperation is a meta-rational outcome, unlike in the "base" game where cooperation is not an individually rational outcome.

With the exception of Operational Research literatures (Hipel et.al. 1974, Hipel et.al 1976, Ragade 1987), game theorists have almost ignored the meta-game approach. This approach does have limitations. First the meta-strategy set is not available for players who play a simultaneous move game; players who play simultaneously simply cannot make their strategy choices dependent on the other players' choice.

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[5] Complete meta-game refers to every meta-game in which each player is named in the title at least once (see Howard 1971, 60).

Players or real life participants in a situation modeled by a PD game - must ultimately make decisions at the level of the base game, not at the level of some abstract construction formulated by a nonplayer called a game theorist (Harris, 1969). Second, meta-game theory maintains that "Cooperation", which is not a Nash-equilibrium in the "base" game is stable, is a "meta-game equilibrium." However, it is generally admitted that only equilibrium can be stable in noncooperative games (see Harsanyi 1964). Considering the current emphasis on equilibrium refinement or selection Game Theory, adding equilibria that are not regarded as an equilibrium in orthodox Game Theory may be controversial even though it provides an "escape from paradox" (Rapoport 1970). The debate on no-equilibrium results is far from being settled, even though there exists evidence for no-equilibrium results (Güth 1990).

Repeated Game Approach

The repeated game or supergame approach probably provides the most important development of work on cooperation in PD games. This approach assumes that players interact with each other repeatedly, and that players maximize their payoffs for the entire period of their interaction. Infinitely iterated games create different equilibria than one-shot games because players choose their strategy contingent upon their opponent's choice in the previous rounds. In iterated games, strategies are complete plans for the future games, whereas one-shot game's strategies are complete plans for a single game. We call strategies in iterated game "super-game strategies". Friedman (1971) proved that multiple equilibria exist in iterated games, and that these equilibria differ from those in the one-shot version of the games. Axelrod (1981, 1984) shows that an iterated PD game can support mutual cooperation as an equilibrium. According to Axelrod, a super strategy called "Tit For Tat" can sustain mutual cooperation as an equilibrium in infinitely iterated PD games, if players do not discount their future payoffs too much.[6] Players who use Tit For Tat cooperate on the first round, and after that, always play what the other player did on the previous round. Axelrod's iterated game model is based on a 2-person PD game. In his computer tournament, the games include more than two players. In Axelrod's tournament, all players interact with all of the opponents, but only pairwise. Mutual cooperation, however, still occurs.

Friedman (1986), Taylor (1987), and Raub (1988) show that a Trigger strategy sustains mutual cooperation as an equilibrium. Players who use Trigger strategy cooperate until a player defects, and after a defection occurs, defect forever. Notice that in an n-person iterated PD game model, monitoring and interpreting the behavior of other players becomes problematic (Kreps 1990). The monitoring and interpreting problems can make voluntary cooperation through the contingent strategy extremely difficult (Hirshleifer and Coll 1988). Bianco and Bates (1990) show that their modified iterated PD game in which a leader monitors followers behaviors solvei these problems.

Bendor (1988) proves that players can maintain mutual cooperation even in a stochastic supergame, in which some exogenous and uncontrollable factors prevent players from accurate monitoring and occasionally keep players from playing what they want. He shows that a "reformulated Tit For Tat" that cooperates on the first move and thereafter <u>tries</u> to give opponents what he thinks he receives on the previous round makes mutual cooperation possible.

The repeated game approach, however, creates one serious problem. According to the Folk Theorem, any individually rational outcome can arise as a Nash equilibrium in infinitely repeated games with sufficiently little discounting (Fudenburg and Muskin 1986; Kreps 1990). This means that the mutual cooperation equilibrium is simply one of the

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[6] It is also possible in finitely iterated games if there is incomplete information. See Fudenburg and Muskins 1986.

infinite number of possible equilibria. Moreover, "always defect" remains a subgame-perfect equilibrium regardless of the value of the discount parameter (Axelrod 1981, 1984; Bianco and Bates 1990).

Empirical evidence shows that players tend not to use contingent super-game strategies such as Tit For Tat or Trigger (Gardner, Ostrom, and Walker 1990; E. Ostrom 1990; Ostrom, Gardner, and Walker 1992). It has also been criticized that human decision makers simply do not develop and use complete strategic plans. Thus, it is neither theoretically nor empirically valid to assume that people calculate a full, pre-programmed plan for all future plays at the beginning of an infinitely repeated game.

Correlated Game Approach

The final approach for explaining cooperation in PD games is the correlated game approach. According to Tsebellis (1990), correlated strategies make mutual cooperation possible in a PD game. Tsebellis (1990, 68-72; 80-86) assumes that the players use the following strategy in a 2-person PD game: when the first player chooses to cooperate, the second chooses to cooperate with probability p, called the probability of instruction; or when the first player chooses to defect, player 2 chooses to defect with probability q, called the probability of retaliation. His assumption employs the concept of correlated strategy: each player chooses a strategy to match the opponent's strategy. Tsebellis asserts that players will choose to cooperate when the expected utility of cooperation is greater than that of defection; and further, that when players use correlated strategies this occurs under some conditions. Let T, R, P, and S denote payoffs for temptation, reward, punishment, and sucker, respectively. The expected payoffs of defection (EU(D)) and cooperation (EU(O) are then:

(2) $EU(D) = T(l-q) + Pq$

(3) $EU(C) = Rp + S(l-p)$

players choose to cooperate if and only if:

(4) $EU(C) > EU(D)$,

which is equivalent to:

(4') $(R-S)p + (T-P)q > (T-S)$.

Therefore, the possibility of cooperation depends on the base payoffs (T, R/ P/ S) and the probability of instruction (p) and retaliation (q).

The correlated equilibria approach, originally introduced by Aumann (1974), also poses problems. Aumann shows that players can overcome the coordination problem or the equilibrium selection problem in games with multiple equilibria if some correlation exists between two players' strategy choices. This approach, however, cannot help a PD game situation (see McGinnis and Williams 1991) because the dominant strategy of a PD game, unlike in Chicken game or Assurance game, makes it individually rational, at least in the short-run, to choose "Defect", irrespective of his opponent's choice. There is no reason to coordinate with the opponent's strategy because "Defect" always pays better than "Cooperate". This means that p is always 0 and q is always 1. If this is the case, the cooperation condition of the Tsebellis model in equation (4') and the payoff ordering of a PD game ($T > R > P > S$) cannot be satisfied at the same time. In other words, to satisfy the cooperation condition (4'), the sucker payoff (S) must be greater than the punishment payoff (P), which is impossible in a PD situation.

We have discussed game theoretic models of the collective action problems in general CPRs, all of which try to demonstrate the possibility of cooperation. These models succeed to some degree in capturing important common aspects of many different problems that occur in diverse CPR settings. But, collective action problems in CPR situations differ, even though they may possibly be described by the pame game -- the PD game (see, Bloomquist, Tang, and Schlager 1990). The trend to categorize all CPR dilemmas as a PD game or one of its variants leads to the mistaken belief that collective action problems in CPR situations are basically identical, which leads to the belief that all CPR situations have one common solution. The behavioral patterns found in empirical settings show substantial dissimilarities among CPRs in terms of the degree of efficiency appropriators achieve without external help. Therefore, we need to develop models of incentive structures in specific CPRs in order to understand the collective action problems of various CPR situations, especially when a model may drive policy.

Irrigation Game

Weissing and Ostrom (1991) develop a game theoretic model of an irrigation system. Their game assumes that a population of appropriators shares a single irrigation system that serves as the main source of water supply for their crops. The authorization to take water from this system rotates among the appropriators according to a predetermined order. At each point of time, only one appropriator holds the position of turn-taker (TT) and is therefore authorized to take water. The other appropriators, the turn-waiters (TW), wait for their turns to take water. At each turn, the turn-taker has two choices --to steal (s) or to take the authorized amount of water (-S). The choices available to turn-waiters are to monitor (M) the turn-taker or to refrain from monitoring {-M). Weissing and Ostrom also assume imperfect monitoring in the sense that a monitoring turn-waiter only detects stealing with a certain probability -- the detection probability, a (0 < α 1).

Table 2.3 illustrates the payoff matrix of this game when there are only two appropriators. In addition to the probability of detection (a) / the payoffs rely on the following parameters: B (the benefit of additional water), L, (turn-waiter's loss), R, (the reward of detecting

Table 2.3: Payoff Matrix of Irrigation Game with One Turn-Waiter

TW: / TT:	¬M	M
-S	0 / 0	0 / $-C_M$
S	B / $-L_r$	$\alpha(-P_I) + (1-\alpha)B$ / $\alpha(R_I-C_M)+(1-\alpha)(-L_r C_M)$

stealing event), P, (punishment), and C_M (monitoring costs). The equilibrium of this irrigation game depends on the relationship between B-a(B+Pi) and 0 on the one hand and a(Rj+Lj)-$L_r C_M$ and -Lj on the other. Depending on the parameter constellation, we can have four possible equilibria. One of them is mixed strategy equilibrium, (σ^*, μ^*),[7] where a and μ denote the probability of stealing and the probability of monitoring, respectively. We can interpret σ and μ as **the stealing tendency** and **the monitoring tendency.**

This 2x2 irrigation game yields two major predictions: (i) stealing occurs in every parameter constellation ($\sigma^* > 0$); and (ii) the equilibrium stealing tendency (a') is less than one (a* < 1) when the detection probability (a) is large enough. Stealing is never totally eliminated. In fact, it falls to intermediate levels only if the cost of monitoring is low compared to its benefits, and if the cost of detected stealing is high compared to the monitoring efficiency of the turn-waiters. Weissing and Ostrom show that this predictions still apply as the number of turn-waiters increases.

The irrigation game shows that players can reduce stealing to intermediate levels without external help, even though they never completely eliminate it. The predictions of this game suggest that under some conditions, appropriators may follow their own rules to some

[7] For the definition of mixed strategy, see Fudenberg and Tirole (1991, 29-30) and Ordeshook (1986, 133).

extent without an external enforcer through self-monitoring and self-enforcing. The game also demonstrates that various parameters influence the degree to which appropriators can resolve collective action problems. The richness of Weissing and Ostrom's irrigation game stems from the detailed assumptions about the payoffs. Most game theoretic models lack this detail. Consequently, they are too over-generalized to be used as a basis for policy recommendation and are better utilized as heuristic metaphor (E. Ostrom 1990). We need game theoretic models with substantive theory on payoff.

Weissing and Ostrom (1991) also enrich this game further by introducing a guard. They show that the introduction of a guard may not be efficient for the system as a whole even if the guard does his/her job. The stealing rate may even rise from an intermediate to a maximum level since the presence of a guard motivates the turn-waiters to not monitor. This model, thus, explains empirical patterns of interactions among appropriators that cannot be explained by models based on the PD game. However, the irrigation game model still considers only appropriation problems.

A New Approach in Modelling Collective Action Problem

In order to answer questions that others have not answered <u>or</u> in order to answer them in a better way, we need new formal models of collective action problems. These new models should depict the incentives facing individual appropriators in CPRs better than the earlier models did. The earlier models are not satisfactory since (i) they lack substantial payoff theory; (ii) they are usually static; and (iii) they consider only one of the two major collective action problems in a CPR situation (i.e., they consider either appropriation problems or provision problems). To develop such a new model, therefore, we need a new approach that uses a substantial payoff theory, is dynamic, and considers both appropriation and provision problems.

Institutional Analysis and Development Framework

First, a new model should have a more substantial payoff theory in order to discern the way that important variables affect the incentive structure of a CPR situation. Except for Weissing and Ostrom's irrigation game, most game theoretic models lack detailed payoff components. This is understandable since these models deal with CPRs in general rather than with one specific CPR. General models, however, do not allow us to explore the impacts of various important variables on the patterns of interactions among appropriators and can hardly be useful as a foundation for policy analysis. A new model, therefore, should have a detailed payoff theory that will enable us to examine how important variables impact the patterns of interactions among appropriators and the outcomes of the game.

The institutional analysis and development framework (hereafter IAD framework) identifies a common set of variables that underlies the incentive structure of all types of CPRs. Using the IAD framework, therefore, one can identify the important variables and their impacts on the patterns of interactions among appropriators. The parametric values for each of the variables differs from one type of CPR to another. The ways these common variables combine with or interact with one another will also differ. Identifying a common set of variables and the way these variables are assigned different values and the way they combine with or interact with one another enables us to create a more detailed payoff theory of particular CPR situations. The IAD framework will be more fully explained later in Chapter 4.

Dynamic Game Theory

A dynamic game[8] is a kind of repeated game model where a game is repeatedly played, just like Axelrod's model (1981; 1984). Notice that, however, Axelrod's repeated PD game model remains static even though repetition is allowed. It is static because the payoff function is not time-dependent (Friedman 1986). In repeated game models, past strategies matter not because they affect the present and the future payoff functions themselves, but because they influence the current and the future strategies of other players (Fudenburg and Tirole 1991). That is, changes in the "physical environment" or the "payoff function" are not considered at all in static repeated game models. Instead, the payoff functions remain the same.

In a dynamic game, on the other hand, the "physical environment" and the "payoff functions" themselves may change over time. Past play affects the current and the future payoff functions so the incentive structure changes over time. Technically, dynamic game models depend heavily upon optimal control theory as well as game theory. Optimal control theory deals with solving multi-period maximization problems where present choices <u>determine</u> future relationships between choices and results (see Kamien and Schwartz 1981; Roxin, Rui, and Sternberg 1977; Fryer and Greenman 1987). Notice the similarity between the technical problems of a one-player dynamic game and an optimal control problem (Gillespie and Zinnes 1975; Fudenburg and Tirole 1991). Dynamic game theory uses two concepts from optimal control theory: a control variable and a state variable. Control variables refer to variables that players can choose or manipulate. State variables are variables that players do

[8] Dynamic game models have been used in studying ground water extraction (Dixon 1989; 1991), fishery management (Berke and Berloff 1984; Hämäläinen, Haurie, and Kaitala 1984; Hämäläinen, Kaitala, and Haurie 1985), arms race (Gillespie and Zinnes 1975), foreign debts management (Feichtinger and Novack 1991), economic stabilization (Pindyck 1973, 1977), and research and development (Reinganum 1982). For more information on dynamic games and their applications, see Case (1969), Isaac (1967), Starr and Ho (1969), Ciletti and Ho (1970), Ho (1970), Foley and Schmtendorf (1971), Friedman (1974), Grote (1974), Başar (1986), Holly (1987), and Başar and Bernhard. (1991)

not control, although choices about the control variables determine the values of state variables.

In the real world, as Hardin points out, "we typically face ongoing collective action problems rather than once-only actions that are isolated from other interactions. To understand these requires an analysis of incentives that depends on dynamic relationships, incentives that would not arise except in dynamic contexts" (Hardin 1982, 3). What happens if we model this situation as a static game? The solution of this misplaced model will be a myopic one. This solution assumes that farmers will appropriate and invest until the marginal benefit equals the marginal cost without considering the effects of their choice on state variables. This solution may parallel the prediction of the PD game that assumes that appropriators have no foresight. But, if appropriators act with foresight, the assumption of myopic behavior leads to an overstatement of the benefit lost in CPRs without central control. It is possible that the result of long-term individual rationality is far from that of short-term individual rationality and that it is very close to that of social optimality. This misplaced policy recommendation comes from the "wrong way of simplification" (McGinnis 1991).

There are two solution concepts for the dynamic game model. In the open-loop solution, each farmer maximizes his/her net present discounted value **given** the strategy paths of the other farmers. This solution is a Nash equilibrium in which each player has no incentive to deviate from his/her strategy path given the path of the other players. The open-loop solution captures forward-looking behavior but assumes that each player does not take into account the effect of his/her behavior on the behavior of other players. That is, it assumes that each player does not think that other players will respond to his/her action; and thus he/she has no reason to alter his/her own action during the course of play.

In most situations, it is more realistic to assume that each player adjusts behavior in response to the action of other players. The outcome of this assumption is called the closed-loop solution to the game. The term "closed-loop solution" refers to a subgame-perfect equilibrium of a game where players can observe and respond to their opponents' action at the end of each period (Fudenburg and Tirole 1991; Dixon 1991). In other words, the closed-loop solution assumes that, at any point in the game, each player responds to an action by picking the strategy path that maximizes personal payoff for the rest of the game. For the dynamic game with perfect information, the closed-loop solution is the natural solution when we do not consider full cooperation of all decision-makers (Haurie and Delfore 1976) .

Nature of Common Pool Resources

By definition, a CPR is a class of natural or man-made facilities (i.e., **stocks)** that produce a **flow** of use units per unit of time where exclusion from the resource is difficult or costly to achieve; and the resource can potentially be utilized by more than one individual or agent simultaneously or sequentially, but joint use involves high subtractability. This definition implies that we need to pay attention to both flow and stock aspects of a CPR at the same time. The relationship between flow and stock varies among different CPRs, and it could have important effects on the incentive structure facing appropriators of CPRs. When we model some complex real life situation, we need assumptions in order to simplify some realities. If the model sacrifices a non-essential reality in the process of simplification, then the conclusions may be robust. However, if the model sacrifices an essential reality, then the conclusions may not be robust. To focus on one type of collective action problem sacrifices too many realities that are essential modelling features. We need a game theoretic model that deals with both appropriation and provision problems simultaneously.

Chapter 3

A Model of an Irrigation System

A dynamic game involves repeating constituent games. A dynamic game model, however, differs from the iterated game models discussed in Chapter 2. Even though they allow repetition, iterated games are static since their payoff functions are not time-dependent (Friedman 1986). The repeated games assume that "payoff functions" and "physical environment" remain constant, even though the game repeats.

In a dynamic game, on the other hand, the "physical environment" and the "payoff function" themselves are allowed to change over time. Past play affects current and future payoff functions because choices about control variables can change state variables and affect the way the payoff functions are determined. In other words, the incentive structure itself changes over time. The same activity may not bring the same payoff over time.[1]

In this chapter, I develop a formal model of the incentive structure of individual appropriators in canal irrigation systems by using a dynamic game theory modelling technique called the difference game model.[2]

The Model; A Hypothetical Irrigation System

[1] There could be a threshold beyond which constant activity cannot bring constant payoff. In this case, constant activity may bring constant payoffs until it reaches the threshold.

[2] We can think of two types of dynamic games. The first is a differential game where the state variables evolve according to a differential equation. The second is a difference game or a multi-stage game where the state variables evolve according to a difference equation. A difference game is an appropriate model for empirical situations where players act at specific time points at specific intervals of time. On the other hand, a differential game is suitable when players make decisions at all time points. I chose the difference game because it is more relevant to assume that farmers make decisions at specific time points rather than at specific intervals of time.

Let us assume that there exists a canal irrigation system with no storage capacity and with n (n 2) appropriators who are entitled to get irrigation water from that system. There are two types of appropriators: headenders (j=l,...,m) and tailenders (k=m+l,...,n), where n m. Headenders and tailenders differ from one another; an asymmetry exists between headenders and tailenders. For simplicity, however, we assume that no asymmetry exists among the headenders or among the tailenders. Headenders are identical in all relevant aspects and tailenders are identical in all relevant aspects. Appropriators try to maximize their benefits from the irrigation system by making decisions on two variables -- the amount of irrigation water they appropriate and the amount of resources they invest in maintenance. Let the amount of irrigation water that they appropriate and the amount of resources that they devote to maintenance be "u_i (0)" and "m_j (0)", respectively.[3] These are the two control variables in our model. Within limits, appropriators decide the values of the two control variables once in each time period, from the time period 1 to the final time period T. Their decisions on the two control variables determine the payoff to appropriators.[4]

Assume that, in this hypothetical irrigation system, appropriators first decide on the amount of water that they will appropriate during the time period t; and after appropriation, they decide on an amount of investment of their labor and resources in maintenance. This means that any single time period t contains two time spans; an appropriation period and a maintenance period. Time period t, thus, can be understood

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[3] There is an upper limit for these two variables, which will be explained later.

[4] They are not the only control variables in natural settings, of course. Other variables, such as choice of crops and amount of fertilizer, also have an impact on the payoff of appropriators who are engaged in farming. In our model, however, all the variables other than our two control variables are simply assumed to be constant so that full attention can be paid to appropriation and provision problems.

as a season containing an appropriation period and a maintenance period. The time period t is defined this way because the appropriators achieve the product of irrigation activity only at the end of the crop season. Since the time period spans a crop season, we assume that (i) appropriation occurs over an appropriation period that is more than one day, and (ii) the sum of each day's appropriation during the appropriation period determines the total benefits, the agricultural product, of each time period.

This model also assumes that the marginal benefit of a unit of irrigation water remains constant over the time period t. In other words, appropriators always receives the same amount of total benefit from the same amount of water every day over the entire time period t; there is no seasonality of demand for irrigation water.

In real world settings, the assumptions of this model may not be fully met. First, some asymmetries may exist among the headenders and the tailenders. Adding more categories of appropriators among the headenders and the tailenders can capture asymmetries among the two types of players in this model.[5] However, this only adds complexity to the model. To avoid this added complexities, I choose to keep the assumption of symmetry among each type of player. Dynamic game models require complicated solution processes, so we need to simplify as much as possible to obtain meaningful results.

Secondly, real world appropriators do some maintenance work during the appropriation period as well as during the maintenance period. However, most of the maintenance work done during the appropriation

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[5] For example, we can assume that there are two types of appropriators among the headenders -- the headenders and the tailenders -- and among the tailenders as well. Then we can have four types of appropriators such as:

(1) the head-headenders,
(2) the tail-headenders,
(3) the head-tailenders, and
(4) the tail-tailenders.

The headenders are now divided into two types, (1) and (2), and the tailenders are also classified into two types, (3) and (4).

period is likely to be emergency repairs or work done on their individual field canals, which are not collective property. I ignore emergency repairs in this model, assuming that they are so urgent that everybody will participate. That is, the incentive structure of an emergency repair situation differs from that of a social dilemma.

Finally, in most empirical settings, the marginal benefit of a set amount of irrigation water differs during the time period t because of the seasonality of demand for irrigation water. My model, however, assumes that the marginal benefit of a unit of irrigation water remains constant for the entire time period t to highlight the effect of the appropriators' choice on the amount of irrigation water and the effect of investment in the maintenance on their payoff at the next time period. This does not mean that the seasonality of demand and supply for irrigation water bears no importance to the appropriators. It means, rather, that we must sacrifice analysis of seasonality to focus on what we want to do in this model since including too much in one model makes the model intractable, or at least extremely difficult to handle.

The hypothetical irrigation system will be helpful in understanding (i) the interaction between appropriation and maintenance, and (ii) the time-dependent characteristics of appropriators' incentive structure, even though it cannot capture all the details of a real world setting.

Game in Extensive Form

Let me explain the game that appropriators in this hypothetical irrigation system play.

(i) At period 1, all headenders, j, simultaneously choose u_{j1}.

(ii) Knowing the choice of all headenders, tailenders, k, simultaneously choose u_{k1}.

(iii) Headenders, j, then, simultaneously choose m_{j1}.

(iv) Knowing the choice of all headenders, tailenders, k, simultaneously choose m_{k1}.

(v) Time periods 2,...,T repeat stages (i) to (iv).

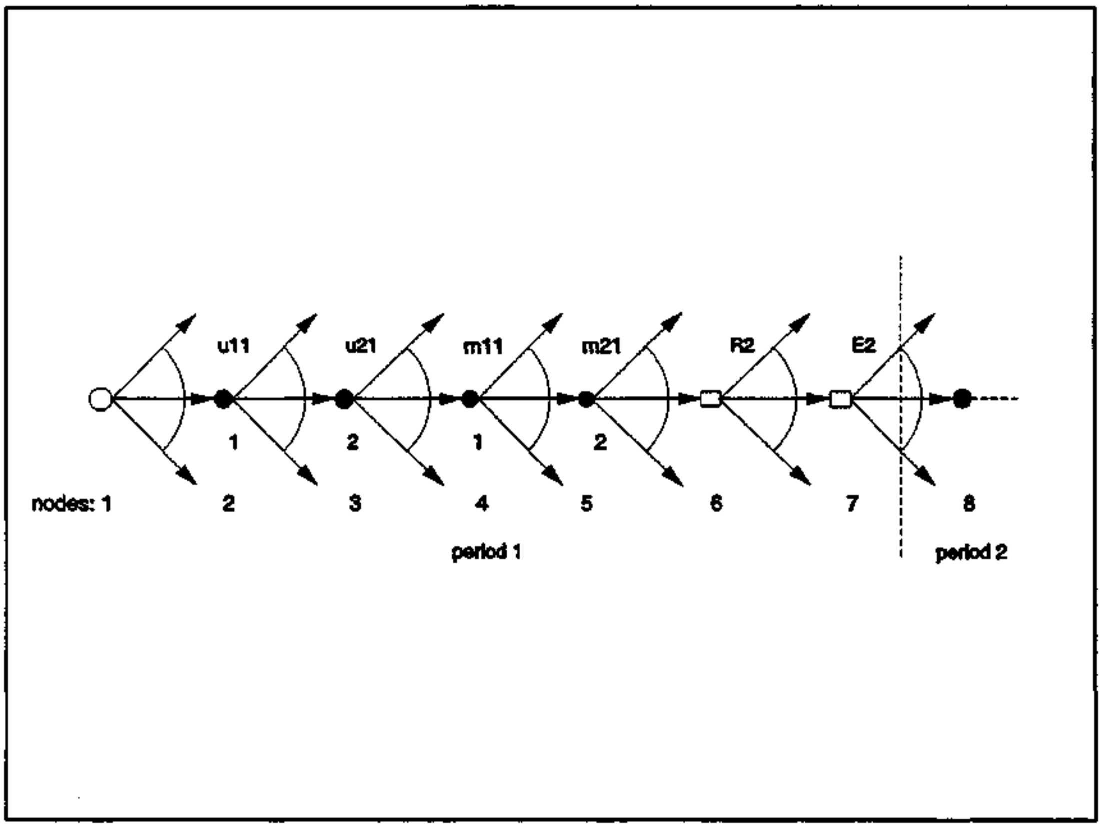
We can understand the way the game is played more easily by representing it in extensive form. For simplicity, let us assume that there are only two players, a headender and a tailender. Figure 3.1 shows this game. At the first node (node 1), nature picks the values of parameters in this game, including the initial values of the state variables.[6] Given these initial values, the headender (player 1) chooses the amount of irrigation water to appropriate at time period 1 (u_{11}), then the tailender (player 2), knowing the headender's decision, chooses the amount of irrigation water to appropriate at time period 1 (u_{21}).[7] These decisions happen at nodes 2 and 3. Notice that the upper limit on u_{i1} is determined by the amount of water at the source and the initial efficiency of water delivery. These two parameters are external to this game. Also notice that the information condition at node 3 implies that the tailender knows what the headender has chosen.

This is also the case at nodes 4 and 5. Both the headender and the tailender know the amount of water each player decided to appropriate. At node 4, the headender chooses the amount of investment in the maintenance at time period 1, m_{11}. After this move, the tailender, knowing the headender's decision, decides the amount to invest in maintenance, m_{21}, knowing headender's decision. This ends the

[6] They are the reliability of water supply and water delivery efficiency. They will be fully discussed later in this paper.

[7] Note that the headender is a leader and the tailender is a follower in this game. Being a follower, the tailender takes the headender's appropriation level as given and optimizes his/her appropriation level with respect to it, as in Nash behavior. The headender, on the contrary, knows that the tailender will act according to his/her Nash reaction path, and hence, the headender will choose an appropriation level that puts him/her in the best position regarding the tailender's reaction path. For more detail, see Sandier (1992; 56-8).

Figure 3.1: Game in Extensive Form



first time period. Players get the payoffs of the first time period Π_{i1}.

This is, however, not the end of the game. Starting with the second time period, the payoff structure is affected by the choices made in previous time periods. This happens at nodes 6 and 7,[8] where the values of reliability and efficiency at time period 2 are determined. Notice that these values are no longer external to the game, but are determined indirectly by the players' decisions at time period 1. They then enter the payoff structure in time period 2. The reliability and efficiency values change the total benefit curve and the upper limit on the amount of water available to the players, so we need to represent this process in the extensive form game. Since the players do not directly control the values of reliability and efficiency, there is no standard way of representing this process in an extensive form game. For this reason, I simply use a square (□) to represent this process at nodes 6 and 7. From node 8, the process I have explained repeats until the final time period. The payoffs for the players will be the sum of the discounted payoffs from period 1 to the final period.

What happens if we model this situation as a static game? The solution of this misspecified model will be the myopic one. It assumes that appropriators obtain water and invest in maintenance until the marginal benefit of each time period equals the marginal cost of each time period, without considering the effects of their choices on state variables. The static solution roughly parallels the prediction of the finitely repeated PD game because the PD game assumes that appropriators have no foresight. But, if appropriators act with foresight, the assumption of myopic behavior leads to an overstatement of the benefit loss resulting from management of irrigation systems without central control. It is possible that the result of long-term individual rationality is far from that of short-term individual rationality and

[8] It does not matter here which one is decided first.

close to that of social optimality. If so, assuming no foresight is likely the "wrong way of simplification" (McGinnis 1991). Predictions based upon this assumption could incorrectly overstate the welfare loss associated with individual rationality and call for more governmental intervention than is actually needed. Thus, I employ a dynamic game approach.

Payoff Functions

Benefit Component

Now, let us discuss the functional form of the payoff function of this model. For convenience, I explain the benefit component and cost component separately. First, the total benefit of irrigation water is given by the area under a linear demand curve for irrigation water. I assume this curve has a negative slope, an assumption common in most previous studies of irrigation water use.[9] It implies that the marginal benefit or "value of the marginal product" (Sparling 1990; Small and Carruthers 1991) diminishes as a function of the supply of irrigation water to the appropriators. The diminishing function occurs because of the biological response of the crop to water. As Small and Carruthers explain:

> When the crop is suffering from severe water shortage, the crop will show a highly positive response. But as additional water is supplied, the increase in production from a given increase in water will be smaller. Eventually if enough water is added, a point will be reached where the total amount is actually in excess of the crop's biological optimum. At this point the crop's response to the additional water will be zero or even negative (Small and Carruthers 1991).

The marginal benefit function of irrigation water use for an individual appropriator i, at time t, can be expressed as:

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[9] For examples, see Gotsch (1975), Kahn and Young (1979), Dixon (1989, 1991), Feinerman and Knapp (1983), Howe (1990), and Sparling (1990).

(1) $MB_{it} = q - r^*u_{it}$ $\quad i=1,\ldots,n, \quad t=1,\ldots,T$
$q,r > 0,$

where q represents the intercept and r represents the slope.

Figure 3.2 shows the marginal benefit function. Note that this function is also thought of as an irrigation water demand schedule that illustrates the amount of water demand at varying levels of water price for some time period (e.g., a crop season). However, since no market for irrigation water exists in many settings, no expressed demand function for irrigation water comes from the appropriators' actions. The demand derives from the profitability of crop production. For this reason, it is thought of as a reflection of the value of marginal product of water in crop production.

The intercept of the marginal benefit function, q, represents the monetary value of the additional output generated by the first unit of irrigation water. This can be measured by any "unit of monetary value per unit of volume of irrigation water." For example, it could be measured by "dollar per acrefeet." In this case, it denotes the dollar value of the agricultural product generated by the first acrefeet of irrigation water applied to the field. If a crop requires more water, q gets larger. The value of this parameter can be estimated from the per acre agricultural benefit from a unit of irrigation water. We can estimate q if we know the market price of a specific crop and how that crop responds to irrigation water. However, examining the response of a specific crop to irrigation water and the market value of irrigation water is beyond the scope of this study. For this reason, I have not paid much attention to the abstract size of q. Instead, I have picked a value of q from the estimates of marginal benefit intercept used by Dixon (1989).[10]

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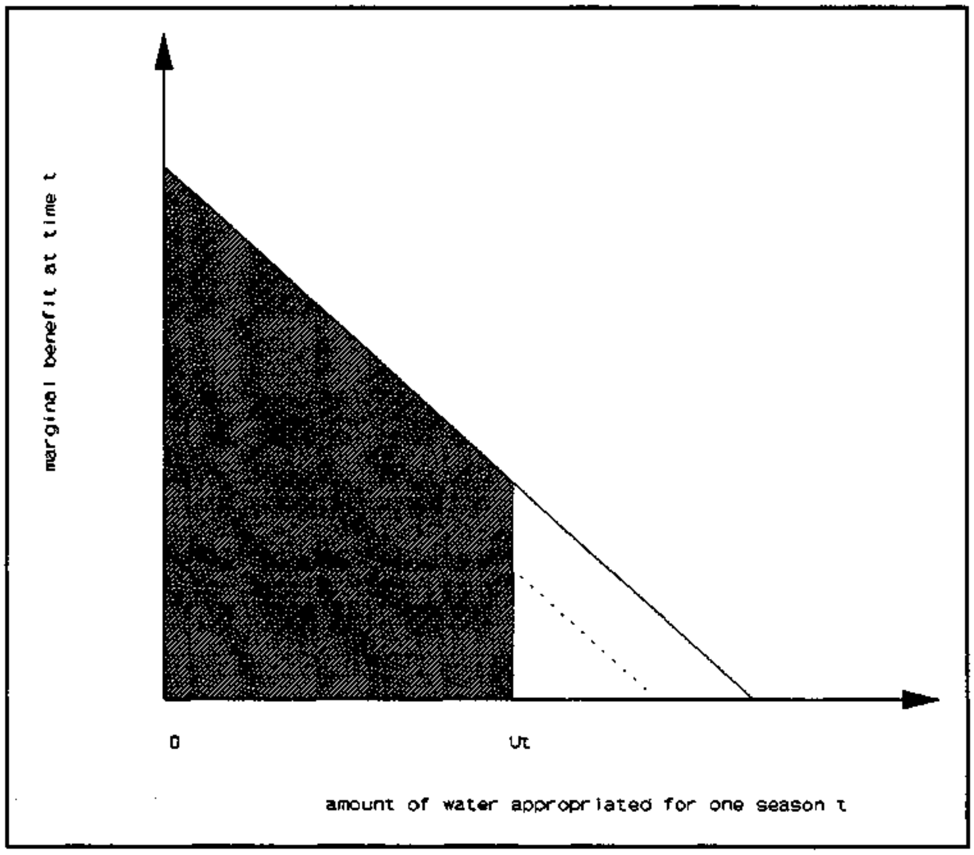
[10] Dixon set the range of marginal benefit intercept (from 70 to 310 \$/acft) and marginal benefit slope (from 20 to 170 $\$/acft^2$) based upon empirical studies of Kern County, California (Dixon 1989, 18-21).

Figure 3.2: Marginal Benefit Function



The slope of the marginal benefit function, r, determines how the marginal value changes as the amount of irrigation water applied to the field changes. Notice that as r rises, the marginal benefit curve becomes steeper. As the marginal benefit curve becomes steeper, the marginal benefit of an additional unit of irrigation water decreases. The marginal benefit becomes zero when we apply "q/r" units of irrigation water. If one applies more irrigation water than this threshold amount ("q/r"), then the marginal benefit becomes negative. The total benefit decreases as one applies more irrigation water. As r rises, the marginal benefit becomes zero faster since "q/r" becomes smaller, given a particular intercept of the marginal benefit function, q. This implies that a smaller r represents an irrigation system with high water-consuming crops that can tolerate excessive water (such as paddy rice). A larger r, on the other hand, depicts an irrigation system with crops that cannot tolerate excessive water.

Given this function, the total benefit of irrigation water is a quadratic function of the supply of the irrigation water to the appropriators. It can be easily obtained by simply integrating the marginal benefit function in equation (1). By integrating equation (1), we can have a total benefit function:

(2) $$\pi_{it}^{B} = q*u_{it} - .5*r*u_{it}^{2}.$$

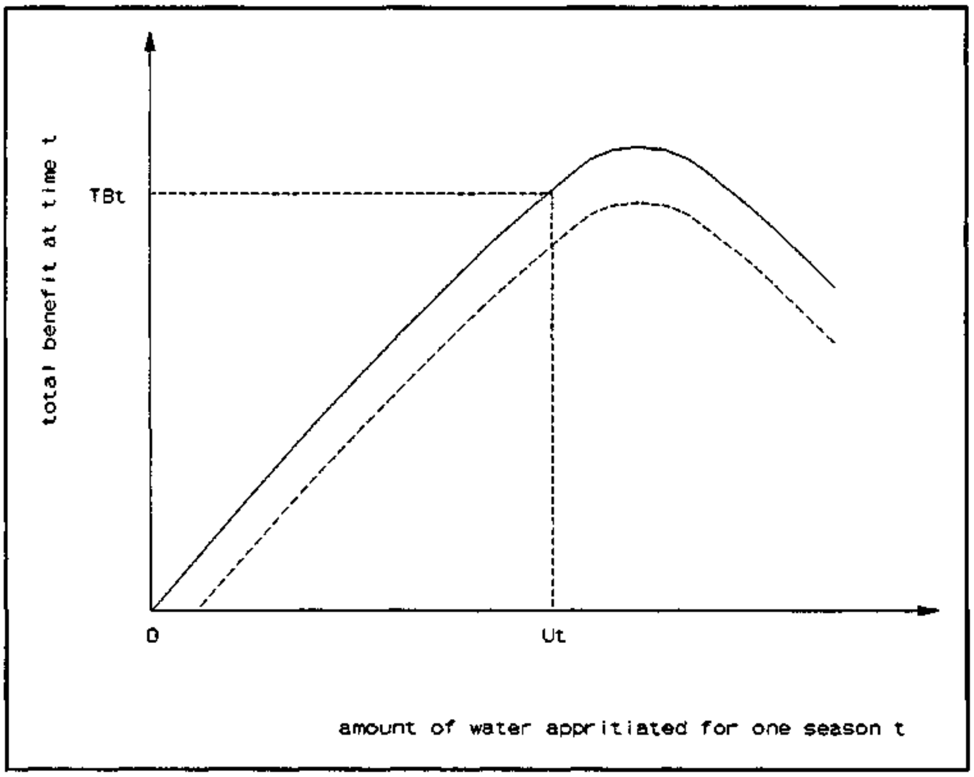
, **where** π_{it}^{B} = the benefit of water use of individual i at time t.

This function is shown in Figure 3.3. Notice that the shadowed area under a linear marginal benefit curve in Figure 3.2 is identical to TB_t, in Figure 3.3. They both represent the total benefit of u_t, amount of irrigation water.

Cost Components

We must next think about the cost components. The appropriation

Figure 3.3: Total Benefit Function



cost could be thought of, for example, as the cost of electricity for pumping water out of an irrigation canal. The appropriation cost increases as appropriators obtain more water. For simplicity, assume that the appropriation cost is the amount of water appropriated times some constant, e. This means that we can write the appropriation cost as "$e*u_{it}$". This seems, however, unsatisfactory because the appropriation cost for an individual i is also affected by the behaviors of other appropriators who can appropriate the irrigation water at least at the same time or before he/she does. Therefore, the appropriation behavior of the tailenders will not affect the headenders' appropriation costs, whereas the appropriation behavior of the headenders will affect the tailenders' appropriation costs. It may become more and more difficult and costly to appropriate as the amount of water appropriated by others increases. This can be summarized as:

(3) $\pi_{jt}^{AC} = e*\Sigma u_{jt}*u_{jt}$ for headenders

$\pi_{kt}^{AC} = e*(\Sigma u_{jt}+\Sigma u_{kt})*u_{kt}$ for tailenders

, where π_{it}^{AC} = appropriation cost for individual i at time t,
e (>0) = appropriation cost coefficient.

As e rises, so does the cost of appropriating irrigation water. An irrigation system with larger e can be thought of as a system that requires more time and effort to appropriate water for whatever reason. For instance, e grows larger if the irrigation system has poor engineering works or if farmers' non-compliance with appropriation rules --no matter formal or informal -- provokes conflicts among appropriators.

In equation (3), the appropriation behaviors of both headenders and tailenders produce exactly the same effects on the tailenders' appropriation cost. But, if an irrigation system is in good condition, headenders' appropriation behavior impacts on the tailenders' appropriation cost less than tailenders' appropriation behavior. In fact, it could even have no impact on the tailenders' appropriation cost at all. This can be captured by introducing another parameter that measures the interdependency between headenders and tailenders, δ, which lies in the interval between zero and one. Using this new parameter, equation (3) can be rewritten:

(3') $$\pi_{jt}^{AC} = e*\Sigma u_{jt}*u_{jt} \qquad \text{for headenders}$$

$$\pi_{kt}^{AC} = e*(\delta*\Sigma u_{jt}+\Sigma u_{kt})*u_{kt} \qquad \text{for tailenders}$$

,where δ = coefficient of interdependency between headenders and tailenders.

The coefficient of interdependency between headenders and tailenders, δ, denotes the degree to which appropriation behavior of the headenders affects the appropriation cost of the tailenders. It varies from 0 to 1. If it equals 0, the headenders' appropriation behavior has no effect on the tailenders' appropriation cost. This may happen if the engineering work of an irrigation system functions well. If the coefficient equals 1, then the appropriation behavior of the headenders affects the appropriation cost of tailenders as much as the tailenders' behavior affects it. If the engineering works of an irrigation system functions poorly, the coefficient may equal 1.

Another cost component is the maintenance cost, m_{it}, which is the amount of resources that appropriators invest in maintenance. This game assumes that maintenance work occurs after water is appropriated. Consequently, the maintenance work at time t cannot increase the benefit to an appropriator at time t; it can only add positive utility to the benefit at time (t+1). Under this assumption, the maintenance cost for individual i at time t is:

(4) $$\pi_{it}^{MC} = m_{it}.$$

The above three equations (2), (3'), and (4) express the payoff for an appropriator. That is, the payoff for an individual i at time t in the default situation[11] is:

(5) $$\pi_{it}^{DF} = \pi_{it}^{B} - \pi_{it}^{AC} - \pi_{it}^{MC}.$$

Since the appropriation costs to headenders and tailenders differ, we re-write equation (5) as:

(5') $$\Pi_{jt} = \pi_{jt}^{DF} + \pi_{jt}^{R} - \epsilon$$
$$= q*u_{jt} - .5ru_{jt}^{2} - e*\Sigma u_{jt}*u_{jt} - m_{jt} \qquad \text{for headenders}$$

and,

$$\Pi_{kt} = \pi_{kt}^{DF} + \pi_{kt}^{R} - \epsilon$$
$$= q*u_{kt} - .5ru_{kt}^{2} - e*(\delta*\Sigma u_{jt} + \Sigma u_{kt})*u_{kt} - m_{kt} \qquad \text{for tailenders.}$$

Players will try to maximize the present value of Π_{it}, where the future payoffs are discounted by the discount parameter ω. We can formally state the present value of Π_{it} as:

(6) $$\Psi_{it} = \Sigma_{t=1}^{T}\omega^{t-1}(\Pi_{it})$$

, where Ψ_{it} = the present value of Π_{it} at time t,
ω = discount parameter.

The discount parameter, ω, denotes the degree to which future payoffs are valued relative to the value placed on present payoffs. Present choices not only determine present outcomes, but can also influence future payoff structures. Therefore, expectations about the future can cast a shadow upon the present action situation. But, players tend to value potential future payoffs less than they values the

---

[11] It refers to the situation where all of the rules are set at their default position, as is the case in Hobbes's "state of nature". In this situation the only factors affecting the structure of a game are those related to the physical domain in which the game is played. For more detail on the rules at their default position, see E. Ostrom, Gardner and Walker (1993, Ch.4).

present payoffs. A standard way to calculate discounted future payoffs treats the payoffs of remaining rounds worth some fraction of the payoffs of the present round (Shubik 1970; Axelrod 1984).

Exogenous and endogenous factors constrain choices on the two control variables. Exogenous factors determine the limit on the amount of investment in maintenance, mB, whereas actions in the previous round and exogenous factors limit the amount of appropriation. The limits on appropriation are discussed later since the discussion requires terminology that has not yet been introduced. The constraints on the amount of investment in maintenance can be written:

(7) $0 \leq m_{jt} \leq mB_j,$ for headenders, and

$0 \leq m_{kt} \leq mB_k,$ for tailenders,

,where mB_j = maximum amount of investment headenders can afford,
mB_k = maximum amount of investment tailenders can afford.

State Variables

Appropriators' choices on the two control variables do not entirely determine the payoff for the appropriators. State variables, which change over time as choices on the two control variables influence them, also affect them. This model assumes that two state variables, the reliability of water supply and the water delivery efficiency of the irrigation system, influence payoffs.

Reliability of Water Supply

The first state variable in this model is the **reliability of the irrigation system.** We assumed earlier that u_{it}, the sum of the irrigation water appropriated for the time period t, determined the total benefit of time period t, Π_{it}. But, the distribution of u_{it} during the appropriation period also affects Π_{it}. Given that the marginal benefit of the irrigation water is fixed over the time period t, the total benefit of a given amount of irrigation water (u_{it}) will be maximized when it is evenly distributed over the time period t. The following example helps to illustrate this point.

Assume that two appropriators exist in two hypothetical irrigation systems and an appropriation period is composed of two days. Both appropriators have the same amount of water at the source and the same amount of water at their field gate during that time period (e.g., 4 units of water, $4u_d$),[12] but for whatever reason the pattern of distribution over time differs. Appropriator A receives one unit (u_d) on one day and three units ($3u_d$) on the second day. Appropriator B, on the other hand, obtains two units ($2u_d$) on each day. In this example, the total benefit for the two appropriators differs because the total benefit of irrigation water is a quadratic function of the supply of irrigation water (see Figure 3.4). Figure 3.4 shows a hypothetical total benefit curve for a day. Recall that the marginal benefit of irrigation water is assumed to be constant over a time period t, so the total benefit curve for each day is identical. According to Figure 3.4, appropriator B obtains 4TB for the time period t (2TB for the one day <u>plus</u> 2TB for the other day), whereas appropriator A receives only 3TB (TB for the one day <u>plus</u> 2TB for the other day). The two appropriators get different total benefits even though the same amount of water flows through their field gates, with the appropriator who enjoys a more even distribution of water (i.e., higher level of reliability) gaining more total benefit from the same amount of water. More precisely, appropriators get the maximum total benefit from a given amount of irrigation water when the water is distributed evenly over time. This is always the case when the appropriation period t is composed of two

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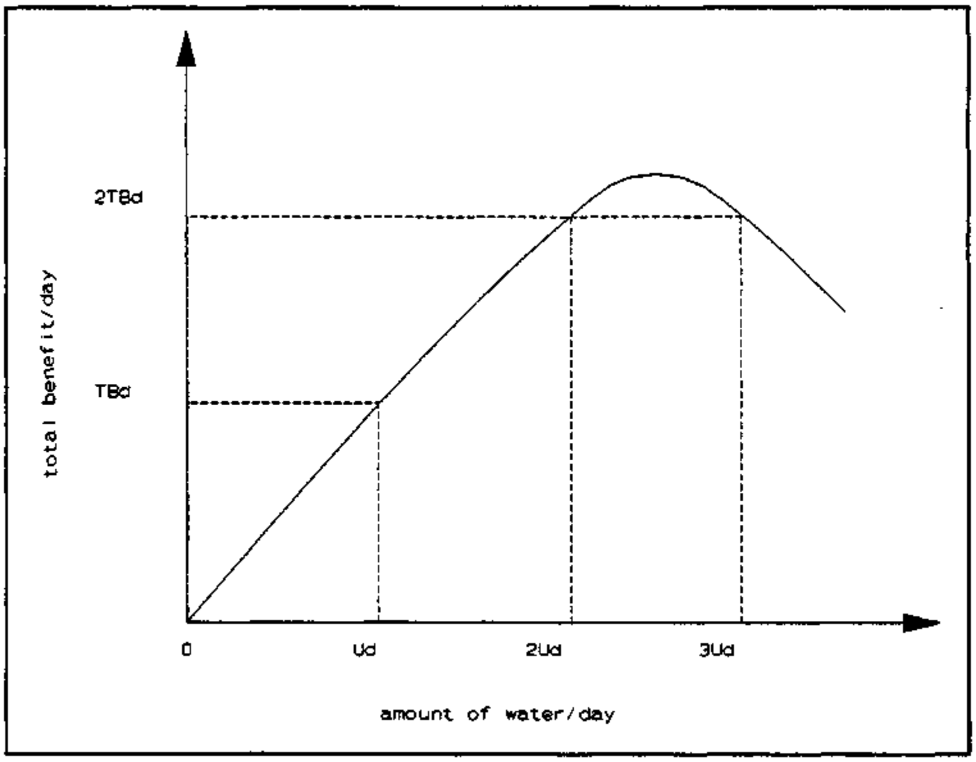
[12] This means that they have the same level of efficiency, which will be explained in the following section. This example also will be helpful to see the difference between the reliability of water supply and the water delivery efficiency.

Figure 3.4: Total Benefit Function for One Day



days.[13]

Appropriators can get the maximum feasible total benefit from a given amount of irrigation water when it is distributed evenly over the time period t. For this reason, appropriators will try to distribute the irrigation water as evenly as possible over the time period t. If the water supply of the irrigation system is completely reliable, then appropriators can evenly distribute the irrigation water over the time period t. Therefore, given my assumption on non-seasonality of demand for the irrigation water, an irrigation system is "reliable" when it distributes the irrigation water evenly over time.

---

[13] This can be deduced from the characteristics of concavity. In my model, the total benefit function is concave. A function "g" is defined as concave if:

$$\text{(a)} \qquad g(\lambda y+(1-\lambda)z) \geq \lambda g(y) + (1-\lambda)g(z), \qquad \forall\ 0 \leq \lambda \leq 1.$$

Let (i) x, y, and z be an amount of water such that y+z=2x and y,z x; and
(ii) g(x) be the total benefit function which is concave.

If λ=0.5, then the equation (a) will be:

$$g(.5y+.5z) \geq .5g(y) + .5g(z).$$

$$g(.5y+.5z) \geq .5g(y) + .5g(z).$$

$$g(.5(y+z)) \geq .5g(y) + .5g(z).$$

This can be re-written as:

$$g(.5(y+z)) \geq .5g(y) + .5g(z).$$

$$g(.5*2x) \geq .5g(y) + .5g(z).$$

Since y+z=2x, It also can be re-written as:

$$g(.5*2x) \geq .5g(y) + .5g(z).$$

$$g(x) \geq .5g(y) + .5g(z).$$

This is equivalent to:

$$g(x) \geq .5g(y) + .5g(z). \text{ or}$$
$$g(x) + g(x) \geq g(y) + g(z).$$

Multiply bot

$$2*g(x) \geq g(y) + g(z) \qquad \text{or}$$
$$g(x) + g(x) \geq g(y) + g(z).$$

As you see, by definition, the left-hand side is always greater than or at least equal to the right-hand side if, the function g is concave. Notice that the left-hand side of the equation (a) refers to the total benefit of the case where "2x" amount of water is evenly distributed over time (x for one day and x for the other day), whereas the right-hand side refers to the total benefit of the case where it is unevenly distributed (y for one day and z for the other day). Based upon this, we can say that one can maximize his/her total benefit of the irrigation water when it is evenly distributed over time.

I formally define the reliability of water supply as:

(8) $$R_t = 1 - \{(\Sigma_{d=1}^{N} u_d - (u_t/N)|)/(u_t/N)\}, \qquad d=1,\ldots,N$$

$$\text{, where } u_d = \text{amount of irrigation water at day d, } \Sigma_{d=1}^{N} u_d = u_t.$$

Reliability lies in the interval between zero and one. It equals one when the water is evenly distributed over the time period t. It equals zero when the system distributes the total amount of irrigation water available for the time period t (u_t) on one day.

The total benefit of the irrigation water depends on the reliability of the water supply of the irrigation system. To depict this, I assume that the total benefit of irrigation water use equals the area under the linear marginal benefit curve shown in equation (1) when the water supply is completely reliable (R_t=l). If the water supply is not completely reliable (R_t<1) , then player i gets only a portion of the level of total benefit when R_t equals one. To reflect the effect of reliability, we change the marginal benefit function to:

(9) $$MB_{it} = R_t q - r u_{it}.$$

If reliability is less than one, then the marginal benefit curve shifts downward and the area under that curve, which represents the total benefit, decreases.[14] Building on the marginal benefit function, the total benefit of water use is:

(10) $$\pi_{it}^{B} = R_t q * u_{it} - .5 r u_{it}^{2}.$$

Several factors influence changes in the reliability of water

[14] See the dotted line in Figures 3.2 and 3.3. Also notice that ideally, the relationship would be non-linear. But here I use linear approximation for simplicity.

supply over time. First, the maintenance work done in the previous period affects the reliability of the water supply of the canal irrigation. If the canals were not well maintained in the previous period, then the canals cannot function well, which decreases the reliability of the water supply. K_t notes the minimum level of investment required to conserve the previous level of reliability. When the sum of investment exceeds that level, the reliability of an irrigation system increases, but when it does not, the reliability of that system decreases.

Secondly, the amount of water extracted in the previous period also affects reliability. If appropriators use too much water, the reliability of water supply diminishes due to the reduction in the amount of water available and the deterioration of the irrigation system. We refer to the maximum level of appropriation allowed to conserve the previous level of reliability as K'_t. If the total water appropriated exceeds that level, the reliability of an irrigation system decreases; if it does not, the reliability of that system increases. In ground water basin systems, the amount of appropriation affects the level of reliability a great deal because the irrigation water is stored. In this model, however, the impact of the amount of water extracted in the previous period on the level of reliability is likely to be smaller than the impact of the maintenance because the irrigation system in this model has no storage capacity which can hold irrigation water.

We can summarize the effects on reliability by a state transformation equation that determines the transition of the state variable representing the reliability of the water supply. The following equation determines the transformation of the reliability of the water supply:

$$R_{t+1} = 0 \qquad \text{if } \{R_t - \alpha(K_{t+1} - \Sigma m_{it}) + \alpha'(K'_{t+1} - \Sigma u_{it})\} < 0, \tag{11}$$

$$=R_t-\alpha(K_{t+1}-\Sigma m_{it})+\theta(K'_{t+1}-\Sigma u_{it})$$

$$\text{if } 0\leq\{R_t-\alpha(K_{t+1}-\Sigma m_{it})+\alpha'(K'_{t+1}-\Sigma u_{it})\}\leq 1,$$

$$=1 \qquad \text{if } \{R_t-\alpha(K_{t+1}-\Sigma m_{it})+\alpha'(K'_{t+1}-\Sigma u_{it})\}>1$$

,where α, α' = sensitivity coefficients[15]
K_{t+1} = the minimum investment required to maintain the previous level of reliability, R_t.
K'_{t+1} = the maximum appropriation allowed to maintain the previous level of reliability, R_t.

The sensitivity of reliability to maintenance, α, depicts the extent to which the amount of investment in maintenance made by appropriators at time t affects the level of reliability of water supply at time (t+1). It varies from 0 to 1. When α equals zero, the amount of investment in the maintenance made by appropriators does not change the level of reliability of water supply. As α becomes larger, the level of the reliability of water supply becomes more sensitive to the amount of investment in the maintenance made by the appropriators. An irrigation system with α equal to zero has a perfect engineering work and can maintain the initial level of the reliability of water supply without any maintenance work. Notice that it is impossible in this case to raise the level of the reliability of water supply higher than the initial level regardless of how much appropriators invest in maintenance. In other words, there is no room for improvement in this irrigation system.

The sensitivity of reliability to appropriation, α', represents the extent to which the amount of irrigation water appropriated by appropriators at time t affects the level of reliability of water supply at time (t+1). α' also varies from 0 to 1. When α' equals zero, the amount of irrigation water appropriated by appropriators does not change the level of reliability of water supply. As α' becomes larger, the level of the reliability of water supply becomes more sensitive to the

[15] Notice that α will be larger than α' since the effect of the amount of maintenance is greater than that of the amount of appropriation in our case.

amount of irrigation water that users appropriate. Because it is usually impossible to store the irrigation water in run-of-the-river systems, α' tends to be small in these irrigation systems. I assume that α' takes on a positive value even though it cannot be large; appropriating an excessive amount of irrigation water harms the irrigation system.

In summary, we need more maintenance work to preserve the present level of reliability and we can appropriate more water without reducing the present level of reliability when the present level of reliability is high than we need when it is low. That is, K_{t+1} and K'_{t+1} are also functions of R_t. For simplicity, let K_{t+1} and K'_{t+1} be linear functions of R_t:

$$
\begin{aligned}
(12) \qquad & K_{t+1} = \gamma * R_t, \\
& K'_{t+1} = \gamma' * R_t.
\end{aligned}
$$

Then equation (11) can be rewritten as:

$$
\begin{aligned}
(13) \qquad R_{t+1} &= 0 && \text{if } \{R_t - \alpha(\gamma * R_t - \Sigma m_k) + \alpha'(\gamma' * R_t - \Sigma u_k)\} < 0, \\
&= R_t - \alpha(\gamma * R_t - \Sigma m_k) + \alpha'(\gamma' * R_t - \Sigma u_k) && \\
& && \text{if } 0 \le \{R_t - \alpha(\gamma * R_t - \Sigma m_k) + \alpha'(\gamma' * R_t - \Sigma u_k)\} \le 1, \\
&= 1 && \text{if } \{R_t - \alpha(\gamma * R_t - \Sigma m_k) + \alpha'(\gamma' * R_t - \Sigma u_k)\} > 1
\end{aligned}
$$

, where γ = minimum requirement coefficient,
γ' = maximum allowance coefficient.

The minimum requirement coefficient, γ, represents some threshold value. The product of this coefficient and the level of the reliability of water supply at time t denotes the threshold value of investment in maintenance at time t. If the appropriators invest in maintenance less than this threshold, the level of the reliability of water supply decreases. Similarly, if the total investment in maintenance surpasses this threshold, the level of the reliability of water supply increases. As γ rises, the irrigation system requires more investment in the maintenance to maintain a present level of the reliability of water supply.

The maximum allowance coefficient, γ', also depicts a threshold value for the amount of irrigation water appropriated. The product of this coefficient and the level of the reliability of water supply at time t identifies the threshold value of appropriation at time t. If the appropriators use more than this threshold, the level of the reliability of water supply decreases. Similarly, if the total amount of irrigation water appropriated is smaller than this threshold, the level of the reliability of water supply increases.

In sum, equation (5') can be re-written as:

(14)
$$\Pi_{jt} = \pi_{jt}^{DF} + \pi_{jt}^{R} - \epsilon$$
$$= R_t q^* u_{jt} - .5ru_{jt}^2 - e^*\Sigma u_{jt}^* u_{jt} - m_{jt} \qquad \text{for headenders}$$

and,

$$\Pi_{kt} = \pi_{kt}^{DF} + \pi_{kt}^{R} - \epsilon$$
$$= R_t q^* u_{kt} - .5ru_{kt}^2 - e^*(\delta^*\Sigma u_{jt} + \Sigma u_{kt})^* u_{kt} - m_{kt} \qquad \text{for tailenders.}$$

And we can re-write equation (6) as:

(15)
$$\Psi_{jt} = \Sigma_{t=1}^{T}\omega^{t-1}(\Pi_{jt}) \qquad \text{for headenders, and}$$
$$\Psi_{kt} = \Sigma_{t=1}^{T}\omega^{t-1}(\Pi_{kt}) \qquad \text{for tailenders.}$$

<u>Water Delivery Efficiency</u>

Water delivery efficiency, the second state variable, also affects the appropriators' payoffs, although it affects the payoffs sightly differently than the reliability of water supply does. Water delivery efficiency influences the payoffs through its impact on the quantity of the irrigation water available to individual appropriators. So far, we have treated the quantity of irrigation water available to an irrigation system (Q) as a constant. The amount of the water at the source (Q^s) is, of course, pretty much beyond appropriators' control.[16] Appropriators' behavior at the previous round cannot change it. Still, we need to distinguish the amount of water at the source (Q^s) from the amount of water available to the irrigation system at the field gate (say, Q^{FG}). The two can be nearly identical when the irrigation system is attached to the source so that there is no canal between the source and the field. If a canal exists between the source and the field <u>and</u> the canal has water leakage, the two differ. This means that the amount of water at the field gate at time t, Q^{FG}_t, is a function of both the amount of water at the source (Q^s) and the water losses in the canal, Q^1.

(16) $$Q^{FG}_t = Q^s - Q^1_t.$$

Q^1 depends on the second state variable in this model, the water delivery efficiency. With proper maintenance, appropriators increase the water delivery efficiency and reduce the water losses in the stretch of a canal. Let the water delivery efficiency (E_t) be a measure of water losses in the stretch of a canal. Although there may be several ways to define the water delivery efficiency, I define it as an index of the efficiency of the canal, which varies from zero to one. It equals "1" when the efficiency of the canal minimizes water loss. It equals "zero" when the inefficiency of the canal allows water loss to reach its maximum.[17] The length of the canal also affected water loss. If the field gate is directly attached to the source of the irrigation water,

[16] It can be changed when, for example, a big dam is built. However, my model considers this sort of change as an exogenous change.

[17] Conceptually, it can be thought of as "the proportion of water entering the reach that is delivered to the other end" (Sparling 1990, 199) per unit of length. If we use this concept, Q^{FG} will be expressed as an exponential function of E_t and we will have some problems solving our game. So, I decided not to use this concept.

no water loss at all occurs; but, Q^{FG} becomes smaller and smaller as the length of the canal from the source to the field gate becomes longer and longer, given any particular values for both Q^{s} and E_t. Let the length from the source to the field gate be 1. The water losses at time period t, Q^{1}_{t}, can then be written as:

(17) $$Q^{1}_{t} = a*(l-E_t)*l,$$

,where a $\{0 \quad a \quad (Q^{s}/1)\}$ = water loss coefficient.

The water loss coefficient, a, represents the amount of water lost in the stretch of the canal. If a is zero, then no water is lost at all. As a rises, so does the water loss.

Combining equations (16) and (17), the amount of water at the field gate at time t can be written as:

(18) $$Q^{FG}_{t} = Q^{s} - a*(1-E_t)*l.$$

Q^{FG} is the amount of water at the headenders' field gate.[18] Since the length of the canal from the source to the tailenders' field gate usually exceeds that for headenders, the tailenders usually receive less water at their field gate than the headenders do even when the tailenders appropriate nothing, due to water losses in the stretch of the canal.[19] When the headenders appropriate some amount of irrigation water, this also reduces the amount of water at the field gate of the tailenders. Let the amount of water at the tailenders' field gate and

[18] Since I assume that the headenders are identical in all respects, I ignore the possible difference in Q^{FG}_{t} among the headenders. This is also the case for the tailenders.

[19] Also notice that the water delivery efficiency at a particular part of a canal can be different from the water delivery efficiency at another part of a canal. That is, the water delivery efficiency of the tailenders can be lower than that of the headenders. But, for simplicity, here I assume a unitary water delivery efficiency for the entire irrigation at time t.

the length of canal from the headenders field gate to the tailenders field gate be Q^{FG}_{t}' and 1', respectively, so that:

$$(19) \qquad Q^{FG}_{t}{}' = Q^{s} - \Sigma u^{*}_{jt} - a*(1-E_t)*(1+1').$$

As with the reliability of water supply, the amount of maintenance work and the amount of appropriation in the previous time period influence the water delivery efficiency. Again, whether sufficient maintenance occurs is identified by two threshold values -- the minimum level of investment required to preserve the previous level of efficiency, K''_t, and the maximum level of appropriation allowed to maintain the previous level of efficiency, K'''_t. The thresholds are also increasing functions of the level of efficiency. When the present level of efficiency is high, we need more maintenance work to preserve the present level of efficiency and we can appropriate more water without reducing the present level of efficiency than when the present level of efficiency is low. Thus, the state transition equation for the water delivery efficiency is:

$$(20) \qquad \begin{aligned} E_{t+1} &= 0 && \text{if } \{E_t-\theta(\gamma''*E_t-\Sigma m_{it})+\theta'(\gamma'''*E_t-\Sigma u_{it})\}<0, \\ &= E_t-\theta(\gamma''*E_t-\Sigma m_{it})+\theta'(\gamma'''*E_t-\Sigma u_{it}) \\ & && \text{if } 0\leq\{E_t-\theta(\gamma''*E_t-\Sigma m_{it})+\theta'(\gamma'''*E_t-\Sigma u_{it})\}\leq 1, \\ &= 1 && \text{if } \{E_t-\theta(\gamma''*E_t-\Sigma m_{it})+\theta'(\gamma'''*E_t-\Sigma u_{it})\}> 1 \end{aligned}$$

,where θ, θ' = sensitivity coefficients,
γ'' = minimum requirement coefficients,
γ''' = maximum allowance coefficient.

The sensitivity of efficiency to maintenance, θ, represents the extent to which the amount of investment in maintenance made by appropriators at time t determines the level of water delivery efficiency at time (t+1). It varies from 0 to 1. When θ equals zero, the level of water delivery efficiency does not change at all, regardless of the amount of investment in maintenance made by appropriators. As 8 becomes larger, the level of water delivery efficiency becomes more sensitive to the amount of investment in maintenance. The sensitivity of efficiency to maintenance, 8, comes close to 0 in completely lined canals.

Sensitivity of efficiency to appropriation, θ', depicts the extent to which the level of water delivery efficiency at time (t+1) is affected by the amount of irrigation water appropriated by appropriators at time t. It also varies from 0 to 1. When θ' equals zero, the amount of irrigation water appropriated by appropriators does not change the level of water delivery efficiency. As 8' becomes larger, the level of the water delivery efficiency becomes more sensitive to the amount of irrigation water appropriated by appropriators.

The minimum requirement coefficient, γ'', represents the threshold value of investment in maintenance that is required to keep the present level of water delivery efficiency. The product of this coefficient and the level of the water delivery efficiency at time t denotes the threshold value of the investment in maintenance at time t. As γ'' rises, maintaining the present level of the water delivery efficiency requires more investment in the maintenance.

The product of the maximum allowance coefficient, γ''', and the present level of water delivery efficiency represents a threshold value of the amount of appropriation. If the total amount of irrigation water used by the appropriators is greater than this threshold, the level of water delivery efficiency decreases. If the total amount of irrigation water used by the appropriators is smaller than this threshold, the level of water delivery efficiency increases. As γ''' rises, appropriators can use more irrigation water without doing any harm to the system.

The amount of investment in maintenance and the amount of appropriation at the previous time period, $\Sigma m_{j(t-1)}$ and $\Sigma u_{j(t-1)}$, respectively, affect the water delivery efficiency at time t, which in turn influences the amount of water available to the individual appropriators, and this amount of water affects their payoffs. Because appropriators cannot physically appropriate that which is not available to them, an upper limit on the appropriators' choice on u_{it} exists. The lower limit is zero since appropriators cannot get a negative amount of water. Let u^*_{it} be a optimal amount of appropriation that maximizes the sum of the discounted payoffs at time t, Ψ_{it} $(=\sum_{t=1}^{T}\omega^{t-1}(\Pi_{it}))$. If u^*_{it} falls between these two limits, then it will be the choice; but if it does not, then either one of the two limits will be the choice. This upper limit is a function of Q^{FG}_t. Both physical and institutional factors determine this function. If a system contains 'm' headenders and 'n-m' tailenders with no institutional constraints, then the maximum amount of water available to the headenders is "Q^{FG}_t/m", which is the available amount distributed evenly among them.[20] If (Q^{FG}_t/m) exceeds Σu^*_{jt}, then the rest goes to the tailenders. In this case, $\{Q^{FG}_t{}'/(n-m)\}$ serves as the upper limit for the tailenders. If $\{Q^{FG}_t{}'/(n-m)\}$ is greater than u^*_{kt}, then the tailenders get as much water as they choose. But if $\{Q^{FG}_t{}'/(n-m)\}$ is small, then it may be that headenders can get as much water as they want <u>but</u> tailenders do not. It may also be that a small Q^{FG}_t keeps even headenders from getting as much water as they want, which is u^*_{jt}.[21] Appropriators' choices about the amount of irrigation water to appropriate is subject to these constraints:

(21) $\quad 0 \le u_{jt} \le (Q^{FG}_t/m)$ for headenders

$\quad 0 \le u_{kt} \le \{Q^{FG}_t{}'/(n-m)\}$ for tailenders.

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[20] We assume that there is symmetry among headenders, which means that there is no difference among them in all aspects.

[21] This situation may be called a "default situation". If there exist some rules concerning the allocation process, the upper limit may be determined in a different way.

Reliability and Efficiency

The reliability of water supply and the water delivery efficiency can be thought of as two different measures of performance of an irrigation system. The reliability of water supply refers to the evenness of distribution of the supply of water over time within a season. The water delivery efficiency, on the other hand, refers to the efficiently with which the water at the source is delivered to the field gate. Reliability refers to **the distribution of** a **given amount of water** and efficiency refers to **the amount of water losses in the stretch of** the canals.

I assume that the two state variables have no effect on each other's state transition equation. When we employ the definition of reliability in equation (8), a perfect reliability does not require any particular amount of water. We have perfect reliability whenever the water is distributed evenly over the time period t. Use this definition with care. It makes sense in our model, since we assume that the marginal benefit of the irrigation water is fixed over the time period t. Since the marginal benefit of the irrigation water is fixed over the time period t, a "reliable water supply" always means "even distribution". If, instead, the marginal benefit of the irrigation water differs over the time period t, then we cannot say that even distribution means a reliable water supply.

To conclude, players in this game maximize the present value of Π_{it} in equation (15) subject to a set of constraints that characterize the reliability and the efficiency of the irrigation system (equations (13) and (20)) and the constraints on the amount of investment in maintenance (equation(7)) and on the amount of water available to the appropriators at each time period (equation(21)). If the upper limit on the amount of water available to an appropriator at time period t is smaller than the $u_{it}*$ that maximizes Ψ_{it}, then the upper limit will be the choice at time t;

if not, u_{it}* will be the choice. The choice of the amount of resources invested the maintenance at time t decides the reliability of water supply and water delivery efficiency at time (t+1), and this affects the payoff functions at time (t+1). This process repeats until the final time period T.

Table 3.1 summarizes 23 parameters used in this model. These parameters can be classified into three groups:

(i) parameters that represent general action situation (Group 1);

(ii) parameters that represent payoff function (Group 2); and

(iii) parameters that represent the state transition equations (Group 3).

Table 3.1: Parameters used in the Model

Parameters		Description
GROUP ONE	n	Number of total appropriators
	m	Number of headenders
	T	Number of repetition
	ω	Discount parameter
	mB_j	Maximum amount of investment in maintenance appropriator, i, can afford
	Q^s	Amount of water at the source
	1	Length of canal from water source to headender's water gate
	1'	Length of canal from headender's water gate to tailender's water gate
GROUP TWO	q	Intercept of marginal benefit function of water
	r	Slope of marginal benefit function of water
	e	Appropriation cost coefficient
	δ	Coefficient of interdependency between headenders and tailenders
GROUP THREE	R_o	Initial value of reliability of water supply
	E_o	Initial value of water delivery efficiency
	α	Sensitivity of Reliability to maintenance
	α'	Sensitivity of Reliability to appropriation
	θ	Sensitivity of Efficiency to maintenance
	θ'	Sensitivity of Efficiency to appropriation
	α	Water loss coefficient
	γ	Minimum requirement coefficient of maintenance for reliability
	γ'	Maximum allowance coefficient of appropriation for reliability
	γ''	Minimum requirement coefficient of maintenance for efficiency
	γ'''	Maximum allowance coefficient of appropriation for efficiency

Chapter 4

The Institutional Analysis and Development Framework and Parameters

We can organize theoretical and empirical studies of diverse policy fields with the institutional analysis and development (IAD) framework, which was developed by scholars associated with the Workshop in Political Theory and Policy Analysis (Kiser and E. Ostrom, 1982; E. Ostrom 1986; Oakerson 1992).[1]

The IAD framework draws attention to the *incentive* structure facing individuals in a setting that leads them to act in ways that generate particular patterns of outcomes. Incentives are positive and negative rewards for behavior, to which individuals assign meaning. A complex mix of the three clusters of attributes -- attributes from a physical world, attributes from a set of institutions, and attributes from the shared beliefs of the members of a community -- generates incentive structures. The IAD framework identifies these three clusters of variables as the key types of variables that need to be considered when undertaking a policy study. A policy analysis that draws on the IAD framework usually starts with a study of the physical world where individuals interact with each other and the problems that come from the interactions. Then the analysis proceeds to study the rules that individuals use in a particular setting as well as the type of shared understandings that exist.

The parameters that represent the incentive structure in this model (i.e., an action situation) are to be viewed as a function of physical attributes, rule configurations, and attributes of the community, which are the key types of variables of the IAD framework.

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[1] This framework has been applied to the studies of many policy fields: general common-pool resources (E. Ostrom 1990; E. Ostrom, Gardner and Walker 1993); irrigation systems (E. Ostrom 1992; Tang 1987; 1992); the sustenance of rural infrastructures in developing countries (E. Ostrom, Schroeder, and Wynne 1993); and urban governance (V. Ostrom, Tiebout, and Warren 1961; ACIR 1987; V. Ostrom, Bish and E. Ostrom 1992).

By changing the values of the parameters, we simulate the impact of changes in the physical attributes, rule configurations, and attributes of the community of specific irrigation systems on the game and its outcomes.

We conceptualize the incentive structures as an *action arena.* Using this conceptual unit helps to analyze, predict, and explain behavior and outcomes of a particular setting with fixed constraints. That is, the action arena serves as the focus of analysis in institutional analyses that use the IAD framework. Action arenas include an action situation component and an actor component.

The action situation refers to "the social space where individuals interact, exchange goods and services, engage in appropriation and provision activities, solve problems, or fight" (E.Ostrom, Gardner, and Walker 1993). A standard mathematical way of representing an action situation is a game (Selten 1975; Shubik 1982; E.Ostrom, Gardner and Walker 1993).[2] Our dynamic game, described in the previous chapter, analyzes an action situation constituted by seven clusters of variables: (1) participants, (2) positions, (3) actions, (4) potential outcomes, (5) a function that maps actions into realized outcomes, (6) information, and (7) the costs and benefits assigned to actions and outcomes. To predict how actors will behave, we must make assumptions about these seven clusters of variables and about the individuals. Most analyses that use formal models do not explicitly mention these assumptions. Without these assumptions, however, we simply cannot analyze what will happen in the action situation.

Below, I briefly show how the parameters of this model specify the actors and the action situation of the action arena. This helps to

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[2] Modern non-cooperative game theory turns out to be a powerful and useful tool for understanding behavior and outcomes within CPR situations, especially when brought within the IAD framework. However, this does not necessarily imply that the IAD framework limits an analyst to the use of any one theory or model. As a matter of fact, an analyst can use the IAD framework as a foundation for investigating the predictive power of complementary or competing theories and models.

explain the assumptions of the dynamic game theoretic model of an irrigation system. Second, I examine how the three key clusters of variables (i.e., physical, institutional, and community attributes) affect the action arena by analyzing the relationship between the three clusters of variables and the parameters of the model.

Action Arena

Actors

In this game, we assume that individuals have *complete information,* which means that they know: (1) the actions that each participant can take at every stage of decision process and those acts that are governed by random operators, if any; (2) the intermediate or final outcomes that can be realized as a result of the actions of various participants, including a random operator; and (3) the preference ranking each participant places on all possible outcomes. That is, individuals know the full game tree in extensive form. Accordingly, we assume that they know the values of the two state variables -- the reliability of water supply, R_t, and the water delivery efficiency, E_t -- at every time period.

Individuals are assumed to be *expected utility maximizers.* The expected utility of an action refers to the weighted average of the utilities that the action yields under different states of the world. The weights assigned to utilities are the probability that the state of the world that yields that particular utility. Individuals choose the options that maximize the sum of the products of the utility derived from the possible outcomes of that choice multiplied by the probabilities that those outcome will occur (i.e., the expected utility).

Another important assumption about the actors in this model is that they have *foresight.* That is, individuals have some notion of the impact of their present actions on the future action situation through the changes they make in the values of the state variables. Individuals, however, evaluate future benefits and costs as less important than present ones in the utility maximization process. There is always a chance that they will not play the game again, for whatever reason. Thus, the maximization process discounts the future. The discount parameter, ω, represents the degree to which future payoff is discounted relative to present payoff. If the discount parameter, ω, equals "zero", players totally discount future payoffs. It is interesting to note that the discount parameter can represent characteristics of individuals as well as attributes of the community to which they belong. For example, a larger ω depicts individuals who care more about the future because the community to which they belong will use the same resource for a long time. All of these assumptions may be summarized by the assumption that individuals are fully rational in the sense that they have complete information, they assign complete preferences over outcomes, they have unlimited computational powers, they conduct complete analysis, and they maximize expected utility.

Full rationality assumptions have generally been accepted as a normative theory. That is, it is widely agreed that when one faces a decision, particularly for a situation in which numerical probabilities can be attached to the various possible outcomes of each course of action, the proper decision criterion is probability calculus. As a descriptive theory, however, the full rationality assumption is not widely accepted. Critics argue that the amount of information required exceeds the amount that individuals can collect and record. Critics also argue that the rule of expected utility calculation is too demanding and too restrictive, and consequently, unrealistic. It is considered too demanding because ordinary people may be unable to calculate the expected utility, too restrictive because expected utility can be calculated in ways other than the rule of probability calculus, and unrealistic in that most people in the real world do not follow the rules of expected utility calculus.

It may be that full rationality assumptions are unrealistic, but in some situations, processes such as learning, natural selection, heterogeneity of individuals, and statistical averaging lead to the same outcomes as rationality with much weaker assumptions about individual rationality (Tsebellis, 1990). In other words, weak rationality assumptions, such as bounded rationality may lead to the same outcomes as pure rationality through these processes. In sum, I assume that individuals act rationally in the action situation of the model for two reasons: the predictions based on rationality assumption have indisputable normative appeal; and the predictions based on rationality assumptions are approximated in some settings through learning, evolutionary, and statistical averaging processes.

Finally, this model assumes that individuals do not possess sufficient resources to take all of the full range of potential actions that might be available to them. In appropriation, we assume individuals are unable to get more water than is physically available to them, which is determined by the amount of water available at the field gate. In provision, we assume that individuals are unable to invest more time and effort in maintenance than they can afford, mB_j for headenders and mB_k for tailenders. Individuals in this model cannot devote all of their time and efforts to appropriation and maintenance activities. They need to do other tasks, which are not included in this model, to maximize the value of agricultural production.

The Action Situation

I now turn to the parameters depicting the action situation of this game and explain how the model action situation and assumptions about actors relate to the three solution concepts which used in the analysis.

(1) **Participants and Positions:** The n players in this game are farmers who need to appropriate irrigation water from an irrigation system. The players fill two positions, headenders and tailenders. There are m headenders and, accordingly, (n-m) tailenders. In the simplest case, n=2 with one (m=l) headender and one (n-m=l) tailender. Due to their locational advantage, headenders can appropriate water before tailenders can. Participants in each position are identical in every respect and all n players interact repeatedly.

(2) Actions: Participants in both positions can make decisions about the two control variables -- the amount of appropriation, u_{jt} for headenders and u^*_{kt} for tailenders, and the amount of investment in maintenance, m_{jt} for headenders and m_{kt} for tailenders --at every time period. The actions in this game are the appropriation and investment choices. The action sets of this game are continuous. Participants can appropriate a specific amount of water and invest a specific amount in maintenance so as to maximize their expected payoffs from a continuum from the lower limit on each control variable to the upper limit on each control variable. The lower limit for both control variables equals zero at every time period. The upper limits on the amount of appropriation at time period t are "$(Q^s\text{-}a(1\text{-}E_t)1)/m$" for the headenders and "$(Q^s\text{-}a(l\text{-}E_t)(1+1'))/(n\text{-}m)$" for tailenders. The upper limits on the amount of investment in maintenance are "mB_j" for headenders and "mB_k" for tailenders.

(3) Potential Outcomes: Participants choose an optimal amount of water to appropriate, u^*_{jt} for headenders and u^*_{kt} for tailenders, and an optimal amount of resources to invest in maintenance, m^*_{jt} for headenders and m^*_{kt} for tailenders, at every time period. Eventually, we can calculate the time paths of these four values. The time paths identify the potential outcomes that participants affect though their actions.

Participants also affect the two state variables that represent the physical conditions of an irrigation system -- reliability of water supply, R_t; and water delivery efficiency, E_t. The two state variables are also potential outcomes of the game.

(4) Transformation Functions: Consider the two state transition functions (equations (13) and (20) in Chapter 3) as transformation functions that map actions into outcomes. Hence, the parameters used in these two state transition equations can be thought of as variables representing transformation functions. They are: (1) the sensitivity of reliability to maintenance, α; (2) the sensitivity of reliability to appropriation, α'; (3) the minimum requirement coefficient of maintenance for reliability, y; (4) the maximum allowance coefficient of appropriation for reliability, y'; (5) the sensitivity of efficiency to maintenance, 8; (6) the sensitivity of efficiency to appropriation, θ'; (7) the minimum requirement coefficient of maintenance for efficiency, y"; and (8) the maximum allowance coefficient of appropriation for efficiency, y^{m}.

In this game, these parameters determine transformation functions in a configurational manner. Through the transformation functions, we link various combinations of participants' actions to the value of the two state variables, which are potential outcomes of this game, and consequently, to the optimal amounts of appropriation and investment in maintenance at the next time period. Physical regularities pose the main constraints on the transformation functions in this game.

(5) Information: Participants of this game have complete information, as explained in the discussion about the action arena. They always know the action sets of all participants, possible outcomes of their actions, the transformation functions, and the preference rankings of each participant. Tailenders know what actions headenders take before tailenders do. In both appropriation and provision activities, headenders take an action before tailenders do. Headenders only know what tailenders did at earlier nodes. This game is not a game of perfect information, since all headenders act simultaneously, as do all tailenders.[3]

All participants of this game have information about the transformation functions. This information assumption is crucial. Without information about the transformation functions, participants cannot play the game as fully rational players. It is the information about transformation function that enables participants to calculate the impacts of their present actions on the future payoff structures.

(6) Payoffs: The payoff function (equation (14) in Chapter 3) determines the payoffs assigned to actions and outcomes. The two parameters that represent the marginal benefit curve of irrigation water, q (intercept) and r (slope), determine the monetary benefit of the outcome. The price offered to an irrigator for crops brought to market serves as the measure of this benefit. The same amount of appropriation and investment in maintenance can yield different payoffs from one year to the next, depending (1) on the price that a farmer can command when selling a crop and (2) on the kind of crop he/she cultivated. In this game, q and r depict these two factors. The appropriation cost coefficient, e, determines the cost of appropriation activity. All of these parameters configurationally assign positive and negative weights to the outcomes and to the actions leading to outcomes.

The discounted parameter, Ω, also affects the assignment of weights to the outcome. Participants weigh future payoffs by the

[3] In a game of perfect information, each participant is allowed to know precisely the choices of all others as well as the ones that he/she made on earlier moves, whenever it is his/her turn to act (Ordeshook 1986, 120). Our game can be a game of perfect information when there are only two participants (one headender and one tailender). However, in our game, participants generally do not have such information since headenders must act simultaneously and so must tailenders.

discount parameters when maximizing the sum of all the payoffs of each time period.

Solution Concepts and the Action Arena

In the action area described here, individuals try to maximize the expected utility, which is a general theory about individual rationality. Different competing models for maximizing expected utility (i.e., solution concepts) exists. Dynamic game-theoretic models can utilize three solution concepts: the closed-loop solution, the myopic solution, and the social optimum solution. These three solutions can be thought of as three different ways of modelling an action arena. In other words, the proper solution concept depends on the assumptions that one makes about the action arena. Next, I explain the three different solution concepts and the assumptions under which they are proper solutions to the game.

(1) The Myopic Solution: A Parallel of Individual Rationality in One-Shot PD Game: In a myopic solution, players try to maximize their payoffs by simply setting a single period marginal benefit equal to a single period marginal cost. In other words, players wrongly treat the game as a one-shot game and try to maximize the payoff of a single period without paying attention to the effects of their behavior on future periods. A myopic solution is, of course, not suitable for the action arena of this game. A myopic solution depicts two situations that differ from the action arena of this game. By examining these two situations, we can learn the importance of institutional arrangements in CPR situations.

First, the myopic solution portrays an action arena where individuals have no foresight into the impact of their behavior on future values of the state variables. Contrary to the players' perception, the game plays repeatedly and the values of the state variables change according to the players' actions on the control variables. The payoff structure of the game itself can drastically change over time. This solution, therefore, likely differs from what is socially optimal. It can parallel the prediction of the one-shot PD game, which represents the inevitable sub-optimal solution to CPR situations. The myopic solution to a dynamic game and the sub-optimal solution ("Defect") to a PD game differ, however, in one important aspect. In PD game, it is totally individually rational to choose "Defect" even though it is not socially optimal. In the dynamic game, the myopic solution may be neither individually rational nor socially optimal because players ignore one of the important parts of the game, the mechanism of changes in the state variables.[4]

Secondly, the myopic solution can depict situations in which even rational individuals with foresight cannot expect repeated interactions among players and, thus, cannot have information about the transformation functions explained earlier. These situations happen either when it is physically impossible to get that kind of information or when the lack of institutional arrangements or social capital makes it impossible. Note that it is impossible to calculate the closed-loop solution when neither institutional arrangement nor social capital exists. Consequently, the myopic solution could be an individually rational solution in "stark institutional settings" (E.Ostrom and Walker 1993).

The myopic solution, therefore, is unsuitable for the action arena of this game; but, I use the myopic solution to parallel the predictions of a one-shot PD game that does not include the impacts of dynamic context on the incentive structure of individuals. This solution highlights the importance of foresight as well as the importance of institutional attributes in CPR situations. This solution also enables

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[4] The myopic solution to a dynamic game can be the individually rational solution if the discount factor (u) equals zero.

us to show that closed-loop solutions reduce efficiency losses thanks to foresight and institutional arrangements.[5]

(2) The **Closed-Loop Solution: Individual Rationality in Richer Institutional Settings:** The closed-loop solution is the most suitable solution to this game since we assume that appropriators interact repeatedly and can get proper information about the transformation functions of the action arena. Without this assumption of institutional settings, even rational individuals with foresight cannot calculate the closed-loop solution as a solution to this game.

In the closed-loop solution, players are expected utility maximizers who try to maximize *the* sum *of all the payoffs of each time period discounted by* a *discount parameter.* Players can know the level of the two state variables and the actions taken by all the participants at the end of every time period. Each player then adjusts his/her behavior in response to the actions of other players. The closed-loop solution offers a more appropriate solution concept for representing such individually rational forward-looking behavior than does the open-loop solution.[6] At any point in the play of the game, players who use a closed-loop solution pick the strategy path that maximizes their payoffs for the rest of the game (Dixon 1991).

To construct a closed-loop solution, we work backwards from the last round to the initial round. Thus, obtaining a closed-loop solution

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[5] The myopic solution will be used as a description of rationality without foresight in Ch. 5, Ch. 6, and Ch. 7, and will be used as a portrayal of stark institutional settings in Ch. 8.

[6] Both closed-loop and open-loop solutions can capture forward-looking behavior. But these two solution concepts differ in their treatment of the strategic interactions among players. In the open-loop solution, it is assumed that each player does not take into account the effect of his/her behavior on the others' behavior. It assumes that each player will not think that other players respond to his/her actions and, accordingly, that each player has no reason to alter his/her own action during the course of play. In the closed-loop solution, on the other hand, players are assumed to adjust their behavior in response to others' behavior.

requires backward induction, which is not required in obtaining the open-loop solutions. The closed-loop solution is equivalent to the subgame perfect Nash equilibrium because the players' strategies constitute a Nash equilibrium in every subgame (Ordeshook 1986; Fudenburg and Tirole 1991; Myerson 1991; Gibbons 1992).[7] The calculation algorithm for the closed-loop solution is shown in the Appendix.

Closed-loop solutions tend to pay less than open-loop solutions pay because the former includes a strategic externality which the latter omits. In other words, the open-loop solution unrealistically understates welfare loss (Dixon 1991). In some cases, the open-loop solution wrongly generates results with no inefficiency in a CPR situation in which the closed-loop solution results show inefficiency (Kemp and Long 1980).

Thus, predictions based on the open-loop solution can be too optimistic. Policy recommendations based on open-loop solution analyses using may overestimate the possibility that self-governing solutions can overcome sub-optimality in CPR situations. If a closed-loop solution predicts that a self-governing solution can overcome sub-optimality problems in a CPR situation, then open-loop solution analysis would also predict the viability of the self-governing solution. For this reason, I employ the closed-loop solution instead of the open-loop solution in this game.

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[7] The result of the backward induction procedure is called either the backward induction *outcome* of the game, or the backward induction Nash *equilibrium* of the game. The subgame perfect Nash equilibrium is simply a more general term for the backward induction Nash equilibrium. An equilibrium is a collection of strategies (complete plans of action) whereas "an outcome is what will happen only in the contingencies that are expected to arise, not in every contingency that might arise" (Gibbons 1992, 125). In our analysis, precisely speaking, what we need is the backward induction *outcome* (which is composed of only unique solutions) rather than the subgame perfect or backward induction *equilibrium* of the game (which is composed of best reaction functions as well as unique solutions).

(3) The Social Optimum Solution as a Criterion for Efficiency Loss: The "Cooperate and Cooperate" outcome of the PD game is its social optimal solution. Because the strategy set of this game is continuous, it is more difficult to determine the mutual cooperation outcome that depicts social optimality. To measure the efficiency loss of the outcomes of individual rationality, we need to calculate the social optimum solution, which can be achieved in a totally different action arena. If all participants can behave as if they are one person to maximize the total payoff, and then to divide the total payoff evenly among them, the result would be the social optimum without any efficiency loss.[8]

The closed-loop algorithm (or backward induction) is also used to calculate the social optimum solution. Because the situation becomes a game with one player in calculating the social optimum solution, we can theoretically calculate the social optimum solution using the open-loop algorithm without using backward induction. To do that, we need to know the end-point values of the state variables; and knowing the end-point value requires asset functions (Fryer and Greenman 1987). In this study, it is extremely difficult to know the asset functions of the two state variables, so, I use the closed-loop algorithm to calculate the social optimum solution.

As with the "Cooperate and Cooperate" outcome in a PD game, this solution cannot be an equilibrium in our game because it is not individually rational, even though it is socially optimal and collectively rational. Players, especially headenders, will be able to increase their private payoffs by deviating from this solution and moving towards the closed-loop solution. Thus, this study uses the social optimum solution not as one of the solutions to the game but as a benchmark that represents the maximum feasible outcome of the game.

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[8] This could be possible only when there is an omnipotent arbitrator who can implement any plan of actions with out transaction costs.

Using this solution, we can measure the welfare losses of the closed-loop as well as the myopic solutions.

Factors Affecting Action Arena

Whenever analysts think about action arenas, they explicitly or implicitly make assumptions about the rules that individuals use to order their relationships, about the attributes of a physical world, and about the nature of the community where the action arenas occur. Implicit or explicit assumptions about these three clusters of variables influence the way the elements of action situations are conceptualized. That the incentive structure of an irrigation system is conceptualized as a dynamic game, and that the closed-loop solution is accepted as a solution to this dynamic game simply reflect some particular combination of the elements of an action arena. Below, I discuss how attributes of rules, physical conditions, and community affect the parameters that portray the action arena of this game

Institutional Attributes

Rules, formal or informal, are linguistic entities that refer to prescriptions commonly known and used by a group of individuals to order repetitive and interdependent relationships (Commons 1957; Ganz 1971; V. Ostrom 1980). Prescriptions refer to the actions that are required, prohibited, or permitted. Rules create feasible sets from the physically possible outcomes (E. Ostrom 1986). As E. Ostrom points out (1986; 6), rules usually do not prescribe one, and only one, action or outcome; they instead affect the structure of an action situation. This implies that the physically possible outcomes that the rules exclude may be technically available to individuals. Individuals who maximize their payoff in the light of a full set of incentives, select actions from a set *of feasible actions,* not from *a set of allowable actions.* In some cases, the action that is not allowed by the rules (i.e., illegal actions or rule-breaking behaviors) can possibly maximize payoffs. Rule-breaking behaviors can occur in equilibria in some cases (see, E. Ostrom, Gardner and Walker 1993; Ch.2). Consequently, rules cannot produce a certain behavior.

Note that the rules used by the individuals should be distinguished from *"the* rules *of the game,"* which a modeler uses to capture the incentive structure of a specific action arena. A modeler may want to know the incentive structure that a specific rule generates if one assumes that every player follows the rules. Rule-breaking behaviors would simply not be available to the players; they would be "ruled-out" by "the rules of the game." Unlike the rules that individuals use in an action situation, "rules of the game" can totally exclude the possibility of rule-breaking behaviors from the game. For example, "the rules of the game" make it strictly impossible for the players in incomplete information games to obtain some pieces of information. However, if an institutional rule proscribes one player from revealing information, that player might still reveal it if there are positive incentives to do so.

The configurational or nonseparable attribute of rules is another important "aspect of institutional attributes. The effect of one rule on incentives and outcomes frequently depends on the other rules in use. Knowing only one rule may not enable us to predict outcomes. We can identify seven broad types of rules that operate configurationally to affect the incentive structure of an action situation (E. Ostrom, Gardner and Walker 1993): (1) position rules; (2) boundary rules; (3) authority rules; (4) aggregation rules; (5) scope rules; (6) information rules; and (7) payoff rules.[9]

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[9] These seven types of rules can be understood both as the types of "rules of the game" and the types of rules-in-use.

(1) **Position Rules:** Position rules specify the number and kind of players interact in a game situation. In our model, appropriators play the game. The position rules allow for two types of players, headenders and tailenders.

(2) Boundary Rules: Boundary rules define the requirements that must be fulfilled before individuals are eligible to withdraw irrigation water from an irrigation system. As these rules become more restrictive, the total number of players (n) becomes smaller. Boundary rules can refer to a variety of requirements, such as citizenship or residence in a local community, the payment of a fixed water fee, or ownership or leasing of land in the location. And these attributes can also affect several parameters.

Boundary rules also define the transmission of entry rights through inheritance and within a single generation of potential appropriators. The transmission of entry right influences several parameters, such as the number of repetitions (T) and the discount factor (ω). If entry rights may be inherited, for example, both the number of repetitions (T) and the discount factor (u) are likely to be larger than in systems without inheritance. Appropriators will tend to care more about the future under such circumstances than in situations where entry rights cannot be inherited. These rules thus affect the parameters of this model.

(3) Authority Rules: Authority rules limit two types of actions: the taking of water from an irrigation system (appropriation), the investing in the maintenance of an irrigation system (maintenance).

Rules concerning appropriation commonly fall into one of four types: continuous flow, rotation, demand, and closed pipe systems (Sampath 1992). The types of appropriation rules can affect some parameters of this model. For example, if appropriators are allowed to withdraw water whenever they desire without any constraint (continuous flow system), the coefficient of interdependency between headenders and tailenders (a) may be larger due to the congestion that might occur during the appropriation process. However, changes in authority rules affect "the way the game is played" much more than they affect "the values of the parameters" of the model.

(4) Scope Rules: Scope rules directly prescribe outcomes that may, must, or must not be achieved. Such rules do not frequently occur on run-of-the-river irrigation systems, so they are not considered in this model.

(5) **Information Rules**: information rules refer to the generation and recording of information. Information about transformation functions enables the closed-loop solution to be the proper solution to this game. Thus, generating and recording information about transformation functions is fundamental. Without this information, the myopic solution would be the one most suitable to this game.

(6) Payoff Rules: Payoff rules specify rewards and sanctions assigned to specific actions. In this model, no reward or sanction against the rule breaking behaviors exists.

(7) **Aggregation Rules:** Aggregation rules specify constraints and requirements on the process used in deciding which actions to take. Players at collective and constitutional choice levels use these rules far more than those at the operational choice level. Aggregation rules do affect parameters, but their effects on parameters that represent action situation at the operational level are not as explicit as those of other rules. For this reason, I exclude these rules from the analysis.

Changes in institutional rules are rarely directly modelled by changing the parameters of payoff functions of a game. Instead, depicting the changes involves changing the types of payoff functions themselves; and more frequently, changing the way the game is played. Therefore, to directly analyze these institutional rules by simply changing the values of parameters is frequently difficult.

Institutional attributes determine how the game should be solved. If, for example, information rules prevent players from knowing the transformation functions, or if boundary rules reduce expectations of repeated interactions, the myopic solution becomes the appropriate solution to a game.

Physical Attributes

Physical attributes refer to the relevant physical variables that influence the incentive structures of the individuals interacting with each other in a game situation. We may be able to say that physical attributes affect every parameter in this model. Physical attributes can even have effects on the parameters that are closely associated with institutional arrangements.

(1) The Crops Cultivated in an Irrigation System : The crops cultivated in the irrigation system affect both the intercept of marginal benefit function (q) and the slope of marginal benefit function (r). If the market price of the cultivated crops rises, then both q and r increase. If the crops of one irrigation system are higher water-consuming crops or are more tolerant to excessive water than those of other irrigation systems, (q/r) becomes larger (r becomes smaller given that q is fixed).

(2) The Supply of Water:

A. The Amount of Water Supply at the Source; This may be the most important physical attribute in an irrigation system. Needless to say, there can be no irrigation system when there is no irrigation water at the source. The incentive structure that appropriators face drastically changes as the amount of the irrigation water at the source changes.

Q^s represents the amount of water at the source. A sufficiently large Q^s enables appropriators to maximize their payoffs without a constraint on the amount of irrigation water that can be appropriated at each period. When Q^s is not big enough, appropriators cannot obtain the amount of water that maximizes their payoffs; obviously they can not appropriate the water that is not available.[10]

B. The Distribution of Water Supply Over Time: Another important aspect of the water supply is the evenness with which it is distributed over time (i.e., the reliability of water source). The initial value of the reliability of the water supply (R_0) is affected by how evenly the water supply is distributed over time.[11] The initial value of the reliability of the water supply can be close to one when the total amount of water at the source is evenly distributed over time.[12]

The reliability of the water supply also influences the sensitivity of reliability to maintenance (a) and the sensitivity of reliability to appropriation (α'). The reliability of water supply at the field gate of an irrigation system with a more reliable water source is likely to be less sensitive to maintenance work and appropriation behavior than that of an irrigation system with a less reliable water source. Therefore, both α and α' drop as the water source becomes more

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[10] For more detail, see the Appendix.

[11] The reliability is also affected by the amount of water at the source. It is easier to get a higher initial level of the reliability when the water at the source is more abundant.

[12] For more detail, see Chapter 3.

reliable.

Along with these two parameters, two other parameters can also be affected by the reliability of water supply at the source: the minimum requirement coefficient of maintenance for reliability (γ), and the maximum allowance coefficient of appropriation for reliability (γ'). The minimum requirement coefficient of maintenance for reliability (γ) drops while the maximum allowance coefficient of appropriation for reliability (γ') rises as the water at the source becomes more reliable.

Notice here that the parameters associated with another state variable, the efficiency of water delivery,[13] will not likely be affected by the supply of water because, by definition, the efficiency of water delivery has nothing to do with the water at the source. Rather, it refers to how efficiently an irrigation system can deliver the water at the source to the field gate, regardless of the sufficiency of water at the source or the reliability of the water supply.

(3) The Topography of an Irrigation System:

The topography of an irrigation system also affects parameters in the model. As the topography of an irrigation system flattens, it may become easier to maintain the irrigation system and to appropriate the irrigation water. That is, the appropriation cost coefficient (e), the sensitivity of reliability to maintenance (α), the sensitivity of efficiency to maintenance (θ), the minimum requirement coefficient of maintenance for reliability (γ) and the minimum requirement coefficient of maintenance for efficiency (γ'') drop as the topography of an irrigation system flattens.

The water losses in the stretch of the canals can be smaller as the soil on which the irrigation system is located is more solid. The

[13] These parameters are the initial value of efficiency (E_o), sensitivity of efficiency to maintenance (8), sensitivity of efficiency to appropriation (8') the minimum requirement coefficient of maintenance for efficiency (γ''), and the maximum allowance coefficient of appropriation for efficiency (γ''').

initial value of the water delivery efficiency (E_o) and the water loss coefficient (a), therefore, decrease when the soil of the irrigation system is more solid.

(4) Engineering Works:

A. The Permanence of Headworks: The permanence of headworks, along with the lining of the canal, have been considered most important for determining the performance of an irrigation system. A temporary headwork cannot function well without investment in maintenance work. Needless to say, primitive and temporary types of headwork made of stones, mud, sticks, and leaves are not very effective and detract from the capability of appropriators to increase agricultural yields. On the other hand, a permanent headworks may function well even with little maintenance.

Therefore, the permanence of the headworks affects the group two parameters concerning the reliability of water supply. First of all, the initial value of reliability (R_0) rises as the headworks of an irrigation system gets closer to perfect permanence since irrigation systems with better headworks can supply irrigation water more reliably. Secondly, irrigation systems with better headworks can perform better, even with less maintenance, than irrigation systems with poorer headwork. Thus, the sensitivity of reliability to maintenance (a), the sensitivity of reliability to appropriation (α'), and the minimum requirement coefficient of maintenance for reliability (γ) drop as the headwork of an irrigation system approaches perfect permanence. In addition, the maximum allowance coefficient of appropriation for reliability (γ') rises as the headworks of an irrigation system nears perfect permanence.

B: The Lining of the Canals: Whether canals are lined or not also has a substantial impact on the parameters of this model. As the lined proportion of canals increases and as the quality of lining improves, more water reaches the appropriators' field gates. As the proportion of lined canals increases and as the quality of lining improves, the amount of maintenance required to keep the canals in good shape decreases.

Most group two parameters, including the parameters concerned with water delivery efficiency, are affected by the lining of canals: the initial value of efficiency (E_o) rises as the proportion of canals that is lined increases. The sensitivity of reliability to maintenance (a), the sensitivity of reliability to appropriation (α'), the sensitivity of efficiency to maintenance (6), the sensitivity of efficiency to appropriation (θ'), the minimum requirement coefficient of maintenance for reliability (γ) and the minimum requirement coefficient of maintenance for efficiency (γ") decrease as the proportion of canals that is lined increases. In addition, the maximum allowance coefficient of appropriation for reliability (γ') and the maximum allowance coefficient of appropriation for efficiency (γ"') increase as the proportion of canals that is lined increases. Finally, the water loss coefficient (a) becomes smaller as the proportion of canals that is lined increases and as the quality of lining improves.

Community Attributes

Differences among appropriators have been regarded as one of the most important community attributes in studies of irrigation systems. This model focuses on locational difference among appropriators. If no locational difference existed, then only one type of appropriators would exists; there would be no need to distinguish between headenders and tailenders.

The maximum amount of maintenance that appropriators can afford (mB_j and mB_k) is also affected by the income level of the community of appropriators. The value of mB_j and mB_k becomes higher as the income level of the community of appropriators becomes higher. In an economically heterogeneous community, mB_j and mB_k differ from each other. As economic disparity between headenders and tailenders increases, the gap between mB_j and mB_k becomes larger.

Representing the impact of changes in specific attributes of the rules and community poses difficulties because the parameters in this model reflect specific rules and/or specific community attributes. As a matter of fact, depicting the effects of major changes in institutional attributes requires changes in the assumptions about the action arena itself and change the way the game is played. We can not portray these changes by changing only parameter values.

As indicated earlier, modelling the CPR situation as a dynamic game with a closed-loop solution assumes that a minimal level of institutions or "social capital" exist (Coleman 1986; E. Ostrom 1993). Without these, the situation should be modelled in a totally different way. Participants in such a situation will not and need not care about the future. The myopic solution of this game could possibly be a proper solution to the game when the lack of institutions makes it impossible, or at least extremely difficult, to obtain information about the transformation functions. In sum, the fact that we model the CPR situation as a dynamic game and find the closed-loop solution to this game itself implies that we assume a minimal level of institution and social capital that makes people care about the future.

Summary

The relative importance of the rules and of the physical world in structuring an action situation varies across different types of action situations. In this game, attributes of rules mainly constitute the way the game is played and the way the solution to this game is obtained. Without institutional arrangements and community attributes, the closed-loop solution cannot be the solution concept in this game because without these attributes, we can not get the information condition and transformation functions. The information condition and the parameters of the transformation functions are, of course, also influenced by the physical world. The physical possibility of actions, the productivity of outcomes, and the linkages of actions to outcomes all heavily depend on the physical world. Without the authority and boundary rules to permit participants to repeatedly appropriate water and to repeatedly invest in maintenance, however, the game itself drastically changes into a totally different game, such as a one-shot game where the information condition and transformation functions will become unimportant.

I have examined the relationships between the parameters used in this model and the three key clusters of variables of the IAD framework. The effects of these key variables on the values of parameters are non-separable; and there is not a one-to-one relationship between changes in parameter values in this model and changes in the key variable of the IAD framework (E.Ostrom, Gardner, and Walker 1993). A change in one parameter value of this model could be caused by changes in many different variables of the IAD framework. In the following Chapters, I examine how the changes in institutional, physical, and community attributes, affect the outcome of the game.

Chapter 5

Initial Parameter Configurations: Water Abundance

In the last chapter, I discussed how the parameters of this game represent assumptions about the key elements of the action arena, and how variables in the key variable clusters of the IAD framework affect these parameters. The value assigned to each parameter represents one or more assumptions about the action arena. One can ascertain the relationships between the key variables of the IAD framework and the values of the parameters in this model. However, determining the specific functional forms of these relationships in real world settings requires detailed technical studies of irrigation systems, which is well beyond the scope of this study. Moreover, the main purpose of this study is not to explore the technical details of irrigation. The main objective of this study is to examine how changes in important variables of the three key clusters of variables in the IAD framework affect the incentive structure facing appropriators from CPRs (especially, irrigation systems), the extent of sub-optimality of the predicted behavior, and the possibility of self-governing solutions to collective action problems in CPRs.

Due to a lack of relevant empirical studies of the parameters of this model (especially of the parameters that portray state transition equations), it is extremely difficult to find ranges for each parameter that are based on relevant empirical studies. Therefore, I choose theoretically reasonable parameter values to form the initial parameter configuration. Once the initial configuration is established, we can change one parameter at a time to analyze the effects of this change on the outcomes. Below, I discuss the initial parameter configuration.

Initial Parameter Configuration

Simplest Situation

Since the game is rather complicated and has many parameters, I analyze the simplest case first. In the simplest case, two players (one headender and one tailender) interact with each other twice without any sanctioning mechanisms. The number of players (n) and the number of iterations (T) are both at 2, with the number of headenders, m, set at be 1.

Depending on which solution concept we employ, this initial configuration depicts two quite different situations. If we use the myopic solution, the outcome of this game represents a situation in which a minimal level of institution exists, but individuals have no foresight. In these situations, maximizing a single time period payoff rather than the sum of the discounted payoffs over time appears individually rational.

When we use the closed-loop solution, the outcomes of this game depict a situation in which individuals have foresight and a minimal level of institutional arrangement exists. Thus, appropriators have information about transformation functions and can expect iterated interactions. In this situation, therefore, it is individually rational for appropriators to maximize the sum of discounted payoffs over time.

This initial parameter configuration represents the simplest case. However, it does not portray the "stark institutional settings used in some experimental settings" (E. Ostrom and Walker, 1993). The closed-loop solution implies that at least a minimal level of institutional arrangements exists to enable appropriators to know the transformation functions.

Scale of The Game

The marginal benefit function, (i.e., the combination of the intercept of the marginal benefit function (q) and the slope of the marginal benefit function (r)) determines the scale of the game. The model parameters do not come from measures of any real unit, such as dollars per acrefeet ($/acft). Consequently, an infinite number of configurations of parameters are possible. To limit them, I first determine a value for the intercept of the marginal benefit function of water, q. All other parameters are then scaled according to this value.

Both q and r are sensitive to the crops cultivated in an irrigation system and to the market price of the crops. In field settings, if the market price of the crop increases, the marginal benefit of irrigation water also increases and appropriators use more water. Since monetary units measure the benefit of irrigation water in real world settings, changes in the absolute size of water use become important. They can be captured by increasing q and decreasing r in this model. As q increases and r decreases, the solution of the game becomes larger. However, in this study, changes in the absolute values of a solution to this game have neither empirical nor theoretical meaning since we never use a real measure of unit.

For this reason, I fix q at "310" and r at "20" from the ranges suggested by Dixon (1989). With Dixon's parameter ranges, this combination represents the situation in which the crops need the most water. This combination depicts "water-intensive crops," such as paddy rice.

In sum, q and r determine the scale of the game. Since the absolute scale of the solution is not relevant to this study, we do not need to analyze the impacts on changes in q and r on the outcomes of this game. This study focuses on the extent of sub-optimality associated with closed-loop and myopic solutions rather than on the absolute size of the solutions. Therefore, q and r remain constant throughout the analysis.

Optimal Amount of Appropriation and Appropriation Costs

Before deciding values of other parameters, I calculate the optimal amount of appropriation for a single time period assuming no appropriation costs (i.e., the appropriation cost, e, equals zero), and perfect reliability of water supply (i.e., the initial value of reliability, R_0, equals one). The optimal appropriation amount is 7.75.[1] Using this value, I determine the appropriation cost. According to Dixon's study (1989), the cost of getting water is "0.15$/acrefeet". In this study, appropriation cost is determined by:

(appropriation cost coefficient, e)*(the amount of appropriation by all appropriators)

I assign 0.02 to appropriation cost coefficient, e, by using Dixon's cost parameter and the calculated optimal amount of appropriation. When the appropriation cost coefficient equals 0.02, appropriation costs about 0.15.[2] I determine the value of the appropriation cost coefficient this way in order to make the unit of measure of the payoffs close to "$/acrefeet", so that empirical estimates of appropriation cost from Dixon's study can be easily used. Bear in mind that the payoffs have no direct empirical interpretation.

The coefficient of interdependence between the headender and the tailender, 5, depicts the extent to which the amount of appropriation by the headender affects the tailender's appropriation cost. This parameter is also associated with appropriation cost. For simplicity, I assign 1 to this parameter, which means that the amount of appropriation by the headender has the same impact on the appropriation cost of the

[1] Notice that this is for both the headender and the tailender. Since the appropriation cost coefficient, e, is now set at 0, there is no distinction between the headender and the tailender.

[2] It is precisely 0.155 (=0.02*7.75). I assign 0.02 to the appropriation cost coefficient since the initial value of reliability, R_0, will always be smaller than 1, in both real world settings and in the analysis. In that case, the optimal amount of appropriation becomes smaller than 7.75, and appropriation cost becomes closer to 0.15.

tailender as the amount appropriated by the tailender does.[3]

The information generated so far allows us to calculate the upper limits on the amount of investment in maintenance for the headender (mB_j) and the tailender (mB_k). The single time period payoff, calculated using the values of parameters already determined equals about 600. I set mB_j and mB_k at 5 because I assume that appropriators usually can not afford to invest more than one one-hundredth of their payoffs in maintenance since they also need to do other works to cultivate the crops.[4] These two could differ, but for simplicity, I assign them the same value in the initial parameter configuration.

Water Abundance

I assume that there is no water shortage in order to ease the observation of how the payoff functions and two state variables, reliability of water supply (R_t and water delivery efficiency (E_t), change over time. Given this assumption, appropriators find it profitable to continue increasing their amount of water use until the resulting additional revenues drop to the point where they exactly equal additional costs. Thus, solutions to this game at every time period can

[3] Notice that 6 varies between 0 and 1. If $\delta = 1$, it implies that the physical condition of an irrigation system causes the headenders' appropriation to affects the tailenders' appropriation cost as much as the tailenders' appropriation does.

[4] I picked 5, which is about 1 percent of the payoff for a single time period, assuming that the reasonable maximum that appropriators can afford to invest in maintenance is about two times greater than what they have actually invested. According to the NIIS database, the average agricultural product is 5776.52 kg/ha, and the average investment in maintenance is 9.47 laborday/ha. Yoder (1986, 63), equates the value of the one day labor to about the value of 2.4 kg of rough rice in Nepal. Thus, we can roughly calculate the value of the average investment in maintenance in terms of the weight of rough rice to be 22.73 kg/ha, which is about 0.4 percent of the average agricultural product. In our initial parameter configuration, 2.3 equals 0.4 percent of the agricultural product in single time period; 5, or 1%, is approximately double these amount.

be interior solutions.[5] Using interior solutions makes it easier to choose parameters for the state transition equations that are theoretically reasonable. Analytically, if we do not assume water abundance, there could exist a variety of cases where the solution to the game cannot be an interior solution because the optimal appropriation exceeds the upper limits on appropriation. In such cases, predicting the general tendencies of changes in the solutions is more difficult. If solutions are always interior solutions, we can predict the tendency of changes in the solutions and more easily determine parameter values for the state transition equations.[6]

To assume water abundance, I set the following values to parameters: I assign 300 to the amount of water at the source (Q^s), 400 to the length of canal from water source to the headenders' field gate (1), and 200 to the length of canal from the headenders' field gate to the tailenders' field gate (1'), and 0.5 to the water loss coefficient (a). With these parameters, we ensure no water scarcity at any time period for the headender and the tailender.

<u>State Transition Equations</u>

I employ one criterion in determining values of parameters for the state transition equations: the levels of reliability and efficiency must always be smaller than 1. This criterion is necessary to prevent the closed-loop solutions from paying better than the social optimum solution. Closed-loop solutions that pay more than the social optimal would be nothing but mathematical artifacts, a possibility since the

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[5] Interior solutions are ones which are obtained from maximization calculation <u>and</u> which fall within the reasonable ranges.

[6] It will probably be optimal for the rational individuals with foresight to get less water at the beginning and more later in most cases, if there is no water shortage. When there is water shortage, this strategy will probably not be the optimal one.

state transition functions of this model are not continuous.[7] Problems can occur when the state variables reach their upper bounds. If state variables reach or go beyond their upper bounds, the maximum payoff achieved in the backward induction process cannot be an actual payoff. The maximum payoff obtained through backward inductions, in such cases, can be realized as a payoff to this game only with state variables that exceed 1, which this game does not allow.

To illustrate, consider what happens if we drop the upper limit on the state transition equation for a moment. In some cases, the closed-loop solution could have perfect reliability and the social optimum solution could have more than perfect reliability. The social optimum solution, then, pays better than the closed-loop solution pays because the social optimum solution appropriates less water in earlier rounds in order to increase the levels of the two state variables in later rounds. When the two state variables are not allowed to exceed 1, the efforts to move the two state variables up to values greater than 1 by reducing levels of earlier appropriation cannot work. Therefore, the social optimum solution could pay less than the closed-loop solution does in some cases.

I also set the initial values of the two state variables, R_0 and E_0, to 0.5 in order to keep the levels of the two state variables from reaching their maximum. Next, I set the two parameters representing sensitivities to maintenance in the state transition equations -- the sensitivity of reliability to maintenance, α, and the sensitivity of efficiency to maintenance, 8 -- to 0.01 to keep the levels of the two state variables from reaching their upper limits. For the same reason, I then set the two parameters that represent sensitivities to

[7] Despite this problem, I use discontinuous state transition functions because the difference game can be "normal" only when state transition functions are linear. The linear-quadratic dynamic game can be said to be "normal" if it is possible to find a unique instantaneous Nash equilibrium for all control variables at every time period. For more detail, see Starr and Ho, 1967; and Fudenberg and Tirole, 1986.

appropriation in the state transition equations -- the sensitivity of reliability to appropriation, α', and the sensitivity of efficiency to appropriation, θ' -- to 0.005. Note that the parameters representing sensitivities to appropriation are smaller than the parameters representing sensitivities to maintenance. As indicated in Chapter 3, it is usually difficult to store water in run-of-the-river irrigation systems. Therefore, the state variables will be less sensitive to appropriation than to maintenance.

The two minimum requirement coefficients -- the minimum requirement coefficient of maintenance for reliability, γ, and the minimum requirement coefficient of maintenance for efficiency, γ'' -- are set at 5. Given these values and the initial values of the two state variables, the threshold values for the amount investment in maintenance in first round equal 2.5. Therefore, it is possible to improve the levels of the two state variables by investing the maximum that appropriators can afford.

I set both of the maximum allowance coefficients -- the maximum allowance coefficient of appropriation for reliability, γ', and the maximum allowance coefficient of appropriation for efficiency, γ''' -- equal to 8. The threshold values for the amount appropriation are then 4 in the first round since the initial levels of the two state variables equal 0.5. Recall that the optimal amount of appropriation in a single time period was around 7. Thus, the levels of the two state variables decrease over time, if appropriators use their optimal amounts and all other factors remain constant.

What happens, then, when we consider the effects of appropriation and investment in maintenance simultaneously? The levels of the two state variables decrease if the magnitude of the positive influence of the investment in maintenance on the level of the state variables fall short of the magnitude of the negative impact of over-appropriation, and vice versa. In the initial parameter configuration, I suspect that the levels of state variables improve over time since the parameters that represent sensitivities to appropriation are set smaller than the parameters that represent sensitivities to maintenance.

Discount Parameter

Finally, I set the discount factor (a) at 0.8. This value is small when compared to the discount factors that other literature uses. For example, Dixon use 0.9524 in his study of the ground water basins (1989), and Axelrod use 0.99654 in his computer tournament (1980). The small discount factor implies my players discount the future more than do players in other studies. I use 0.8 in the initial parameter configuration to depict a situation in which the future has relatively little impact on the present. If we can obtain relatively cooperative outcomes with a small discount factor, then we can get even more cooperative outcomes with a larger discount factor.

Table 5.1 summarizes the initial parameter configuration with no water scarcity. In the next section, I analyze the three solutions of this game -- the closed-loop solution, the myopic solution, and the social optimum solution -- to examine the efficiency losses of the closed-loop and myopic solutions, given initial parameter configuration.

Efficiency Losses of Individual Rationality

Definition of Efficiency Losses

The results of the simulation using the initial parameter configuration without water scarcity are shown in Table 5.2. As expected, the group payoff (i.e., the sum of the payoffs to the headender and to the tailender) of the closed-loop solution is smaller than the group payoff of the social optimum solution and greater than the group payoff of the myopic solution. The group payoffs for the myopic solution, the closed-loop solution, and the social optimum

Table 5.1; Initial Parameters Configuration

Parame-ters		Description
2	n	Number of total appropriators
1	m	Number of headenders
2	T	Number of repetition
0.8	ω	Discount parameter
5	mB_i	Maximum amount of investment in maintenance appropriator, i, can afford
300	Q^s	Amount of water at the source
400	l	Length of canal from water source to headender's water gate
200	l'	Length of canal from headender's water gate to tailender's water gate
310	q	Intercept of marginal benefit function of water
20	r	Slope of marginal benefit function of water
0.02	e	Appropriation cost coefficient
1	δ	Coefficient of interdependency between headenders and tailenders
0.5	R_0	Initial value of reliability of water supply
0.5	E_0	Initial value of water delivery efficiency
0.01	α	Sensitivity of Reliability to maintenance
0.005	α'	Sensitivity of Reliability to appropriation
0.01	θ	Sensitivity of Efficiency to maintenance
0.005	θ'	Sensitivity of Efficiency to appropriation
0.5	a	Water loss coefficient
5	γ	Minimum requirement coefficient of maintenance for reliability
8	γ'	Maximum allowance coefficient of appropriation for reliability
5	γ''	Minimum requirement coefficient of maintenance for efficiency
8	γ'''	Maximum allowance coefficient of appropriation for efficiency

solution are 1866.3, 2229.8, and 2234.95, respectively.

To compare the three solutions of the game more systematically, let us define "efficiency loss in payoff" as the percent change of the group payoff of the closed-loop solution and the myopic solution from the group payoff of the social optimum solution.[8] In Table 5.2, "Closed %A" refers to the percent change for the closed-loop solution and "Myopic % " refers to the percentage change for the myopic solution . Using this definition, we can say that efficiency losses occur when appropriators try to maximize individual utility, as most standard CPR literature predicts. Individual rationality, even with the assumption of forward looking behavior in the closed-loop solution, cannot achieve the socially optimal outcome. We can also examine the extent to which the efficiency losses of the two different solutions concepts differ, how the efficiency losses of both one are affected by changes in important parameter values. As you can see in Table 5.2, the efficiency loss associated with the closed-loop solution is smaller than the efficiency loss associated with the myopic solution. The efficiency losses are 0.23% for the closed-loop solution and 16.50% for the myopic solution.

The findings in Table 5.2 imply that predictions based on short term individual rationality without foresight, represented by the myopic solution of this game, overstate the efficiency losses of rational individuals in field settings. The efficiency losses of individual rationality are better represented by the closed-loop solution. If individuals take into account the impacts of their present action on their future payoff structure, it is not individually rational to maximize only the present payoff (i) by using water until the resulting

[8] Formally, the efficiency loss in payoff can be written as:
$(1-\Pi_{CL}/\Pi_{SO})*100$ for the closed-loop solution, and
$(1-\Pi_{MY}/\Pi_{SO})*100$ for the myopic solution
,where Π_{CL} = group payoff of the closed-loop solution,
Π_{MY} = group payoff of the myopic solution, and
Π_{SO} = group payoff of the social optimum solution.

Table 5.2:
Efficiency Losses of Individual Rationality
in Water Abundant Initial Parameter Configuration

Myopic u_j	{7.73453, 6.46132}
Myopic u_k	{7.72681, 6.45487}
Myopic m_j, m_k	{0, 0}
Closed u_j	{7.23453, 8.08565}
Closed u_k	{7.228, 8.07758}
Closed m_j, m_k	{5, 0}
Optimal u_j, u_k	{6.71842, 8.15668}
Optimal m_j, m_k	{5, 0}
Optimal Payoff	2234.95
Myopic %Δ	-16.50% (1866.3)
Closed %Δ	-0.23% (2229.8)

Key

Myopic u_j : Optimal amount of appropriation for the headenders in the myopic solution {t=l, t=2}

Myopic u_k : Optimal amount of appropriation for the tailenders in the myopic solution {t=l, t=2}

Myopic m_j, m_k : Optimal amount of investment in the myopic solution {t=l, t-2}

Closed u_j : Optimal amount of appropriation for the headenders in the closed-loop solution {t=l, t=2}

Closed u_k : Optimal amount of appropriation for the tailenders in the closed-loop solution {t=l, t=2}

Closed m_j, m_k : Optimal amount of investment in the closed-loop solution {t=l, t=2}

Optimal u_j, u_k : Optimal amount of appropriation for both headenders and tailenders in the social optimum solution

Optimal m_j, m_k : Optimal amount of investment for both headenders and tailenders in the social optimum solution

Optimal Payoff : The group payoff of the social optimum solution

Myopic %A : Efficiency loss of the myopic solution (i.e., percent change of myopic group payoff from social optimum group payoff)

Closed %A : Efficiency loss of the closed-loop solution (i.e., percent change of closed-loop group payoff from social optimum group payoff) additional revenue of a single time period drops to the point where it exactly equal additional cost of a single time period; and (ii) by investing nothing in maintenance.

Optimal Amounts of Investment in Maintenance

Two factors cause the difference in the efficiency losses of the myopic solution and the closed-loop solution. First, the closed-loop solution and the myopic solution have different solutions for the level of investment in maintenance. In the myopic solution, it is optimal to invest nothing in maintenance in every round because we assume that appropriators do not to consider the effects of their decisions on the future payoff structures. The amount of investment in maintenance at time (t) is therefore always considered merely a cost since it cannot bring any benefit at the time period when the investment is made.

On the contrary, it is not optimal to invest nothing in maintenance in the closed-loop solution. When appropriators care about the effects of their decisions on future payoff structures, then the amount of investment in maintenance is literally an investment cost that can bring positive benefits in the future. In the closed-loop solution, it turns to be optimal to invest in maintenance up to the upper limit (mB_j and $m\grave{B}_k$) . This is also the case in the social optimum solution.

In the closed-loop solution, the sum of discounted payoffs over time increases as more investment is made in maintenance. In more formal terms, when enough water is expected at the next round, the value function at time (t) ($\Psi_t = \pi_t + \omega^*\Psi_{t+1}$) will be convex in the amount of investment in maintenance (m_t) . Therefore, either one of the two extreme values of the boundary for the amount of investment in maintenance (0 and mB_i) will be the solution.

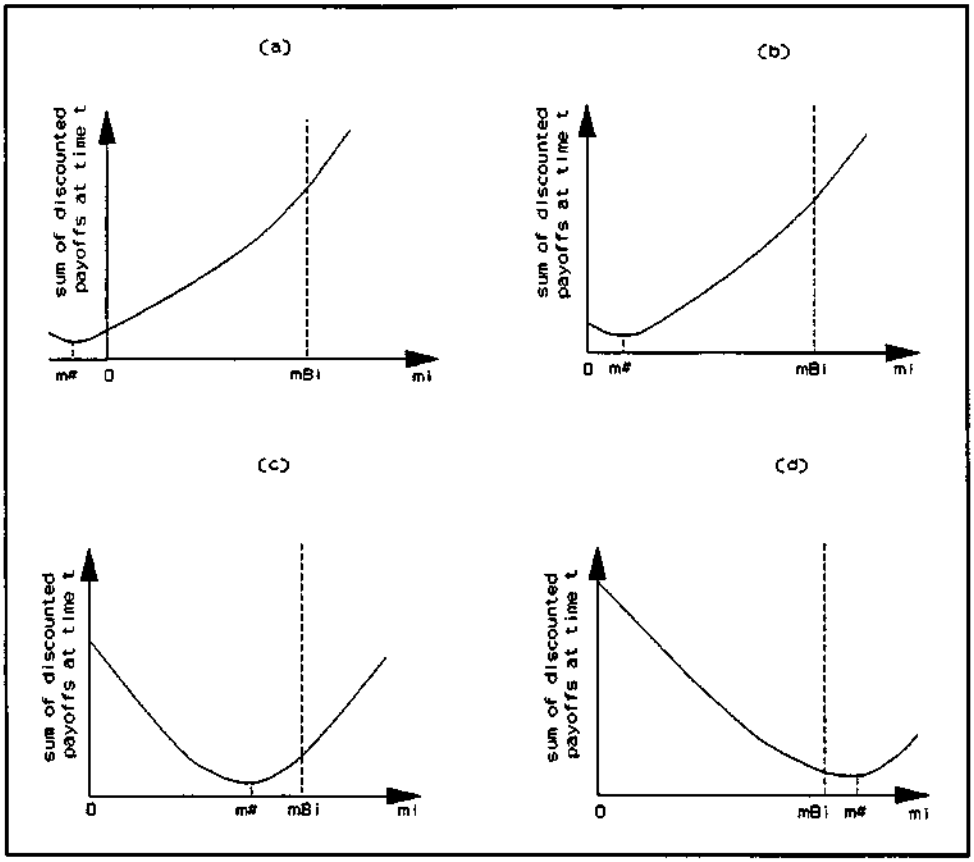
Let the solution for the investment in maintenance that minimizes the value function be $m^{\#}$. This solution, of course, has no meaning in this analysis, except that it allows us to see when "mB_i" is the solution and when 0 is the solution for investment in maintenance. Figure 5.1 shows the four possible combinations of the relative sizes of $m^{\#}$ to 0 and "mB_i".

When $m^{\#}$ is smaller than zero, as in (a) of Figure 5.1, mB_i maximizes the value function because the value function always increases within the (0, mB_j) boundary. When $m^{\#}$ exceeds mB_i, as in (d), the value function is maximized at 0 because the value function always decreases within the (0, mB_i) boundary. When $m^{\#}$ falls between "0" and "mB_i", the value function is neither ever-increasing nor ever-decreasing within the (0, mB_i) boundary, as shown in (b) and (c). If $m^{\#}$ is closer to 0, as in (b), then mB_i maximizes the value function. If $m^{\#}$ is closer to "mB_i", as in (c), then 0 maximizes the value function.

After a series of simulations, I found that $m^{\#}$ always lies closer to 0 (as in Figure 5.1 (b)), so that mB_i maximizes the value function in all parameter configurations that yield meaningful results. Thus, the optimal solution for the amount of investment in maintenance in this game is mB_i (i.e., invest up to the upper limit) rather than 0 (i.e., invest nothing) when there is sufficient water. This is the case in both the closed-loop solution and in the social optimum solution. The optimal amount of investment in maintenance is, thus, identical to its upper limits in the closed-loop and the social optimum solutions. Hence, when there is no water scarcity, efficiency losses in the closed-loop solution result only from over-appropriation, not from the lack of investment in maintenance. On the contrary, efficiency losses in the myopic solution result from both the lack of investment in maintenance and from over-appropriation.

It is not optimal to invest up to the maximum, even in the water abundance situation, if the maximum that players can afford is too large. This is because the state transition functions are not continuous. It is not optimal to invest more than what is required to achieve the upper limit of the state variables which happens to be

Figure 5.1: The Four Possibility of the Shapes of the Value Functions



"one", since our two state variables are not allowed to exceed "one". As a matter of fact, the group payoff declines as the amount of investment in maintenance increases after state variables reach their upper limits. This upper limit is on mB_i is 28.6 in our initial parameter configuration. Let this limit on mB_i be $mB_i^{\#}$. If mB_j and mB_k are greater than $mB_i^{\#}$, then it is individually rational to invest only 28.6 in maintenance instead of investing up to mB_j or mB_k. When there is no water scarcity, the value function of this game looks like the one shown in Figure 5.2. Note, the value function is ever-decreasing so that mB_i cannot maximize the value function after it passes $mB_i^{\#}$.

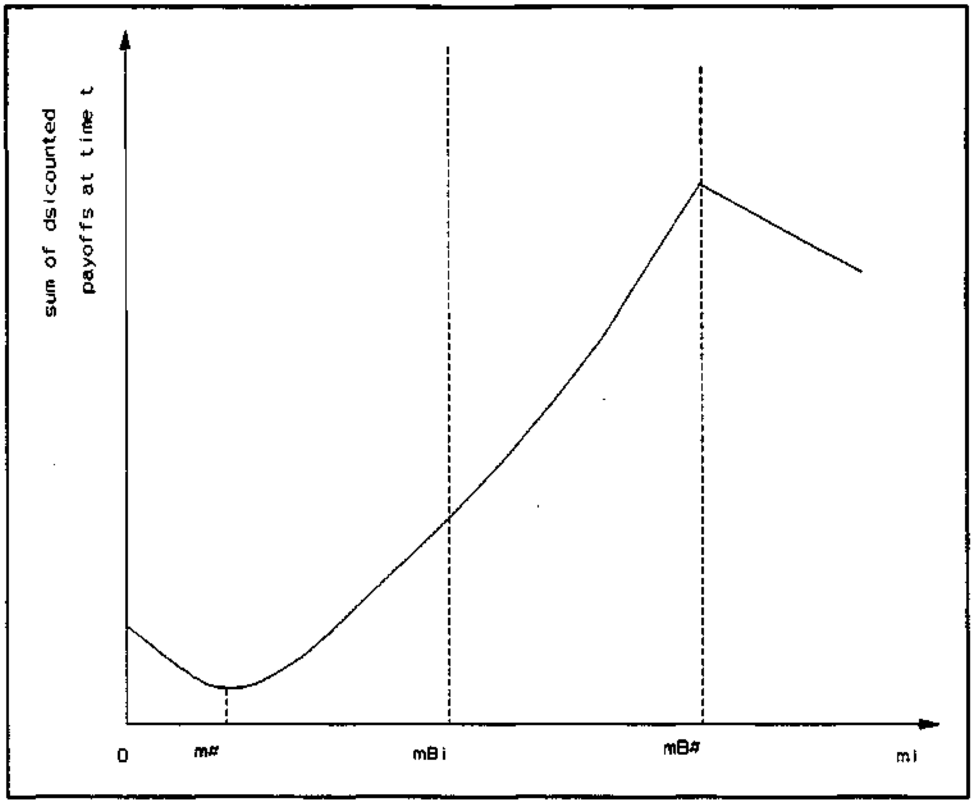
However, I do not include this limit on mB_i in my analysis. Including the upper limit on investment makes the solution process more complicated. Moreover, it makes little empirical sense that appropriators can afford large amount of investment in maintenance. So, I calculate the upper limit in several parameter configurations and exclude the possibility that players can invest more than this limit by setting mB_i smaller than $mB_i^{\#}$. The limit on investment tends to become smaller as α, α', θ, and θ' increase (see Table 5.3). In this table, 8 is set equal to α, and α' and θ' are set equal to half of a. I did not report cases where α is greater than 0.09 since they do not yield meaningful outcomes.

Table 5.3: New Limits on mB_i ($mB_i^{\#}$)

α^*	Limits on mB_i
0.01	28.6
0.02	15.6
0.03	10.9
0.04	8.3
0.05	6.5
0.06	5.1
0.07	3.9
0.08	3.3

As a matter of fact, this game yields meaningful outcomes only when α is smaller than 0.06. When α exceeds 0.06, the group payoff of

Figure 5.2: The Shape of the Value Function



the closed-loop solution is greater than the group payoff of the social optimum solution even when mB_i is relatively small because R_2 reaches 1 so quickly in the social optimum solution. Moreover, in cases where α exceeds 0.06, the optimal amount of appropriation in the first round becomes zero. Appropriating nothing and investing up to the maximum amount in maintenance maximizes the sum of discounted payoffs over time. Although analytically possible, a mathematical artifact results instead of a meaningful outcome. Thus, I exclude the cases with a?'s larger than 0.06. I report here the cases in which α is greater than 0.06 simply to show that $mB_i^{\#}$ decreases as α gets.

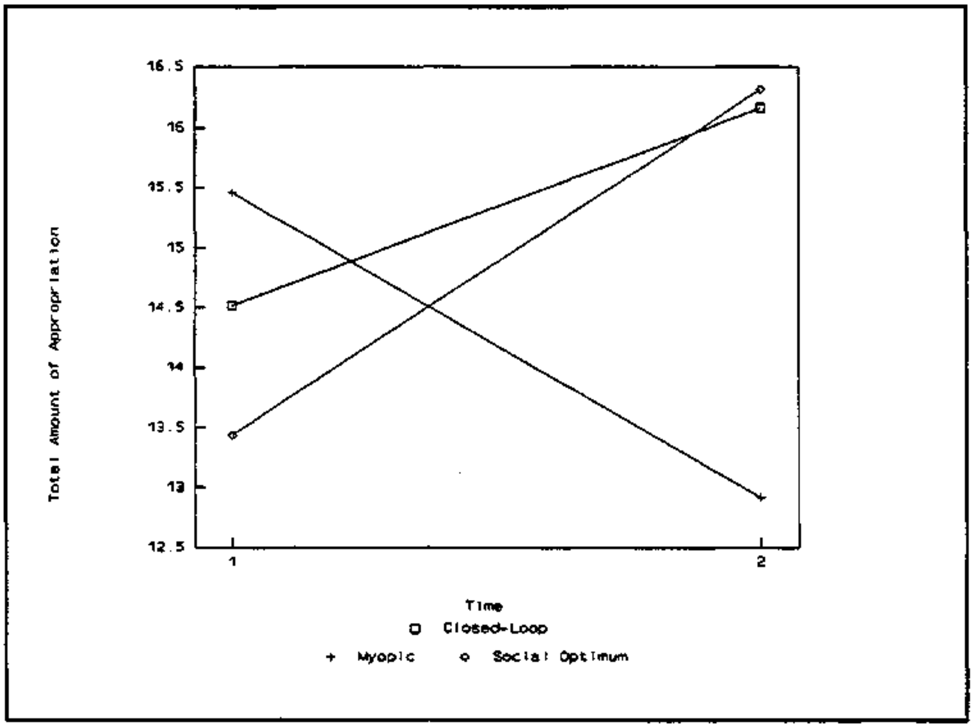
Of course, R_2 of the social optimum solution can also reach 1, and the group payoff of the closed-loop solution can become larger than the group payoff of the social optimum even when α is relatively small; but this happens only when mB_i is almost as large as $mB_i^{\#}$. For example, when α equals 0.01, the group payoff of the closed-loop solution becomes larger than the group payoff of the social optimum after mB_i exceeds 28.3. Notice that $mB_i^{\#}$ (the upper limit on mB_i) is 28.6 in this case.

Optimal Amounts of Appropriation

Over-appropriation is a second factor that causes the efficiency loss of the closed-loop solution to differ from the efficiency loss of the myopic solution. Players who use the closed-loop solution appropriate less water in the earlier round and more water in the later round than one using the myopic solution. Players who use the social optimum solution get even less water in the earlier round and even more water in the later round than players who use the closed-loop solution. Figure 5.3 shows these relationships.

In the first round, the total amount of appropriation is largest for the myopic solution (15.4613; 7.73453 for the headender and 7.72681 for the tailender) and the total amount of appropriation is smallest for the social optimum solution (13.4368; 6.71842 for both the headender and

Figure 5.3: Total Amount of Approprition
in The Initial Parameter Configuration without Water Scarcity



the tailender). The optimal amount of appropriation for the closed-loop solution lies between the two (14.9625; 7.73453 for the headender and 7.228 for the tailender). Thus, the single time period group payoff of the myopic solution exceeds that of the other two solutions in the first round, with the single time period group payoff of the closed-loop solution coming second, and the single time period group payoff of the social optimum solution coming last.

The exact opposite relationship occurs in the second round. The myopic solution has the smallest total amount of appropriation (12.8562; 6.40132 for the headender and 6.45487 for the tailender) among the three solutions in the second round. Since players using the myopic solution appropriated the greatest amount of water and invested nothing in maintenance in the first round, the reliability of water supply as well as the water delivery efficiency of the myopic solution are smaller than those of the other two solutions in the second round. The social optimum solution provides the largest total amount of appropriation in the second round (16.3134; 8.15668 for both the headender and the tailender), since the least amount of water was appropriated and investment in maintenance was made in the first round. In the closed-loop solution, the level of investment in maintenance was the same as that of the social optimum solution. However, more water was appropriated in the first round. For this reason, the closed-loop solution can appropriate more water than the myopic solution, but less water than the social optimum in the second round. The total amount of appropriation in the closed-loop solution is 16.1632 (8.08565 for the headender and 8.07758 for the tailender).

The gap between the efficiency losses of the closed-loop solution and the myopic solution becomes larger as the parameters describing the physical conditions becomes more sensitive to appropriation (i.e., as α' and θ' get increase). As the levels of physical conditions become more sensitive to appropriation, players using the closed-loop solution will appropriate less water in the first round. In the myopic solution, however, the same amount of water is appropriated irrespective of the changes in the sensitivities of the physical conditions to appropriation. Therefore, in the myopic solution, the physical conditions of the system deteriorate more when the levels of the physical conditions become sensitive to appropriation.

In the second round, appropriators in the myopic solution receive a smaller amount of water than that which is available for the appropriators in the social optimum solution in the first round. To make matters worse, appropriators in the myopic solution have to face a lower reliability of water supply than appropriators in the other two solutions since (i) they do not invest in maintenance, and (ii) they use more water than the others in the first round. Thus, the group payoff is largest for the social optimum solution, second largest for the closed-loop solution, and smallest for the group payoff of the myopic solution.

Effects of More Iterations

When we assume that appropriators are rational and that they do care about the future and that repeated interactions are expected and that relevant information about transformation function is available, the efficiency losses associated with individual rationality are smaller than the predictions that literature based on rationality without foresight make. More importantly, the efficiency losses in the payoffs of the closed-loop solution are quite small when a sufficient supply of water exists, as is the case in our initial parameter configuration. In the initial parameter configuration, the efficiency loss associated with the closed-loop is 0.23%. This could imply that the closed-loop solution almost achieves the socially optimal in the absence of water scarcity. In other words, even without sanctioning mechanisms, a minimal level of institutional arrangements greatly improve efficiencies in terms of payoffs, if individuals are rational and have foresight.

However, we must interpret this result with caution since it is obtained from simulations in which the game is played only twice. Before making a final interpretation, we need to know what happens to the efficiency losses when the game repeats more than twice. I expect that the efficiency losses of the closed-loop solution become larger as T increases. As T gets larger, both the social optimum solution and the closed-loop solution will appropriate less and less water in the earlier rounds and will become able to get more and more water in the later rounds. The social optimum solution appropriates even less water in the earlier round and will become able to get even more water in the later rounds than the closed-loop solution will, causing the efficiency losses of the closed-loop solution to increase as T increases.

Table 5.4 shows the results of series of simulations with more iterations. The efficiency loss in payoff in the closed-loop solution becomes 0.62% when T equal 3 and increases to 1.56% when T equals 5. In the closed-loop solution, increasing T from 2 to 3 reduces the total optimal amount of appropriation at the first round by 4.92%, and increasing T from 2 to 5 reduces it by 10.93%. The total amount of appropriation in the first round of the social optimum solution is reduced by 10.81% when T increases from 2 to 3, and by 24.35% when T increases from 2 to 5. Both closed-loop and social optimum solutions reduce the amount of appropriation in the first round, but the social optimum solution reduces it more than the closed-loop does as T gets larger. The closed-loop solution appropriates 114.73% and 126.73% of the socially optimal amount of appropriation when T equals 3 and 5, respectively, whereas it appropriates 107.63% of the socially optimal level when T equals 2.

The efficiency losses of the myopic solution drop much faster than those of the closed-loop solution. The levels of the reliability of

Table 5.4: The Effects of Longer Iterations

(a) T = 3

Myopic u_j Myopic u_k Myopic m_j, m_k	{7.73453, 6.46132, 5.3977} {7.72681, 6.45487, 5.39232} {0, 0, 0}
Closed u_j Closed u_k Closed m_j, m_k	{6.87505, 7.61708, 8.42812} {6.87539, 7.6125, 8.41971} {5, 5, 0}
Optimal u_j, u_k Optimal m_j, m_k	{5.99241, 7.20339, 8.61836} {5, 5, 0}
Optimal Payoff Myopic %Δ Closed %Δ	3151.95 -28.95% (2239.61) -0.62% (3132.3)

(b) T = 5

Myopic u_j Myopic u_k Myopic m_j, m_k	{7.73453, 6.46132, 5.3977, 4.50917, 3.7669} {7.72681, 6.45487, 5.39232, 4.50467, 3.76314} {0, 0, 0, 0, 0}
Closed u_j Closed u_k Closed m_j, m_k	{6.43746, 7.04539, 7.65271, 8.29846, 9.03461} {6.44484, 7.04981, 7.65287, 8.29341, 9.0256} {5, 5, 5, 5, 0}
Optimal u_j, u_k Optimal m_j, m_k	{5.08277, 6.00898, 7.00463, 8.13988, 9.50988} {5, 5, 5, 5, 0}
Optimal Payoff Myopic %Δ Closed %Δ	4668.89 -45.08% (2564.38) -1.56% (4596.23)

water supply and of the water delivery efficiency drop rapidly in the myopic solution since players do not invest in maintenance at all and since they appropriate more water in the earlier rounds. When T equals 5, for example, the level of reliability of water supply in the final round of the myopic solution drops to 0.2435, and the efficiency loss in payoff climbs to 45.08%. In sum, as the number of iterations increases, the efficiency losses of the closed-loop solution increase when no water scarcity exists. The efficiency losses of the myopic solution also increase as T grows larger.

To test for a steady state, I set T at 60. If T equals 60, the discount factor for payoff in period 61 becomes 0.00000153 ($=0.8^{60}$) when ω equals 0.8. The efficiency loss in the payoff of the closed-loop solution in this case equals 4.77%. The efficiency loss in the payoffs of the closed-loop solution increases but the rate of increase diminishes as the number of iterations (T) grows. When T is greater than about 30, the efficiency loss of the closed-loop solution comes very close to 4.77%. Therefore, we could say that the efficiency loss of the closed-loop solution will be around 4.77% in the initial parameter configuration when the game repeats a sufficient amount. The efficiency loss of the myopic solution equals 67.79% when we set T at 60. The myopic solution loses so much efficiency because the levels of the physical conditions deteriorate rapidly. The reliability of water supply of the myopic solution in the final round is 0.000012 when T is set at 60, whereas the reliability of water supply in the closed-loop solution in the final round is 0.7047.

A large enough number of iterations is possible only when we can be sure that the level of water is sufficient to eliminate the need for branching in the backward induction. If we cannot ensure a sufficient level of water, it takes about 12 hours to run the simulation when T only equals 5. Rather than focusing on the absolute sizes of the efficiency losses of each solution, this study focuses on the relative sizes of the efficiency losses of the closed-loop and the myopic solutions and on the effects of changes in the parameters on these efficiency losses. If the patterns of outcomes remain unchanged as T grows larger, we need not to iterate this game more than twice.

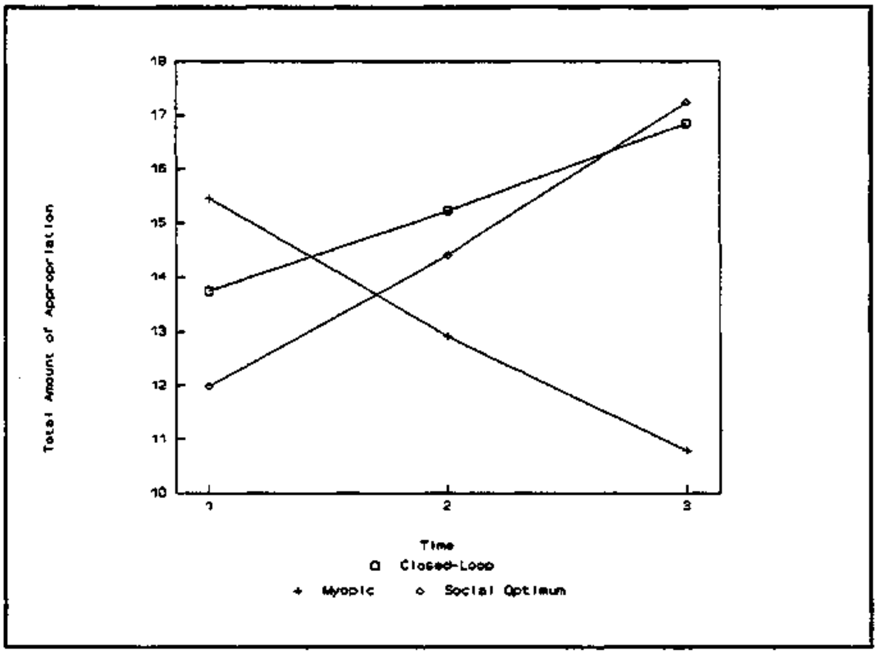
Figure 5.4 shows the changes in the total amount of appropriation as T gets increases. The patterns in the total amounts of appropriation for the three solutions when T equals 3 and 5 are almost identical to the pattern that exists when T equals 2 (see Figure 5.3). The time paths of optimal investment in maintenance will not change over time. In both closed-loop and social optimum solutions, it is always optimal to invest up to the maximum and in the myopic solution it is optimal to invest nothing. The payoffs and the levels of physical conditions in the final round also show the same patterns at each level of T. In the closed-loop and the social optimum solutions, both the total payoffs and the levels of physical conditions in the final round increase as T gets larger. In the myopic solution, the total payoff increases but the physical conditions in the final round decreases. To recapitulate, discovering the absolute magnitude of the efficiency losses is not as important as revealing the relationships among important variables. Running many simulations with a small T reveals the meaningful relationships more effectively than running a few simulations with a large T.

Conclusion

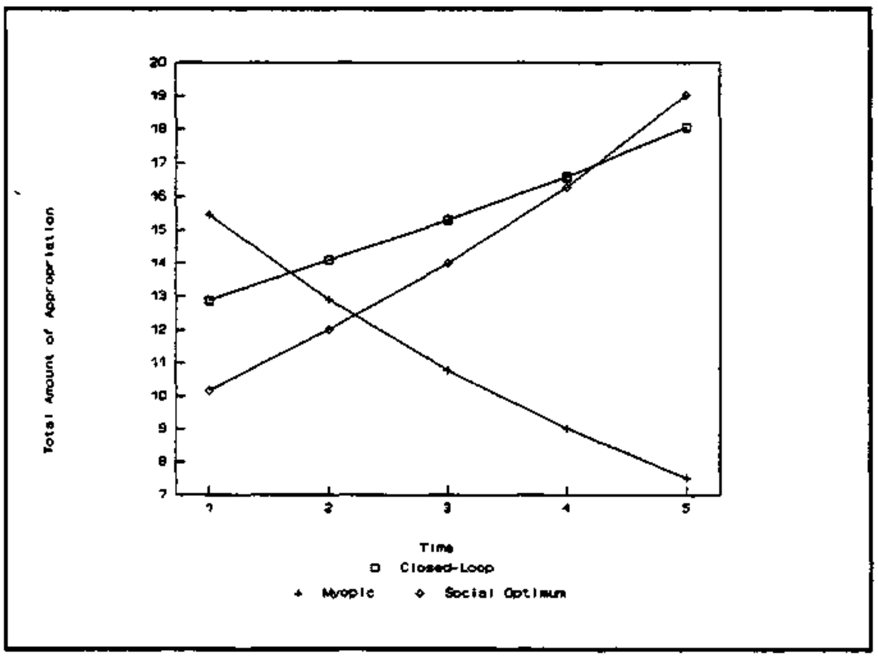
The results from the initial parameter configuration show that individual rationality cannot achieve the socially optimal outcome, just as standard CPR literature predicts. Yet, they also show that the extent of sub-optimality of individual rationality in the closed-loop solution is much smaller than that predicted by studies that consider individual rationality without foresight. The closed-loop solution is

Figure 5.4: Total Amount of Approprition
in the Cases of Larger T

(a) T=3; Q^S=300



(b) T=5; Q^S=300



possible only when (i) appropriators care about the future; (ii) appropriators expected repeated interactions; and (iii) appropriators can get proper information about the transformation functions due to the existence of institutional arrangements or social capital. Note that the closed-loop solution can operate without sanctioning mechanisms. If more than one of these three conditions are not met, however, the myopic solution becomes the solution to the game. We cannot use the closed-loop solution as a solution to the game unless we assume that at least a minimal level of institutional arrangements exists in the action arena.

The implications of these findings is that, when the water supply is sufficient, a minimal level of institutional arrangements can greatly reduce the efficiency losses of individual rationality, even in the absence of sanctioning mechanisms. In the initial parameter configuration with enough iterations, the efficiency loss in payoffs can be reduced from 67.79% to 4.77%, by moving to a closed-loop solution which assumes at least minimal institutional arrangements.

It turns out that the patterns in the outcomes for the three solutions remain unchanged as T increases. As T gets larger, the efficiency losses increase and the payoffs and the physical conditions in the final round also increase. However, the directions of changes in the payoffs and the physical conditions in the final round do not change as T increases. Consequently, there is no reason to set T larger than 2 when analyzing water abundance cases. If we remember that efficiency losses are understated when the game only iterates twice, we do not lose much by limiting T to 2.

The major purpose of this chapter was to provide an initial parameter configuration as a comparative framework for further analyses. Once the initial configuration is established, we can analyze the effect of parameter changes on the outcomes of this game by changing one parameter at a time and by comparing the outcomes of the simulations. We can also analyze the effects of the key variable clusters of the IAD framework by changing a group of parameters that represent these variables as a group and by comparing the outcomes of simulations of the parameter configurations.

Chapter 6

Effects of Water Scarcity and Number of Iteration

Patterns of Water Scarcity Using Three Solution Concepts

Analyses in the previous Chapter show that efficiency losses associated with independent, rational actors who use foresight can be small even in settings where there is little institutional structure when water is sufficient. In the closed-loop solution of the initial parameter configuration rational actors achieve 99.77% of the payoffs of the social optimum solution (i.e., efficiency loss is as low as 0.23%). In the myopic solution, on the other hand, rational actors can achieve 83.50% of the payoff of the social optimum solution (i.e., efficiency loss is 16.50%). This could be taken as an evidence for the argument that individual rationality with foresight can almost achieve social optimality without any external help when proper institutional settings exist.

In the previous Chapter, the analyses assume an abundant water supply. Water is more likely to be scarce in most irrigation systems. One expects the efficiency losses attributed to independent rational actors to become larger when water is scarce. Thus, I will examine a variety of cases where water is not abundant. Now the analytic problem becomes that of defining water scarcity and analyzing how different degrees of scarcity affect outcomes.

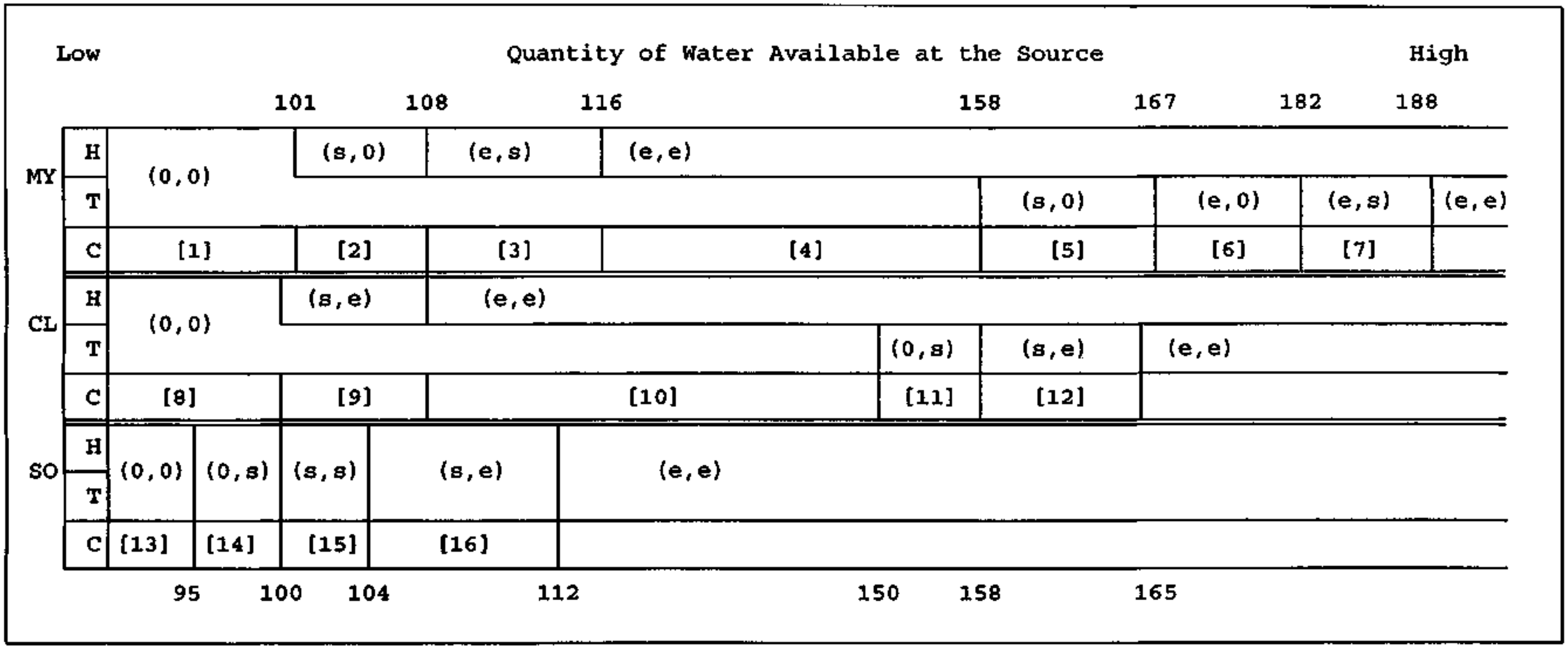
This Chapter takes the task of defining levels of water scarcity. To do this, I hold all of the parameters described in Chapter 5 at the initial level while changing the quantity of water available at the source. The highest level of water scarcity occurs when neither the headender nor the tailender can obtain any water in multiple rounds. The lowest level of water scarcity occurs when both the headender and the tailender can obtain as much water as they can put to use in each round. In the first part of this Chapter, we will focus on two iterations. The number of iteration increases in the last part of the Chapter.

The quantity of water that demarks the lower and upper bounds of water scarcity depend on the model of the individual that the dynamic game uses to compute a solution. When one assumes that individuals do not use foresight (the myopic solution), more water is needed at the source for both the headender and the tailender to obtain sufficient water. Consequently, the relevant values for relative levels of water scarcity depend both on the solution concept being used and on the quantity of water at the source, holding other parameters constant.[1] To see how the amount of water affects the outcomes of the game when water is scarce, I ran an initial series of simulations with two time periods.

[1] Note that the solution to this game will not change once the amount of water at the source (Q^s) becomes sufficient enough so that both headender and tailender can have the interior solutions as their actual choices for them. The outcomes of this game, for example, will be the same when Q^s increases from 300 to 3000 because the optimal choices are not limited by the amount of water at the source. Thus, when interior solutions can be realized as actual choices, an irrigation system can be defined as "a system where appropriators can get an **unlimited** amount of water." Similarly, when interior solutions cannot be realized as actual choices due to water shortage, an irrigation system can be defined as "a system where appropriators can get **limited** amount of water." Only one pattern of outcomes exists for water abundance situation: an unlimited amount of water in every round. This implies that the amount of water at the source has no impact on the outcomes of this game in water abundant situation.

This is not the case in water scarcity situations. In many cases of water scarcity, the outcomes of the games depend on the amount of water at the source, as well as the solution concepts used. Of course, other parameters, such as the length of canals (1 and 1') and water loss coefficient (a) can also affect the outcomes of the game. But for simplicity, I fixed them as in the initial parameter configuration in this Chapter.

Figure 6.1: Water Scarcity and the Water of Water at the Source: Patterns of Water Scarcity in Three Solution Concepts



Key

MY: Myopic Solution
CL: Closed-Loop Solution
SO: Social Optimum Solution
H: Headender
T: Tailender
C: Water Scarcity Case Number
0: no water available
s: limited amount of water available (interior solution cannot be an actual choice)
e: unlimited amount of water available (interior solution can be an actual choice)

* example : (s,e)=limited amount of water is available in the first round and unlimited amount of water is available in the second round

Figure 6.1 shows 16 cases of scarcity that need consideration.[2] First, I show how the relationships between the outcomes of this game and the amount of water at the source differ in these cases. In addition, I examine how increasing the number of iterations affects the patterns of the outcomes of this game when water shortage exists; and I find the minimum number of iteration that can approximate the impact of enough iterations. Let me identify the first seven cases of water scarcity that occur when one uses the myopic solution.

Water Scarcity When Players Follow the Myopic Solution

Using the myopic solution, we find 7 different water scarcity cases. The seven cases of water scarcity range from the scarcest to the least scarce case.

(1) Case 1 (Myopic) : $Q^s < 101$

When the amount of water at the source is smaller than 101 units, no one can obtain any water in any round.

(2) Case 2 (Myopic) : $101 \quad Q^s < 108$

When the amount of water is greater than or equal to 101 units <u>but</u> smaller than 108 units, only the headender receives water in the first round but the amount of water the headender can get is limited. The interior solution cannot be the actual choice.

(3) Case 3 (Myopic) : $108 \quad Q^s < 116$

When the amount of water is greater than or equal to 108 units <u>but</u> smaller than 116 units, only the headender can get water as before; but the headender can get water in both the first and the second rounds. In the first round, the amount of water that the headender can use is not limited; the headender can get the interior solution as an actual choice, but the interior solution still cannot be the actual choice in the second round.

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[2] In this Figure, all parameter values other than the amount of water at the source, Q^s, remain unchanged, as in the initial parameter configuration in the previous Chapter.

Therefore the parameter configurations in this Figure can be expressed as "(IPC|Q^s=i) ", that refers to the parameter configuration that is same as the initial parameter configuration expect for the Q^S that equals "i", instead of "300" as is in the initial parameter configuration. In general, if the parameters of a parameter configuration, p_1, p_2, ..., p_n, have values $v_1, v_2, \ldots, v_n$, which are different than those in the initial parameter configuration, then this parameter configuration can be expressed as:

(IPC|$p_1=v_1$; $p_2=v_2$; ..., $p_n=v_n$) .

(4) Case 4 (Myopic) : 116 $Q^s < 158$

When the amount of water is greater than or equal to 116 units, the headender can obtain an interior solution as the actual choice in both the first and the second rounds (i.e., once the amount of equals or exceeds 116 units, the headender can appropriates an unlimited amount of water in the first and the second rounds).

(5) Case 5 (Myopic) : 158 $Q^s < 167$

The tailender first begins to be able to get water when the amount of water becomes greater than or equal to 158 units. When the amount of water is greater than or equal to 158 units <u>but</u> smaller than 167 units, the tailender gets a limited amount of water in the first round.

(6) Case 6 (Myopic) : 167 $Q^s < 182$

When the amount of water at the source increases a little bit more, so that it equals or exceeds 167 units <u>but</u> falls short of 182 units, then the interior solution can be an actual choice for the tailender in the first round, the tailender still cannot get water in the second round.

(7) Case 7 (Myopic) : 182 $Q^s < 188$

When the amount of water at the source equals or exceeds 182 units <u>but</u> remains smaller than 188 units, the tailender can obtain water in both first and second rounds. The tailender can now use the interior solution as an actual choice in the first round, but the amount of water that tailender can obtain in the second round is still limited.

When the amount of water at the source equals or exceeds 188 units, then both the headender and the tailender can appropriate unlimited amounts of water at their field gates in both rounds because water is no longer scarce. Note that the optimal amounts of appropriation in the first round are always greater than the optimal amounts of appropriation in the second round for both the headender and the tailender. Both always find it individually rational to invest "nothing" in every round in the myopic solution. Consequently, the levels of physical conditions deteriorate over time. Due to this, both players cannot get as much water in the second round as they did in the first round, even though the amount of water at their field gates is not limited. So, in the myopic solution, it is rational for both the headender and the tailender to get as much water as possible during the first round.

Water Scarcity When Players Follow the Closed-Loop Solution

The closed-loop solution offers 5 different water scarcity cases.

(1) Case 8 (Closed-Loop) : $Q^S < 100$

When the amount of water is smaller than 100 units, neither player gets any water in either round.

(2) Case 9 (Closed-Loop) : $100 \quad Q^s < 108$

When the amount of water equals or exceeds 100 units <u>but</u> smaller than 108 units, only the headender can get water, just as in the myopic solution. Unlike in the myopic solution, the headender receive water in both the first and the second rounds. In the first round, the amount of water the tailender can obtain is limited. In the second round, the headender can appropriate an unlimited amount of water, because the headender uses less water and invests up to the maximum amount in maintenance in the first round.

(3) Case 10 (Closed-Loop) : $108 \quad Q^s < 150$

Once the amount of water becomes greater than or equal to 108 units, the headender gets an unlimited amount of water at his/her field gate in both rounds.

(4) Case 11 (Closed-Loop) : $150 \quad Q^s < 159$

When the amount of water at the source equals or exceeds 150 units, the tailender begins to receive water. Until the amount of water of the source reaches 159 units, the tailender gets water only in the second round. Note that the tailender obtains water earlier in the closed-loop solution, than in the myopic solution. This occurs because it is possible for the headender to make an investment in maintenance in the closed-loop situation, which can improve the levels of physical conditions. Moreover, unlike in the myopic solution, it is optimal to appropriate nothing and to invest something in maintenance in the first round in order to get water in the second.

(5) Case 12 (Closed-Loop) : $159 \quad Q^s < 165$

When the amount of water equals or exceeds 159 units <u>but</u> fall short of 165 units, the tailender gets water in both the first and the second rounds. As in the headender's case, the optimal strategy chooses to get less and invest up to the maximum in maintenance in the first round and get the interior solution as an actual choice in the second round.

Once the amount of water at the source reaches 165 units, both the headender and the tailender enjoy an unlimited amount of water at their field gates in every round. Therefore, when the amount of water at the source equals or exceeds 165 units we have a case of water abundance. Water abundance exists in the myopic solution when the amount of equals or exceeds 188 units. Notice that the water abundance case occurs with a smaller amount of water in the closed-loop solution than in the myopic solution. In other words, a smaller amounts of water at the source can provide an unlimited amount of water at the field gates when a rational headender and a rational tailender act in an independently foresighted manner than when the players do not act with foresight. Rational players who look ahead invest more in the maintenance and appropriate less water in the first round than rational players who do not look ahead.

Only 5 water scarcity cases exist in the closed-loop solution while 7 exist in the myopic solution. In the closed-loop solution, it is optimal to invest in maintenance in the first round whereas investment in maintenance is not rational in the myopic solution. In closed-loop solution situations, no case exists in which a lack of investment in maintenance prevents appropriators from receiving enough water. Lack of investment causes water scarcity twice -- once for the headender (Case 3 - Myopic) and once for the tailender (Case 7 - Myopic).

Water Scarcity Cases in the Social Optimum Solution

Four water scarcity cases exist in social optimum solutions. Social optimum solutions make no distinction between the headender and the tailender in terms of either the optimal amount of appropriation or the optimal amount of investment in maintenance. In other words, the headender and the tailender act as if they are one player.

(1) Case 13 (Social Optimum) : $Q^s < 95$

When the amount of water at the source is smaller than 95 units, no one gets water in any round.

(2) Case 14 (Social Optimum) : 95 s Q^s < 100

When the amount of water at the source equals or exceeds 96 units <u>but</u> falls short of 100 units, appropriators can access water in the second round. To get water in the second round, however, they need to invest in maintenance and refrain from appropriating in the first round.

(3) Case 15 (Social Optimum) : 100 Q^S < 104

When the amount of water at the source reaches is greater than or equal to 100 units <u>but</u> smaller than of 103 units, appropriators get a limited amount of water in both rounds.

(4) Case 16 (Social Optimum) : $104 \leq Q^s < 112$

When the amount of water at the source reaches or exceeds 104 units <u>but</u> falls short of 112 units, appropriators can get an unlimited amount of water in the first round and a limited amount of water in the second round.

Once the amount of water at the source reaches 112 units, all appropriators enjoy an unlimited amount of water in the second round. The social optimum solution can create water abundance with the smallest amount of water at the source. When the amount of water at the source reaches 96 units, both appropriators access water. Once the amount of water at the source reaches or exceeds 112 units, no water scarcity-exists in the social optimum solution. In the closed-loop solution, it is impossible for tailender to get any water when the amount of water at the source equals 112 units. In the social optimum solution, it is possible for the tailender to invest in maintenance and to appropriate no water and still receive the half of the total group payoff even when they cannot access water.

In the following sections, I examine how the amount of water at the source affects the optimal amounts of appropriation, the optimal amounts of investment in maintenance, the group payoffs, and the efficiency losses of individual rationality.

Optimal Behaviors in Three Solutions and Water Scarcity

In the first section, I examine the effect of the amount of water at the source on the optimal amounts of appropriation and on the optimal amounts of investment in maintenance in the three solutions.

Optimal Behaviors in the Myopic Solution

In the myopic solution, appropriators take as much water as they can in the first round and invest nothing in maintenance in any round, causing the physical conditions of an irrigation system to deteriorate. As the amount of water at the source rises above the threshold at which appropriators start to access water, the level of appropriation in the first round becomes positive. Only after the interior solution appears as an actual choice in the first round will the amount of appropriation in the second round become positive. When only the headender gets a limited amount of water in the first round, the amount that the headender appropriates in the first round increases as the amount of water at the source increases. Once the headender receives an unlimited amount of water, his/her amount of appropriation in the first round remains constant but his/her amount of appropriation in the second round increases as the amount of water at the source increases. In the myopic solution, when the amount of water that appropriators receive is limited the amount of appropriation always increases as the amount of water at the source increases. On the other hand, when the amount of water that appropriators access is <u>not</u> limited, the amount of appropriation remains constant, even though the amount of water at the source increases. In the myopic solution, we cannot have an interior solution in the second round without also having an interior solution in the first round. Interior solutions are feasible choices in both rounds or only in the first round.

General patterns of optimizing behavior that apply to the headender and the tailender in the myopic solution are:

(i) When water is extremely scarce, take as much water as possible in the first round; continue to increase the amount of appropriation in the first round as the amount of water at the source increases;

(ii) Once water becomes sufficient to make the interior solution a choice in the first round, the amount of appropriation in the first round remains unchanged; get more water in the second round as the amount of water increases;

(iii) Once water becomes sufficient to generate the interior solution as a choice in both rounds, the amounts of appropriation remain unchanged at the interior solution amounts.

Optimal Behaviors in the Closed-Loop Solution

In the closed-loop solution, it is almost always optimal for players to show restraint in appropriating and to invest in maintenance in earlier rounds; and then to take more water in later rounds. When the amount of water at the source passes the threshold at which water becomes available to both appropriators (in Case 9 - Closed-Loop), the headender takes a small amount of water in the first round and invest in maintenance, which provides the headender an unlimited amount of water in the second round. The amounts of appropriation in the second round decrease as the amount of water at the source increases. The optimal amounts of appropriation remain unchanged only when interior solutions qualify as actual choices for all appropriators who receive water in every round. If not, the optimal amount of appropriation decreases as the amount of water at the source increases, since the levels of the physical conditions decrease as the amount of water at the source increases.

In Case 9 (Closed-Loop), the upper limits on the amount of appropriation in the first round increase as the amount of water at the source increases. Therefore, the amount that the headender appropriates in the first round increases as the amount of water at the source increases. Note that the investment in maintenance equals the maximum that the headender can afford since the headender expects no water shortage.

In Case 10 (Closed-Loop), changes in the amount of water at the source do not affect the optimal solutions of the game because headender, who is the only player that gets water from the system, enjoys an unlimited amount of water in every round.

The relationships between the amount of water at the source and the optimal choices for the tailender are, in general, very similar to those for the headender. The tailender also optimizes by refraining from excessive use and by making investments in maintenance in earlier rounds in order to get more water in later rounds. However, the amount of water in the second round for tailender is limited when water first becomes available to the tailender, while the amount of water in the second round for the headender is unlimited when water first becomes available to the headender. This creates a big difference between the optimal choice for the headender and the optimal choice for the tailender. When the amount of water in the next round is limited (i.e., water shortage is expected), it is no longer optimal for the tailender to invest up to the maximum that he/she can afford in maintenance. The value function at time (1) ($\Psi_{k1} = \pi_{k1} + \omega^*\Psi_{k2}$) is concave in the amount of investment in maintenance (m_{k1}) when players expect that there will not be enough water in the second round. An interior solution then exists, which could be smaller than the maximum that the tailender can afford. In other words, when no water shortage exists, the optimal amount of investment in maintenance always equals the maximum amount that appropriators can afford, irrespective of the amount of water at the source. When a water shortage is possible, however, the optimal amount of investment in maintenance is less than or equal to the maximum amount that appropriators can afford, and it varies as the amount of water at the source.

In Case 11 (Closed-Loop), the tailender starts to get water from the system in the second round, which changes the optimal choices for the headender. The underlying logic is as follows: The amount of water for tailender in the second round is limited. Consequently, the optimal amount of investment in maintenance for the tailender in the first round is smaller than the maximum that the tailender can afford. The tailender increases the amount of investment in maintenance as the amount of water at the source increases in order to make more water available in the second round. Moreover, the tailender appropriates 0 units in the first round. Therefore, the total amount of investment in maintenance improves the levels of the two state variables, which increases the optimal amount of appropriation that is an interior solution for the headender in the second round.

When the amount of water at the source reaches the level found in Case 12 (Closed-Loop), we expect no water shortage in the second round. The optimal amount of investment in maintenance for the tailender becomes the maximum affordable investment. The tailender still gets a limited amount of water in the first round. As the amount of water at the source increases, the tailender's limit on appropriation in the first round increases. Consequently, the total amount of appropriation in the first round increases as the amount of water at the source increases. This causes the levels of the state variables in the second round to decline, which results in a decrease in the optimal level of appropriation in the second round for both the headender and the tailender as the amount of water at the source increases. This relationship continues until the amount of water at the source reaches 165 units. Once the amount of water at the source hits this point, both the headender and the tailender enjoy an unlimited amount of water in every round, and the amount of water at the source does not influence the solutions.

In sum, the general patterns of optimal behavior under conditions of water scarcity in the closed-loop solution are:

(i) When water is extremely scarce, take nothing on the first round and invest a little to increase the amount of water available in the second round; increase the amount of investment as the amount of water at the source increases;

(ii) As water becomes a little bit more available, continue to increase the amount of investment in the first round and get more water in the second round as the amount of water at the source increases;

(iii) Once water becomes sufficient to make the interior solution a feasible choice in the second round, get more water in the first round as the amount of water at the source gets larger; in this period, the amount of investment in maintenance in the first round remains unchanged at the upper limit (mB_i) ;

(iv) When water becomes completely sufficient so that the interior solution can be a choice in both rounds, the amount of appropriation and the amount of investment in maintenance remain unchanged at the interior solution and the upper limit (mB_i) .

Optimal Behaviors in the Social Optimum Solution

The social optimum solution differs from the two other solutions in that the headender and the tailender invest and receive the same amount in each round. The social optimum solution allows the appropriators to obtain an unlimited amount of water from a smaller amount of water than do any of the other two solutions. In the social optimum solution, just as in the closed-loop solution, it is optimal to get less water and to invest in maintenance in earlier rounds in order to access more water in later rounds. As Case 14 (Social Optimum) shows, by getting no water and investing in maintenance in the first round, appropriators can get water in the second round. Note that, in this interval, to invest up to the maximum that the appropriators can afford is not optimal. Water shortage is expected even in the social optimum solution, which leads to the following value function at time (1) : $\Psi_{i1} = \pi_{i1} + \omega^*\Psi_{i2}$, which is concave in the amount of investment in maintenance (m_{i1}) .

Note that water shortage is also expected in Case 15 (Social Optimum) and Case 16 (Social Optimum). The optimal amounts of investment in maintenance equal the maximum that appropriators can afford in these two intervals. This is because the interior solutions are greater than the maximum that the appropriators can afford in these cases, which means that they cannot be realized as actual choices.

Efficiency Losses of Individual Rationalities and Water Scarcity

Since we have a variety of water scarcity cases, we also have a wide variety of suboptimalities. In this section, I briefly examine how water scarcity affects the efficiency losses of individual rationality.

Group Payoffs

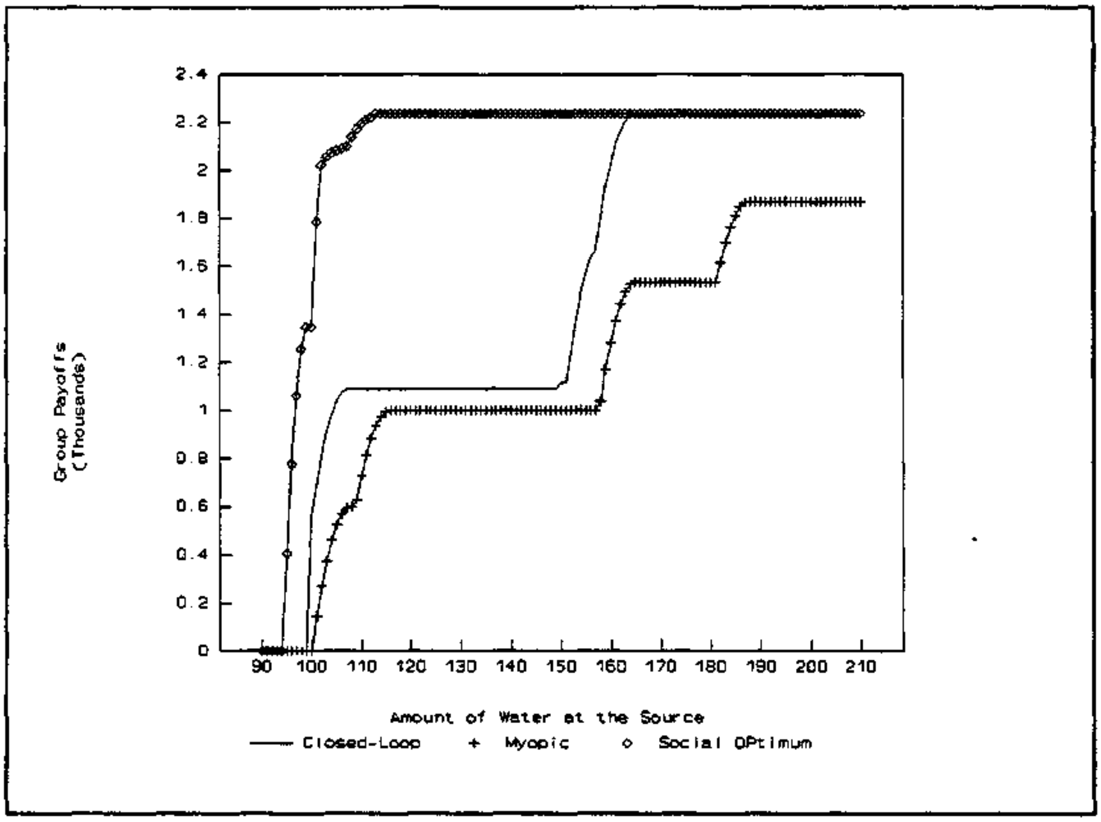
Figure 6.2 shows the group payoffs of three solutions. As one would expect, the group payoff of the social optimum solution exceeds the group payoffs of both the closed-loop and the myopic solutions. The group payoff of the social optimum solution reaches its maximum when the amount of water at the source is 113 units. After it reaches the maximum, it remains constant because the amount of water at the source no longer affects the outcomes of the game once sufficient water exists.

As is the case when water is sufficient, the group payoff of the myopic solution is the smallest among the three; the group payoff of the closed-loop solution is larger; and the group payoff of the social optimum is the largest of the three. When water is sufficient, the group payoffs of the closed-loop and the myopic solution become insensitive to the changes in the amount of water at the source.

Group payoffs can also be insensitive to the amount of water at the source when water is not sufficient. In Case 10 (Closed-Loop), for example, the headender receives sufficient water to ensure the interior solutions to be his/her actual choice in both rounds, even though water is insufficient at the system level. In this case, the tailender gets no water. Therefore, the amounts of appropriation for both the headender and the tailender in every round do not change; the group payoff is insensitive to the changes in the amount of water at the source. This implies that we cannot always increase the groups payoffs by increasing the amount of water at the source. Building a dam, for example, cannot guarantee an increase in the group payoff for individuals in an irrigation system.

However, we still can say that the group payoff tends to increase as the amount of water at the source increases. For example, the group payoff in Case 4 (Myopic) is much smaller than the group payoff in Case 6 (Myopic) because only the headender gets water in Case 4 (Myopic),

Figure 6.2: Group Payoff of Three Solutions



while both the headender and the tailender get water in Case 6 (Myopic).

Efficiency Loss in Payoffs

Group payoffs of the myopic solution cannot be as close to the group payoff of the social optimum solution as the group payoff of the closed-loop solution can. This becomes clear when we compare the efficiency losses of the two solutions (see in Figure 6.3). Efficiency losses in payoffs tend to decrease in both closed-loop and myopic solutions as the amount of water at the source increases. When the amount of water at the source reaches 188 units, all the outcomes become exactly the same as the outcomes of the initial parameter configuration. The efficiency losses in payoff again equal 0.23% for the closed-loop solution and 16.50% for the myopic solution. Once the amount of water at the source exceeds 188 units, water becomes abundant in all three solutions.

Figure 6.3 demonstrates that individual rationality with foresight achieves a much higher level of efficiency than individual rationality without foresight does. Figure 6.4 shows changes in the gap between efficiency losses in payoffs in the closed-loop solution and the myopic solution that occur as the amount of water at the source changes. The gap between the efficiency losses is the largest in Case 6 (Myopic); no water shortage exists in the closed-loop solution, whereas the tailender can get water only in the first round in the myopic solution. The gap between the efficiency losses in the closed-loop solution and the myopic solution becomes smallest when the amount of water reaches the interval between 116 and 160 units (116 Q^s l50), which represents the intersection of Case 4 (Myopic) and Case 10 (Closed-Loop). In this case, only the headender receives water and he/she gets an unlimited amount.

According to Figure 6.3, the efficiency losses in the group payoff increase as the amount of water at the source increases from 108 to 112

Figure 6.3: Efficiency Losses in Payoffs

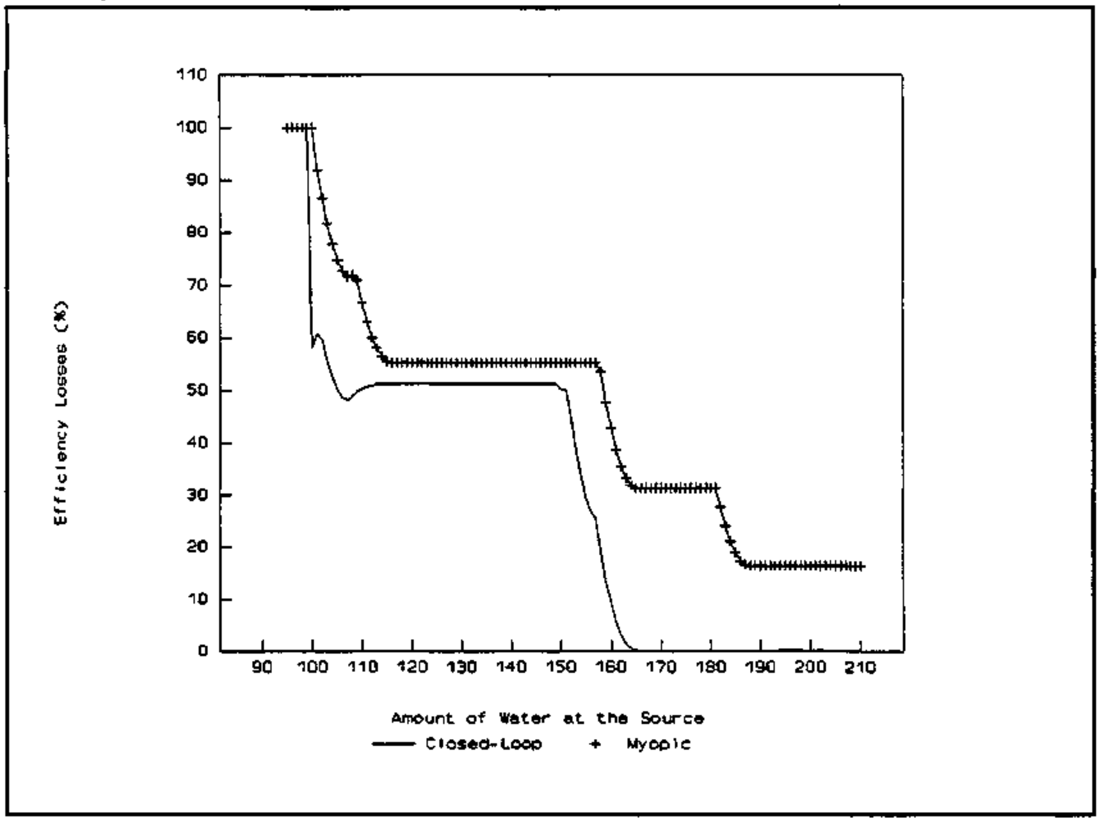
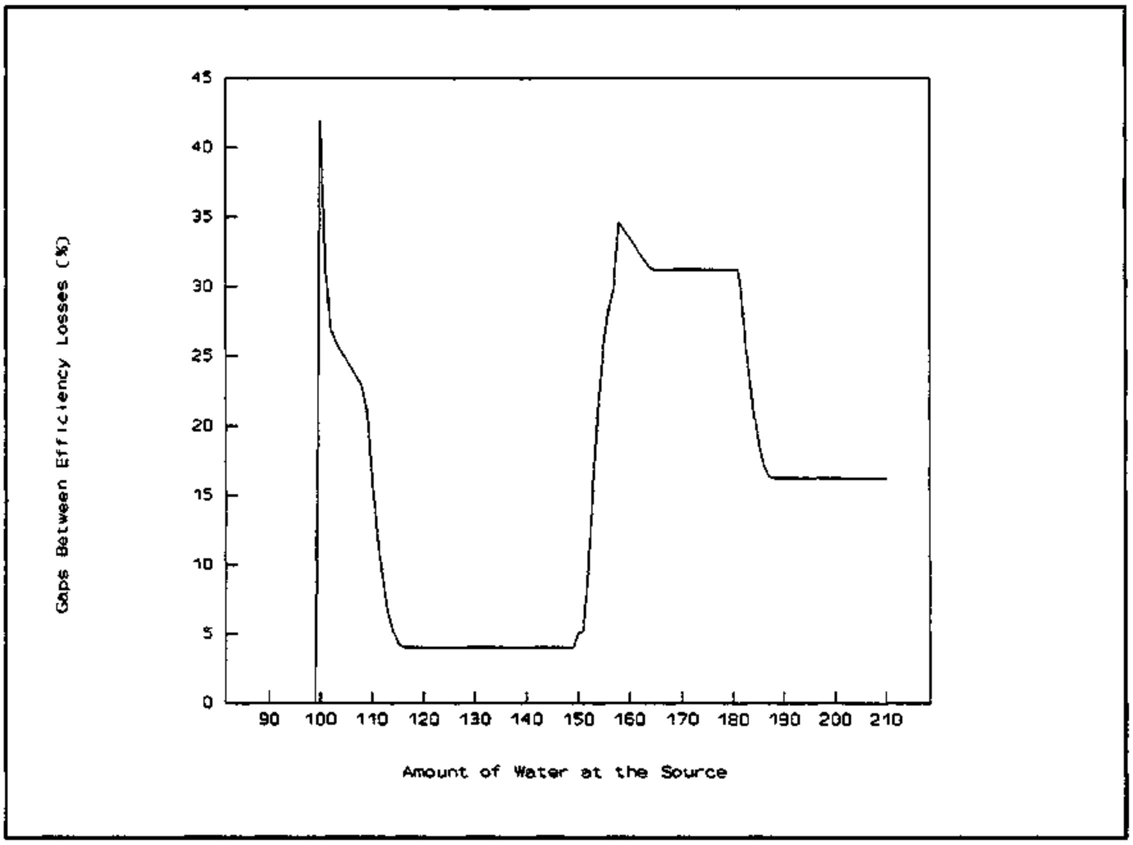


Figure 6.4: Gaps Between Efficiency Losses in Payoffs



units, as found in the intersection of Case 10 (Closed-Loop) and Case 16 (Social Optimum). In this interval, the group payoff of the closed-loop remains unchanged as the amount of water at the source increases, while the group payoff of the social optimum increases as the amount of water at the source increases. Therefore, the closed-loop solution loses an increasing amount of efficiency as the amount of water at the source increases in this interval. This implies that an improvement in physical conditions that increases the amount of water at the source does not always reduce the efficiency losses of individual rationality. In fact, the improvement cannot bring about any change at all when the amount of water at the source remains within intervals where efficiency losses in payoff are insensitive to changes in the amount of water at the source. In the worst case, even though it's rather rare, it could even worsen the situation.

Effects of More Iterations

In Chapter 5, we saw that the patterns of outcome of this game do not change in meaningful ways if we increase the number of iterations when water is sufficient. Efficiency losses increase at decreasing rates as the game iterates more, but the patterns of optimal behavior do not change. Are there changes in the patterns of outcomes as the game iterates more than twice when water is insufficient? We can group the patterns of the relationship between the amount of water at the source and the outcomes of this game by intervals of water scarcity. To see the possible effects of additional iterations, I pick four "typical" parameter configurations that represent levels of water scarcity.

Four Parameter Configurations of Water Scarcity

I include only those cases where both players receive water in at least one round of the closed-loop solution. If one player cannot obtain any water in both rounds, only one player plays the game. Excluding the case where only one player can obtain water, we are left with 4 different water scarcity cases. In each case, the headender always gets an unlimited amount of water in every round.

(a) Water Scarcity I (IPC|Q^S=155) : This is the case in which the tailender can get a limited amount of water only in the second round in the closed-loop solution. In this case, the tailender does not get water in both rounds of the myopic solution. This represents the intersection of Case 11 (Closed-Loop) and Case 4 (Myopic).

(b) Water Scarcity II (IPC|Q^s=160) : In this case, the tailender gets water in both rounds in the closed-loop solution. The tailender receives an unlimited amount of water in the second round and a limited amount of water in the first round in the closed-loop solution. In the myopic solution, the tailender obtains a limited amount of water in the first round. This case represents the intersection of Case 12 (Closed-Loop) and Case 5 (Myopic).

(c) Water Scarcity III (IPC|Q^s=180) : The tailender gets an unlimited amount of water in every round of the closed-loop solution and an unlimited amount of water in the first round of the myopic solution, which represents Case 6 (Myopic).

(d) Water Scarcity IV (IPC|Q^S=185) : In this case, the tailender finally gets water in every round, even in the myopic solution. The tailender gets an unlimited amount of water in the first round and a limited amount of water in the second round. This represents Case 7 (Myopic).

In the next sections, I examine how more iterations affect the outcomes of this game in these four water scarcity cases.

Effects of More Iterations in Water Scarcity I

Table 6.1 lists the outcomes of the game in the case with differing values of T. Notice that additional iterations change the outcomes of the game. When we repeat this game two or three times, the tailender only gets a limited amount of water in all but the first round, when the tailender gets no water at all. When the game is iterated more than three times, the tailender gets an unlimited amount of water in all but the first round, when he/she still gets no water.

As T grows larger, investments made during the earlier rounds increase the levels of state variables in more rounds and bring more water to appropriators in later rounds. If the game repeats only twice, for example, the investment in the first round increases the levels of

Table 6.1: Efficiency Losses of Individual Rationality in Water Scarcity I

(a) T=2:

Myopic u_j	7.7345, 7.0589}
Myopic u_k	{0, 0}
Myopic m_j, m_k	{0, 0}
Closed u_j	{7.7345, 8.1507}
Closed u_k	{0, 4.9202}
Closed m_j	{5, 0}
Closed m_k	{2.0576, 0}
Optimal u_j, u_k	{6.7184, 8.1567}
Optimal m_j, m_k	{5, 0}
Optimal Payoff	2234.95
Myopic %Δ	-55.31% (998.854)
Closed %Δ	-29.62% (1573.14)

Parameter Configuration: (IPC|Q^s=155)

(b) T=3:

Myopic u_j	{7.7345, 7.0589, 6.4424}
Myopic u_k	{0, 0, 0}
Myopic m_j, m_k	{0, 0, 0}
Closed u_j	{7.7345, 8.1437, 8.3622}
Closed u_k	{0, 4.7917, 8.8105}
Closed m_j	{5, 5, 0}
Closed m_k	{2.0124, 3.4066, 0}
Optimal u_j, u_k	{5.9924, 7.2034, 8.6184}
Optimal m_j, m_k	{5, 5, 0}
Optimal Payoff	3151.95
Myopic %Δ	-59.87% (1265.01)
Closed %Δ	-22.18% (2452.86)

Parameter Configuration: (IPC|Q^s=155)

(c) T=5:

Myopic u_j	{7.7345, 7.0589, 6.4424, 5.8797, 5.3661}
Myopic u_k	{0, 0, 0, 0, 0}
Myopic m_j, m_k	{0, 0, 0, 0, 0}
Closed u_j	{7.7345, 7.4035, 7.96345, 8.5707, 9.2770}
Closed u_k	{0, 7.4080, 7.9636, 8.5655, 9.2677}
Closed m_j	{5, 5, 5, 5, 0}
Closed m_k	{5, 5, 5, 5, 0}
Optimal u_j, u_k	{5.0828, 6.0090, 7.0046, 8.1400, 9.5100}
Optimal m_j, m_k	{5, 5, 5, 5, 0}
Optimal Payoff	4668.89
Myopic %Δ	-66.58% (1560.55)
Closed %Δ	-7.87% (4301.44)

Parameter Configuration: (IPC|Q^s=155)

the state variables only once. If the game repeats 5 times, the investment in the first round increases the levels of the state variables 4 times, in the second, third, fourth, and fifth rounds. Therefore, as the game repeats more, investments in maintenance make the levels of the state variables in the last round becomes higher.

In sum, the tailender only gets a limited amount of water in the final round when the game repeats 2 or 3 times; but when the game repeats more, the tailender receives an unlimited amount of water in all rounds after the first round. A larger T changes the patterns of the outcomes of this game in this case of water scarcity (water *scarcity I)*. Changes occur when T exceeds 4.

In the myopic solution, efficiency losses in payoff increase as the game repeats more. However, in the closed-loop solution, efficiency loss in payoff decreases as the game repeats more when water is scarce, whereas efficiency loss in payoff increases as the game repeats more when there is sufficient water.

Effects of More Iterations in Water Scarcity II

The outcomes of the game in this case are shown in Table 6.2. The levels of the state variables in the final rounds of the closed-loop solution exceeds those of the social optimum solution when the game repeats two or three times. The levels of physical conditions in the final round equal 0.5450 (T=2) and 0.5607 (T=3) in the closed-loop solution, whereas they equal 0.5278 (T=2) and 0.5577 (T=3) in the social optimum solution. The total amounts of appropriation in the first round are smaller in the closed-loop solution than in the social optimum solution. The amount of investment in maintenance by the tailender is substantial in both the closed-loop and the social optimum solutions. The amount of appropriation by the tailender is limited in the first round of the closed-loop solution, but not in the first round of the social optimum solution. Thus, the levels of physical conditions at the

Table 6.2: Efficiency Losses of Individual Rationality in Water Scarcity II

(a) T=2:

Myopic u_j Myopic u_k Myopic m_j, m_k	{7.7345, 6.8837} {2.2655, 0} {0, 0}
Closed u_j Closed u_k Closed m_j Closed m_k	{7.7345, 8.4310} {2.2655, 8.4222} {5, 0} {5, 0}
Optimal u_j, u_k Optimal m_j, m_k	{6.7184, 8.1567} {5, 0}
Optimal Payoff Myopic %Δ Closed %Δ	2234.95 -42.79% (1278.64) -9.30% (2027.15)

Parameter Configuration: (IPC|Q^s=160)

(b) T=3:

Myopic u_j Myopic u_k Myopic m_j, m_k	{7.7345, 6.8837, 6.2825} {2.2655, 0, 0} {0, 0, 0}
Closed u_j Closed u_k Closed m_j Closed m_k	{7.7345, 7.8920, 8.6728} {2.2655, 7.8872, 8.6641} {5, 5, 0} {5, 5, 0}
Optimal u_j, u_k Optimal m_j, m_k	{5.9924, 7.2034, 8.6184} {5, 5, 0}
Optimal Payoff Myopic %Δ Closed %Δ	3151.95 -51.40% (1531.75) -5.51% (2978.34)

Parameter Configuration: (IPC|Q^s=160)

(c) T=5:

Myopic u_j Myopic u_k Myopic m_j, m_k	{7.7345, 6.8837, 6.2825, 5.7337, 5.2329} {2.2655, 0, 0, 0, 0} {0, 0, 0, 0, 0}
Closed u_j Closed u_k Closed m_j Closed m_k	{7.7345, 7.2460, 7.8267, 8.4509, 9.1703} {2.2655, 7.2503, 7.8268, 8.4458, 9.1611} {5, 5, 5, 5, 0} {5, 5, 5, 5, 0}
Optimal u_j, u_k Optimal m_j, m_k	{5.0828, 6.0090, 7.0046, 8.1400, 9.5100} {5, 5, 5, 5, 0}
Optimal Payoff Myopic %Δ Closed %Δ	4668.89 -61.17% (1812.8) -4.03% (4480.56)

Parameter Configuration: (IPC|Q^s=160)

final round may be higher in the closed-loop solution than in the social optimum solution.

When the game repeats long enough, the levels of the state variables in the final round become larger in the social optimum solution than in the closed-loop solution. This occurs when the game repeats more than three times. The minimum T that approximates the impact of many iterations is four.

In the closed-loop solution, the efficiency losses in payoff decreases as the game repeats more. In the myopic solution, the efficiency losses in payoff increase as the game iterates more. The group payoffs in both the closed-loop and the myopic solutions increase as the game is repeated more, but this reflects the fact that the payoffs of more rounds enter the group payoff sum as the number of iterations rises.

Effects of More Iterations in Water Scarcity III

In this case, the tailender gets an unlimited amount of water in the first round but cannot get water in the second round when using the myopic solution; whereas no water shortage exists at all in both the closed-loop and the social optimum solutions. Table 6.3 shows these results. `Since there is no water shortage in both the closed-loop and the social optimum solutions, the group payoffs and the levels of the state variables of these two solutions are identical to those in Tables 5.2 and 5.4.

In the myopic solution, however, water shortage still exists. The tailender gets water only in the first round, no matter how long the game repeats. As before, efficiency losses in payoffs increase as the game repeats more. Compared to the other cases of water scarcity (water *scarcity I* and water *scarcity II)* , the group payoffs exceeds those of the other cases; but the levels of the state variables in the final rounds are less than those of the others because total amounts of

Table 6.3: Efficiency Losses of Individual Rationality in Water Scarcity III

(a) T=2:

Myopic u_j	$\{7.7343, 6.4613\}$
Myopic u_k	$\{7.7268, 0\}$
Myopic m_j, m_k	$\{0, 0\}$
Closed u_j	$\{7.2323, 8.0857\}$
Closed u_k	$\{7.2280, 8.0776\}$
Closed m_j	$\{5, 0\}$
Closed m_k	$\{5, 0\}$
Optimal u_j, u_k	$\{6.7184, 8.1567\}$
Optimal m_j, m_k	$\{5, 0\}$
Optimal Payoff	2234.95
Myopic %Δ	-31.44% (1532.31)
Closed %Δ	-0.23% (2229.8)

Parameter Configuration: (IPC|Q^s=180)

(b) T=3:

Myopic u_j	$\{7.7345, 6.4613, 5.8970\}$
Myopic u_k	$\{7.7268, 0, 0\}$
Myopic m_j, m_k	$\{0, 0, 0\}$
Closed u_j	$\{6.8751, 7.6171, 8.4281\}$
Closed u_k	$\{6.8754, 7.6125, 8.4197\}$
Closed m_j	$\{5, 5, 0\}$
Closed m_k	$\{5, 5, 0\}$
Optimal u_j, u_k	$\{5.9924, 7.2034, 8.6184\}$
Optimal m_j, m_k	$\{5, 5, 0\}$
Optimal Payoff	3151.95
Myopic %Δ	-44.31% (1755.31)
Closed %Δ	-0.62% (3132.3)

Parameter Configuration: (IPC|Q^s=180)

(c) T=5:

Myopic u_j	$\{7.7345, 6.4613, 5.8970, 5.3819, 4.9112\}$
Myopic u_k	$\{7.7268, 0, 0, 0, 0\}$
Myopic m_j, m_k	$\{0, 0, 0, 0, 0\}$
Closed u_j	$\{6.4375, 7.0454, 7.6527, 8.2985, 9.0346\}$
Closed u_k	$\{6.4448, 7.0500, 7.6529, 8.2934, 9.0256\}$
Closed m_j	$\{5, 5, 5, 5, 0\}$
Closed m_k	$\{5, 5, 5, 5, 0\}$
Optimal u_j, u_k	$\{5.0828, 6.0090, 7.0046, 8.1400, 9.5100\}$
Optimal m_j, m_k	$\{5, 5, 5, 5, 0\}$
Optimal Payoff	4668.89
Myopic %Δ	-57.10% (2002.98)
Closed %Δ	-1.56% (4596.23)

Parameter Configuration: (IPC|Q^s=180)

appropriation increase in water *scarcity III.* In this case, a larger T seems not to have an impact on the outcomes of the game.

Effect of More Iterations in Water Scarcity IV

Table 6.4 lists the results of various numbers of iterations in the fourth condition of water scarcity. The outcomes of the closed-loop solution in this case parallel the outcomes of *water scarcity III.* The patterns of outcomes of the myopic solution in water *scarcity IV* match the patterns of outcomes in water *scarcity III,* except that the tailender gets water in the second round. The increase in Q^s changes the outcome of this game to provide water to the tailender in the first and the second rounds.

Another increase in Q^s would enable the tailender in the myopic solution to get water in the third round, too (i.e., an added water *scarcity V).* These possibilities cannot be seen when the game only repeats twice. We could add many levels of water scarcities by adding more iterations. As the amount of water at the source increases, the efficiency losses in payoffs decreases; the efficiency losses in water *scarcity V* will be smaller than the efficiency losses in water *scarcity IV,* just as the efficiency losses in water *scarcity IV* are smaller than the efficiency losses in *water scarcity III.* Since the patterns of outcomes in additional water scarcity cases do not basically differ from each other in meaningful ways, I exclude them from the analysis.

Conclusion: Possibility of Self-Governing Solutions to Collective Action Problem

The prediction of the literature based on the logic of the one-shot PD game has been that rational players who are interact with each other in a CPR dilemma cannot achieve the socially rational and Pareto-optimal outcome because this outcome is not an equilibrium. It also has been presumed that individuals cannot reach this outcome in collective

Table 6.4: Efficiency Losses of Individual Rationality in Water Scarcity IV

(a) T=2:

Myopic u_j	{7.7343, 6.4613}
Myopic u_k	{7.7268, 3.8467}
Myopic m_j, m_k	{0, 0}
Closed u_j	{7.2323, 8.0857}
Closed u_k	{7.2280, 8.0776}
Closed m_j	{5, 0}
Closed m_k	{5, 0}
Optimal u_j, u_k	{6.7184, 8.1567}
Optimal m_j, m_k	{5, 0}
Optimal Payoff	2234.95
Myopic %Δ	-18.93% (1811.77)
Closed %Δ	-0.23% (2229.8)

Parameter Configuration: (IPC|Q'=185)

(b) T=3:

Myopic u_j	{7.7345, 6.4613, 5.5994}
Myopic u_k	{7.7268, 3.8467, 0}
Myopic m_j, m_k	{0, 0, 0}
Closed u_j	{6.8751, 7.6171, 8.4281}
Closed u_k	{6.8754, 7.6125, 8.4197}
Closed m_j	{5, 5, 0}
Closed m_k	{5, 5, 0}
Optimal u_j, u_k	{5.9924, 7.2034, 8.6184}
Optimal m_j, m_k	{5, 5, 0}
Optimal Payoff	3151.95
Myopic %Δ	-36.14% (2012.84)
Closed %Δ	-0.62% (3132.3)

Parameter Configuration: (IPC|Q'=185)

(c) T=5:

Myopic u_j	{7.7345, 6.4613, 5.5994, 5.1104, 4.6640}
Myopic u_k	{7.7268, 3.8467, 0, 0, 0}
Myopic m_j, m_k	{0, 0, 0, 0, 0}
Closed u_j	{6.4375, 7.0454, 7.6527, 8.2985, 9.0346}
Closed u_k	{6.4448, 7.0500, 7.6529, 8.2934, 9.0256}
Closed m_j	{5, 5, 5, 5, 0}
Closed m_k	{5, 5, 5, 5, 0}
Optimal u_j, u_k	{5.0828, 6.0090, 7.0046, 8.1400, 9.5100}
Optimal m_j, m_k	{5, 5, 5, 5, 0}
Optimal Payoff	4668.89
Myopic %Δ	-52.09% (2236.82)
Closed %Δ	-1.56% (4596.23)

Parameter Configuration: (IPC|Q'=185)

action associated with using or managing irrigation system. David Freeman describes this situation:

> ...The logic of the individually rational utility seeker may not coincide with the logic of the community. If, for example, farmers individually observe that their leaky and misaligned water course requires improvement, they will not invest in collective action on individually rational grounds. Assuming a sizable number of farmers, each will calculate as follows. If one farmer invests time, energy, and money requires to improve the channel going through his or her own land and other farmers do not make comparable collective investments in a coordinated fashion, then the payoff in improved water supply and control (the collective good) is negligible.
>
> However, if many farmers undertake the improvement efforts on their sections, and one individually rational decision-maker does not do so, she or he will still enjoy a substantial share of the benefit provided by the works of others, at no personal cost. Therefore, the rational, calculating individual will choose to do nothing either way. The collective good will not automatically evolve, even though the individuals in question may possess full and accurate information about the potential benefits of improving the channel and may have the required know-how and resource to do so (Freeman 1990, 115).

This line of logic leads to the assumption that the obstacles and temptations that limit the collective action in CPR situations are so substantial that only a national government has the ability to overcome them. That may be the case when farmers consider only short-run payoffs or when no institutional setting exists. It becomes individually rational to invest nothing in maintenance in the myopic solution.

Contrary to Freeman's prediction, the simulation results show that it can be individually rational to invest in maintenance up to the maximum that the irrigators can afford in the absence of water shortage, and to invest a non-zero amount less than or equal to the maximum in situations with water shortage, when repeated iterations are expected and information about transformation functions is available. Moreover, we saw in *water scarcity I* that a larger T can make investing up to the affordable maximum the optimal solution. Since *water scarcity I* represents the case with the most severe shortage, this finding implies that it is almost always optimal to invest in maintenance up to the affordable maximum (i.e., the upper limit on the investment in maintenance). In the simulations, we assume that this amount is relatively small. Farmers must invest efforts in other agricultural work, besides maintaining the irrigation system in order to yield agricultural products. Secondly, we assume that the levels of state variables influence the payoffs; regardless of the abundance of water at the source, the appropriators get the maximum feasible payoffs only if the invest in maintenance to preserve the levels of state variables. Some field settings will not meet these assumptions.

In both the closed-loop and the myopic solutions, efficiency losses in payoffs becomes greater when water shortages exist. The absolute size of the group payoffs also becomes smaller when water is scarce. Compared to when there is sufficient water, larger T has different impacts on the patterns of outcomes of this game when water shortage exists. In the closed-loop solution, as T increases, the efficiency loss in payoffs <u>increases</u> when there is no water scarcity, but <u>decreases</u> when there is water scarcity. In the myopic solution, on the other hand, the efficiency loss in payoffs decreases as T increases, regardless of the level of water.

A large enough T might possibly change the patterns of the outcomes of this game when water shortage exists. Theoretically, by simulating a game that repeats many times, we could discover how the efficiency losses and the patterns of the outcomes change. Unfortunately, this is simply not possible. It takes too long to run simulations when T is large. For example, the simulation takes about 12 hours when T is only 5.[3] It takes so long because of the branching method. Therefore, I looked for the minimum T that allows us to infer the possible patterns of the outcomes that occur when the game repeats long enough. It turns out that this minimum is 4. The patterns of the outcomes of this game when T equals 4 do not differ from the patterns of

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[3] I ran simulations using Mathematica 2.0 in STARRS constellation at Indiana University, Bloomington. The STARRS configuration consists of IBM Rise System/6000 Model 560 POWERserver, which is the fastest available in Bloomington.

the outcomes of this game when the game iterates more. Hence, I use T=2 as a representation for short iterations and T=4 for long iterations in the future analysis.

When T equals 4, the tailender receives an unlimited amount of water in all rounds but the first one and it is optimal to invest up to the maximum in every round except the final one; this is also the case when the game iterates longer (Water Scarcity I). When T equals 4, the levels of the state variables in the final round are also higher in the social optimum solution than in the closed-loop solution (Water Scarcity II).

It is practically impossible to iterate this game 60 times when water is scarce due to the complex calculation process. However, I assume that the steady state of the efficiency loss of the closed-loop solution will be in the neighborhood of 4.77 %, as in the case of water abundance. When the game is iterated enough: (i) the optimal amount of investment in maintenance becomes equal to the maximum that the appropriators can afford so that there will be no difference in the time paths of the optimal amount of investment in maintenance between water scarcity and water abundance; and (ii) as the game iterates more, the effect of the earlier rounds, in which tailenders receive only a limited amount of water, on the group payoff becomes smaller. Thus, the efficiency loss of the closed-loop solution decreases as the game iterates more when water is scarce. Eventually, the efficiency loss of the closed-loop solution in water scarcity will come very close to the efficiency loss of the closed-loop solution in water abundance.

Individuals who possess foresight can do much better than predictions based on the one-shot PD game expect under some circumstance, even though they may not fully achieve the socially optimal outcome. In other words, predictions based on one-shot PD game understate the possibility of successful collective action without external help. If individuals behave as the closed-loop solution prescribes, it is likely that individuals will voluntarily contribute to collective action, not from altruistic motivations, but from pure, individually rational motivations.

Chapter 7

Effects of Engineering Works

The types of policy interventions that have dominated the development literature related to agricultural policy have been making financial investments in irrigation infrastructure. The presumption has been that primitive engineering works stifle agricultural productivity. Instead of the cement lined canals and the permanent gates that characterize irrigation system in developed countries, farmers in many developing countries rely on irrigation systems that are unlined and use a combination of mud, sticks, and stones to divert water rather than permanent headworks. In this Chapter, I explore the impact of changes in engineering works on outcomes. I modify the initial parameter configurations discussed in Chapters 5 and 6 to represent different types of physical changes in the way an irrigation system operates.

There are a number of different physical attributes that could be explored. The length of canal from water source to headenders' water gate (1), for example, can affect the outcomes of this game. As the length of the canal from the water source to the headenders' water gate gets longer, the amount of water at the headenders' field gate diminishes. This water loss affects the payoffs and the optimal amounts of appropriation. The topography of an irrigation system also influences the outcomes of this game by changing the values of the sensitivity of reliability to maintenance (α), the sensitivity of efficiency to maintenance (8), the minimum requirement coefficient for reliability (γ), and the minimum requirement coefficient for efficiency (γ"). As the topography of an irrigation system flattens, it becomes easier to get irrigation water to the tailender and easier to maintain the system.

In this Chapter, however, the effects of changes in these kinds of parameters on the game will not be considered because these parameters cannot be easily manipulated. The length of the canal and the topography are conditions that affect performance, not policy tools. Despite the fact that an irrigation system with shorter canal can perform better than an irrigation system with longer canal when all the other parameters are held constant, the length of a canal depends on the distance between the water source and the fields. This distance is often not under farmers' control. These physical attributes, in other words, are exogenous factors that frame the action arena in which appropriators interact. For this reason, I examine the only physical attributes that are the engineering works, which are the headworks and the lining. These physical attributes can be, and have been, policy tools in efforts to improve performance of irrigation systems.

Improvements in Engineering Works : Headworks and Lining

The permanence of headworks and the lining of canals have been considered important physical attributes that affect the performance of an irrigation system. The headworks of an irrigation system refers to an "intake point" where water moves from a water source into an irrigation system. The headworks of a system are therefore a "production resource of the irrigation system...[that makes] water available at locations and times when it does not naturally occur in the form of precipitation and immediate runoff" (Tang 1992, 38). Appropriators can construct headworks each year from local materials such as mud. Such headworks are **temporary** and require construction or substantial repair each year. Headworks can instead be built out of rocks set in concrete or in containers made of gabion wire and have permanent gates (Shivakoti et al. 1992). Such headworks are relatively **permanent;** they last longer without a considerable amount of repair. Irrigation systems with permanent headworks have been regarded as better able to perform than irrigation systems with temporary headworks because the permanent headworks last longer with less maintenance. Thus, one of major tools of governmental intervention has been an effort to make headworks more permanent. In the NIIS date base,[1] for example, 78 percent of the AMIS (Agency Managed Irrigation System) contain permanent headworks whereas only 28 percent of the FMIS (Farmer Managed Irrigation System) possess permanent headworks (Shivakoti et al. 1992). These statistics imply that constructing better headworks has been one of major policy tools in Nepal.

Canal linings also affect the performance of an irrigation system. The canals of an irrigation system are the "distribution resource."[2] The canals require repair and cleaning to prevent the accumulation of silt and the breakdown of the canal walls problems, which tend to reduce water delivery efficiency of canals. It is often presumed that an irrigation system with completely lined canals performs better than systems without them because lined canals lose less water. It also costs less to maintain irrigation systems with completely lined canals than irrigation systems without them. Consequently, lining has also been used as one of major policy tools of governmental intervention. All of the AMIS systems in the NIIS data base, for example, are at least partially lined, whereas 40 percent of FMIS systems are not lined at all (Shivakoti et al. 1992), which suggests that lining canals has been a major policy tool.

Improvements in engineering works are analytically continuous parameters. We can conceptualize a continuum that represents the degree

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[1] NIIS data base refers to the Nepal Irrigation Institutions and System data base that contains information about 127 irrigation systems in Nepal. Colleagues associated with the Workshop in Political Theory and Policy Analysis at Indiana University construct NIIS data base by developing a series of structured coding and extracting information from the written records. For more detail, see E.Ostrom, Benjamin, and Shivakoti 1992.

[2] Smaller canals also can be classified as an "appropriation resource." These smaller canals, however, are not considered in this study.

of permanence of headworks or the proportion of lined canals. An irrigation system can have completely permanent headworks that lasts forever without any maintenance. Another irrigation system can have completely temporary headworks that lasts only one season, even with maintenance work. Still another irrigation system can have an headworks that is a "in-between", headwork that lasts several seasons with proper maintenance. Similarly, canals of an irrigation system can also be completely lined, partially lined, or not lined at all.

Imagine an irrigation system with completely permanent headworks and completely lined canals, built so perfectly that no damage can be done to them. The physical conditions of this system (i.e., reliability of water supply and water delivery efficiency) remain unchanged no matter how much water appropriators extract and how much appropriators invest in maintenance. The physical conditions of an irrigation system become less and less sensitive to appropriation and maintenance as the engineering work improves.

As the permanence of the headworks and the proportion of lined canals decrease, the physical conditions of an irrigation system become more sensitive to maintenance works and to the appropriation behavior. As the permanence of the headworks and the proportion of lined canals decrease, the system requires additional amounts of maintenance and less water appropriation to preserve its present levels of physical conditions.

Improvement in engineering works also affects the values of other parameters representing the initial levels of physical conditions. For example, if the headworks of an irrigation system improve, the initial value of the reliability of water supply (R_1) , and the amount of water at the source (Q^s) increase. Similarly, the initial value of water delivery efficiency (E_1) increases when the lining of canals improves. These improvements in engineering works that change the initial values of physical conditions are more comprehensive than the improvements that can change only the sensitivity of physical conditions to appropriation and maintenance works.

We can classify two kinds of improvements in engineering works: (i) those that change only the parameters that represent sensitivities of physical conditions to appropriation and maintenance; and (ii) those that change the parameters representing the initial levels of physical conditions of an irrigation system as well as the parameters representing sensitivities of physical conditions to appropriation and maintenance. We call the former **"partial improvement"** and the latter **"full improvement".** The effects of these two kinds of improvement projects differ from each other.

In this game, participants do not pay for improvements in engineering works; The improvements are exogenous and they represent the type of exogenous changes that result from donor grants or donor loans that are allocated to individual irrigation systems in which the donor makes no effort to collect any money. The analysis, then, does not consider the costs of improvements.

Improvements in engineering works vary in regard to whether they are made (i) only in the headworks; (ii) only in the lining; or (iii) both in the headworks and in the lining. In sum, we have six possible types of improvements in engineering works:

(1) Type 1 : Partial Improvement in Headworks Only;
(2) Type 2 : Full Improvement in Headworks Only;
(3) Type 3 : Partial Improvement in Lining Only;
(4) Type 4 : Full Improvement in Lining Only;
(5) Type 5 : Partial Improvement in Headworks and Lining; and
(6) Type 6 : Full Improvement in Headworks and Lining.

In the following sections, I operationalize these six types and examine their effects on the outcomes of the game.

Operationalization of Improvements in Engineering Works

Parameters Representing Improvement in Headworks and Lining

We can represent improvements in headworks and lining through using the parameters that represent initial levels of physical conditions and sensitivities of physical conditions to appropriation and maintenance. The parameter for the amount of water at the source (Q^s), the initial value of the reliability of water supply (R_1), and the initial value of water delivery efficiency (E_1) portray the initial physical conditions of an irrigation system. As the permanence of the headworks increases, the amount of water at the source (Q^s) and the initial value of the reliability of water supply (R_1) increase. The improved headworks make more water available to an irrigation system and make the water supply more reliable. The initial value of water delivery efficiency (E_1) increases as the lined proportion of canals increases. Efficiency increases because less water is lost in the stretch of the canals. Note that only **"full improvements"** change the values of these parameters.

Eight parameters represent sensitivities of the physical conditions of an irrigation system. They are: the sensitivity of reliability to maintenance (a); the sensitivity of reliability to appropriation (α'); the sensitivity of efficiency to maintenance (θ); the sensitivity of efficiency to appropriation (θ'); the minimum requirement coefficient of maintenance for reliability (γ); the maximum allowance coefficient of appropriation for reliability (Γ'); the minimum requirement coefficient of maintenance for efficiency (γ''); and the maximum allowance coefficient of appropriation for efficiency (γ''').

"Partial improvements" and **"full improvements"** in engineering works affect these parameters. As the headworks of an irrigation system improve, the sensitivity of reliability to maintenance (a), the sensitivity of reliability to appropriation (α'), and the minimum requirement coefficient of maintenance for reliability (γ) decrease. As headworks improve, the reliability of water supply becomes less sensitive to appropriation and maintenance. In other words, more water can be appropriated without hurting the present level of the reliability of water supply and less investment in maintenance is required to preserve present level of the reliability of water supply. The maximum allowance coefficient of appropriation for reliability (γ') increases as the headworks improve; as headworks improved more water can be used without damaging the status quo level of reliability. Note that improvements in headworks do not affect the parameters for water delivery efficiency; the headworks ar solely a production resource and has nothing to do with the water delivery efficiency.

Improvements in lining affect parameters for both reliability of water supply and water delivery efficiency. Water delivery efficiency becomes more sensitive to both appropriation and maintenance as the proportion of lined canals decreases. Thus, as the lining improves, the sensitivity of efficiency to maintenance (θ), the sensitivity of efficiency to appropriation (θ')/ and the minimum requirement coefficient of maintenance for efficiency (γ'') become smaller. The maximum allowance coefficient of appropriation for reliability (γ') becomes larger as the lining improves. In addition, the stretch of canals loses less water as the lining of canals improves. The water loss coefficient (a), thus, decreases as the lining improves.

Expansion of the lined proportion of the canals can also possibly reduce the sensitivity of the reliability of water supply to appropriation and to maintenance. With better lining, the level of the reliability of water supply can be less sensitive to appropriation and maintenance because the better lining reduces the chances of water disappearing unexpectedly in the stretch of canals, which makes the supply of water more reliable. Again, the sensitivity of reliability to maintenance (α), the sensitivity of reliability to appropriation (α'), and the minimum requirement coefficient of maintenance for reliability (γ) decrease as the lining of an irrigation system improves. The maximum allowance coefficient of appropriation for reliability (γ')

increases as the lining improves.

Table 7.1 summarizes the changes that improvements in headworks and lining make in the parameters of this model.[3] In this Table, " + " denotes the cases in which improvements in the headworks and/or in the lining generate a larger value for the parameter whereas "-" refers to the cases in which improvements in the headworks and/or in the lining lead to a smaller value of parameter. "0" denotes the cases in which no relationship exists. As mentioned before, more parameters are involved in full improvements than in partial improvements. The amount of water at the source (Q^s) and the initial value of reliability (R_1) are included in full improvement in headwork, and initial value of efficiency (E_1) is included in full improvement in lining, whereas they are not included in partial improvements in both headworks and lining.

Index of Improvements in Engineering Works

We can portray improvements in headworks by changing the values of six parameters and improvements in canal lining by changing the values of eleven parameters. In this study, we assume that improvements in engineering works change the values of all of the relevant parameters at the same time. A partial improvement in lining, for example, changes the values of nine parameters (those marked by "+" or "-" in Table 7.1) simultaneously.

To depict the six types of improvements in engineering works and to analyze the effects of these improvements on the outcomes of this game, I construct an index of improvement in engineering works. I assign ten different values to each parameters. When the parameters have a positive relationship with improvement, the parameters move to a higher value. When the parameters have a negative relationship with

[3] Other parameters, such as the coefficient of interdependence between headender and tailender (6), the appropriation cost coefficient (e), can also be affected by improvements in engineering works. They are excluded here because their effects on the outcomes of this game are insignificant.

Table 7.1: Parameters Representing Improvements in Engineering Works

Parameters		Headwork		Lining		H & L	
Symbols	Descriptions	F	P	F	P	F	P
Q^s	Amount of water at the source	+	0	0	0	+	0
R_1	Initial value of reliability	+	0	0	0	+	0
E_1	Initial value of efficiency	0	0	+	0	+	0
α	Sensitivity of reliability to maintenance	-	-	-	-	-	-
α'	Sensitivity of reliability to appropriation	-	-	-	-	-	-
θ	Sensitivity of efficiency to maintenance	0	0	-	-	-	-
θ'	Sensitivity of efficiency to appropriation	0	0	-	-	-	-
γ	Minimum requirement coefficient of maintenance for reliability	-	-	-	-	-	-
γ'	Maximum allowance coefficient of appropriation for reliability	+	+	+	+	+	+
γ''	Minimum requirement coefficient of maintenance for efficiency	0	0	-	-	-	-
γ'''	Maximum allowance coefficient of appropriation for efficiency	0	0	+	+	+	+
a	Water loss coefficient	0	0	-	-	-	-

Key

H & L : headworks and lining
F : full improvement
P : partial improvement
+ : positive relationship
- : negative relationship
0 : null relationship

improvement, the parameters change to a lower value. Table 7.2 lists the ten values of each of the parameters when water is sufficient.[4]

This process yields six indexes, one for each of the six types of improvements in engineering works. A full improvement only in headworks with a score of 1, for example, can be coded as the case in which all of the six relevant parameters are assigned their first values -- the smallest values when they have a positive relationship with improvement and the largest values when they have a negative relationship with improvement. When all of the six relevant parameters are assigned their last values due to the full improvement, that improvement will have a score of 10.

By varying these ten values of relevant parameters while keeping the other parameters at their base line parameter configuration values, we obtain ten different parameter configurations. These ten parameter configurations, then, represent ten irrigation systems with different levels of improvements in engineering work. Examining differences in the outcomes of these ten different parameter configurations allows us to analyze the effect of each type of improvement in engineering work. In the next section, I examine how improvement in engineering work affects the outcome of this game when water is sufficient. Later sections, then, I examine the effects of improvements in engineering work in cases where water is not sufficient.

Effects of Improvements in Engineering Works When Water is Sufficient

This section analyzes the effects of six types of improvements in engineering works on the outcomes of this game when water is sufficient,

[4] These ten values for each parameter are chosen in the neighborhood of the values used in the base line parameter configuration in order to keep the outcomes of this game in a meaningful range. By changing Q^s further, we can also have water shortage cases. Q^s values for water shortages cases are shown in footnote 9 later in this Chapter.

Table 7.2: Parameter Values Used in Indexes

Parameters	1	2	3	4	5	6	7	8	9	10
Q^s	298.5	299.0	299.5	300.0	300.5	301.0	301.5	302.0	302.5	303.0
R_1	.34	.38	.42	.46	.5	.54	.58	.62	.66	.7
E_1	.54	.58	.62	.66	.7	.74	.78	.82	.86	.9
α	.0185	.017	.0155	.014	.0125	.011	.0095	.008	.0065	.0025
α'	.00925	.0085	.00775	.007	.00625	.0055	.00475	.004	.00325	.0025
θ	.0185	.017	.0155	.014	.0125	.011	.0095	.008	.0065	.0025
θ'	.00925	.0085	.00775	.007	.00625	.0055	.00475	.004	.00325	.0025
γ	6.6	6.2	5.8	5.4	5.0	4.6	4.2	3.8	3.4	3.0
γ'	6.4	6.8	7.2	7.6	8.0	8.4	8.8	9.2	9.6	10.0
γ''	6.6	6.2	5.8	5.4	5.0	4.6	4.2	3.8	3.4	3.0
γ'''	6.4	6.8	7.2	7.6	8.0	8.4	8.8	9.2	9.6	10.0
a	.66	.62	.58	.54	.5	.46	.42	.38	.34	.3

for T=2 and for T=4. There are no significant differences between the simulations for T=2 and T=4. For this reason, the figures only report the results of when T=2.[5]

Improvement in Headworks

First, let us consider the improvement only in headworks (a Type 1 or Type 2 improvement). Improvement Type 1 refers to a partial improvement in headworks; Improvement Type 2 refers to a full improvement in headworks. Improvement Type 1 creates changes in four parameters while Improvement Type 2 changes six parameters are changed.[6] The effects of these two types of improvements differ as shown in Figure 7.1 and Figure 7.2.

Figure 7.1(a) shows the relationship between partial improvement in headworks and the group payoffs when T=2. Note that a partial improvement in headworks does not always enhance the performance of an irrigation system as measured in terms of group payoffs. The group payoff of the closed-loop solution increase as the headworks improve up to the point where the improvement index reaches the score of 5 when T=2 (and 4 when T=4). After that point, however, the group payoff of the closed-loop solution decreases as the headworks improve. Interestingly, an irrigation system with an improvement index score of "1" performs better than irrigations systems with improvement index scores of 8 or higher. This is the case both when T=2 and when T=4.

The findings of Figure 7.1(a) imply that improvements in headworks, especially when they are partial, do not always enhance the performance of an irrigation system. As a matter of fact, when players

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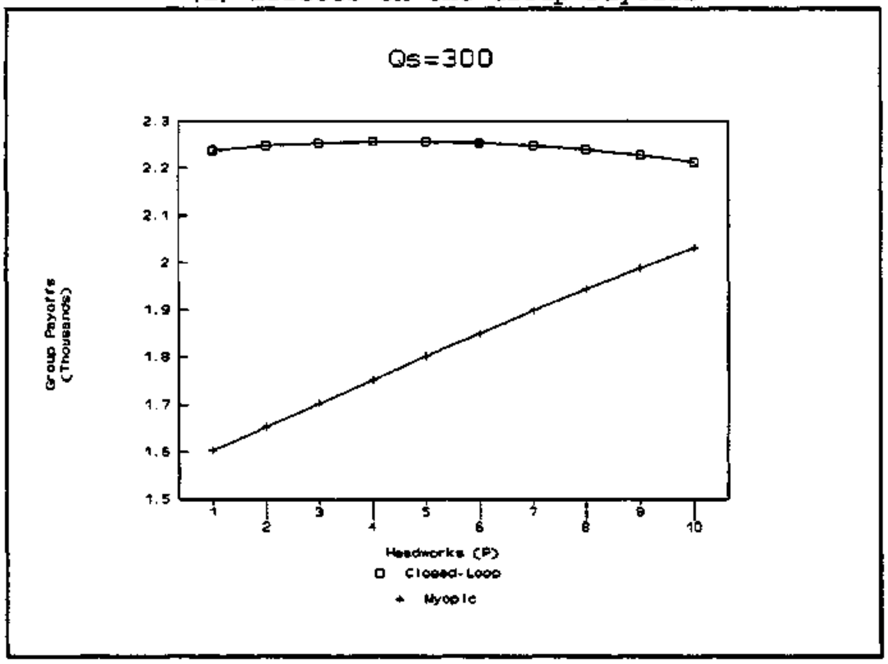
[5] This is also the case when water is scarce.

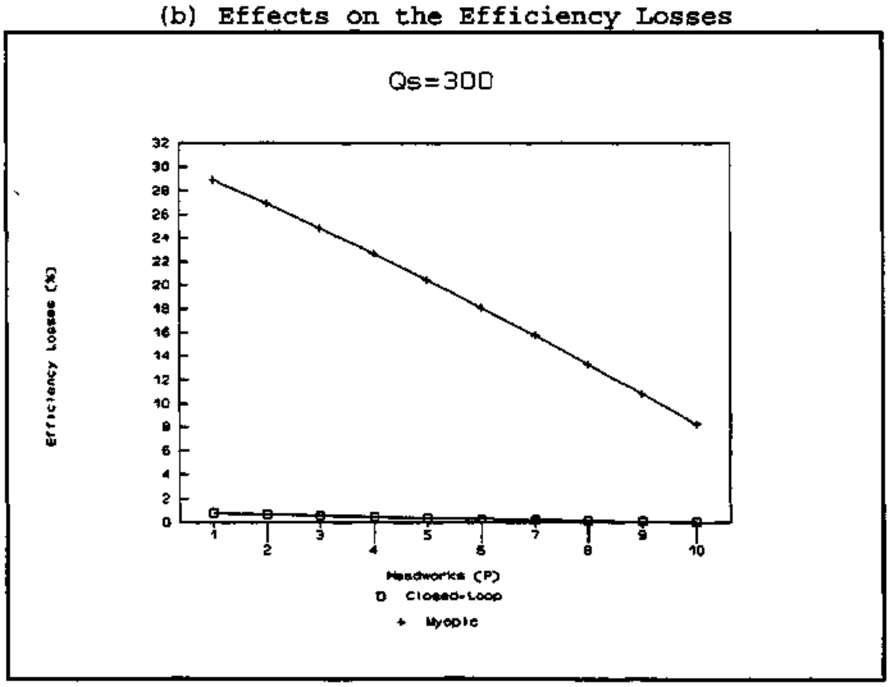
[6] See Table 7.1 for the names of the parameters affected here. Note that when water is sufficient, changes in the amount of water at the source (Q^S) do not change the outcome of this game. Therefore, full improvement in headworks can be represented by five parameters by excluding the amount of water at the source. This is not the case when water is not sufficient.

Figure 7.1: Effects of Partial Improvement in Headworks When Water is Sufficient

(a) Effects on the Group Payoffs



(b) Effects on the Efficiency Losses



behave as the closed-loop solution prescribes, a partial improvement in headworks can even reduce the performance of an irrigation system. Making the physical conditions of an irrigation system less sensitive to appropriation and maintenance does not always guarantee better performance. As the physical conditions of an irrigation system become less and less sensitive to appropriation and maintenance, they also become more and more difficult to improve.

As the physical conditions become less sensitive, more water can be appropriated without damaging the level of the physical conditions (i.e., the optimal amount of appropriation increases). Yet the optimal amount of investment in maintenance always equals the maximum that appropriators can afford when water is sufficient. Accordingly, the level of the physical conditions in the remaining rounds begin to deteriorate when the negative effect of an increased amount of appropriation cannot be canceled out by a positive effect of an investment in maintenance because investment in maintenance is fixed at the maximum that appropriators can afford. This deterioration occurs when the improvement index has a score of 5 when T=2 and 4 when T=4. From this point on, payoffs for both the headender and the tailender begin to decrease, as engineering works improve.

The group payoff of the closed-loop solution is maximized when the improvement index score equals 5 when T=2 and 4 when T=4. Let this level of improvement be "I*". At this point, the marginal benefit of the investment in improvement equals zero. After this point, the marginal benefit of the investment in improvement becomes negative.

In the myopic solution, on the other hand, the group payoff always increases as the headworks improve. Thus, players maximize the group payoff of the myopic solution when the improvement index score equals 10 (i.e., I* = 10 in this case). Notice that the group payoffs of the myopic solution are always smaller than the group payoffs of the closed-loop solution at every stage of improvement in headworks. This suggests that even though partial improvement in headworks can enhance the performance of an irrigation system when players behave as the myopic solution predicts, we increase the group payoff much more by letting the players behave as the closed-loop solution prescribes than by improving the headworks of an irrigation system.

Imagine an irrigation system with headworks that have an improvement score of 1 and with appropriators who behave as the myopic solution prescribes. Improving the headworks of this system up to an improvement score of 10, increases the group payoff to 2031.15 units when T=2. However, letting appropriators behave as the closed-loop solution prescribes without changing the improvement index increases the group payoff to 2238.23 units, which is larger than the 2031.15 units that we can get by improving the headworks of the system.

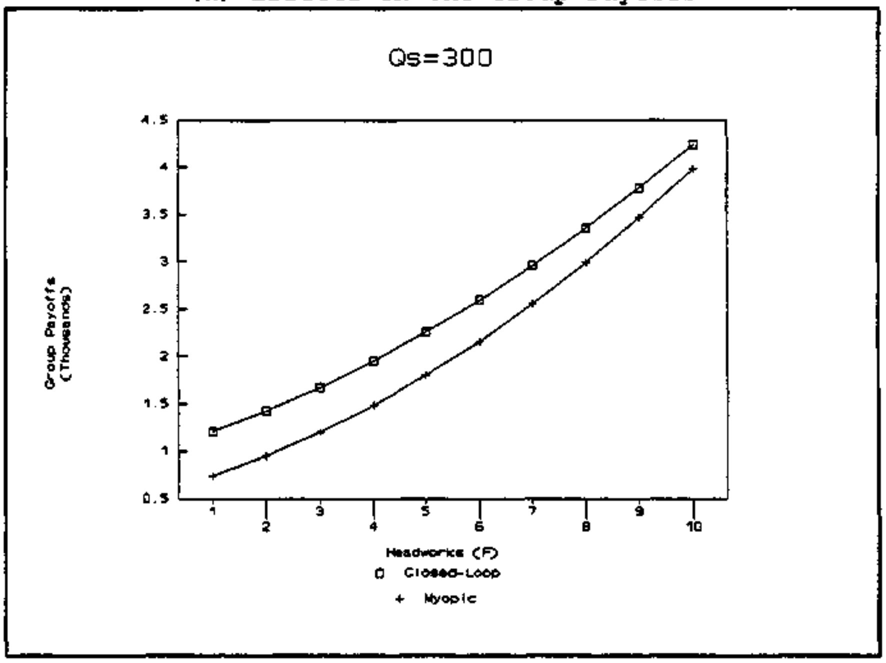
Figure 7.2(a) shows that full improvement in headworks always enhance the group payoff of the game even in the closed-loop solution. Since full improvement in headworks always increases the group payoffs of the game, I" is always 10. Full improvement in headworks is able to increase the initial value of the reliability of water supply (R_1) and the amount of water at the source (Q^S) , both of which greatly influence the size of the group payoffs, especially when water is not sufficient. As R_1 gets larger, the marginal benefit of water increases, so the optimal amount of appropriation increases.[7] By increasing the values of these two parameters, full improvement in headworks always guarantees an enhancement in the performance of an irrigation system.

Figures 7.1(b) and 7.2(b) show that improvements in headworks, partial and full, always reduce the efficiency losses in payoff. In partial improvement in headworks, the efficiency loss in payoffs is minimized when the improvement index score of reaches 10 in the closed-loop and myopic solutions. Yet, the group payoff of the closed-loop

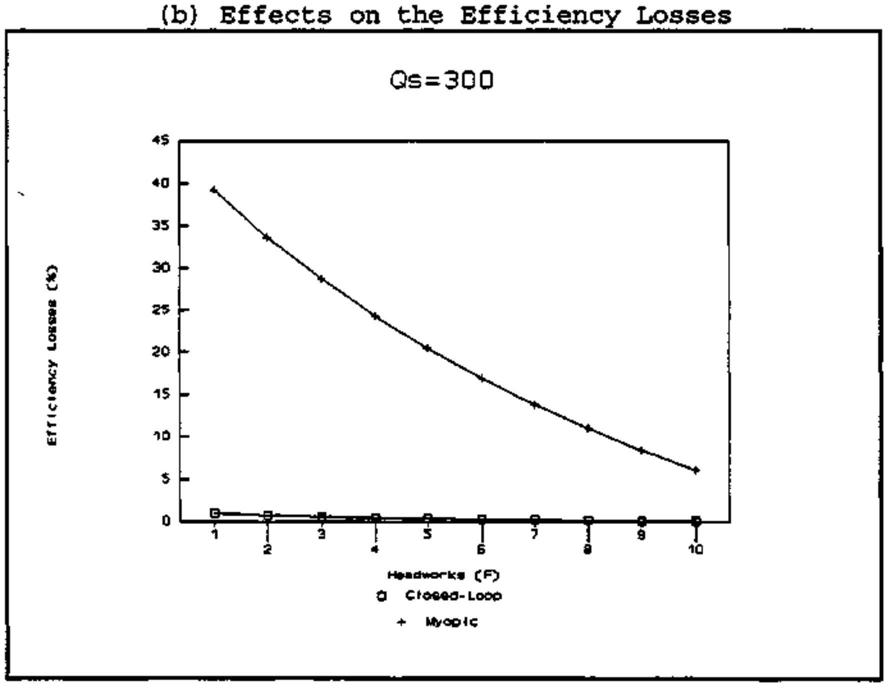
[7] For more detail, see, Figure 3.2 in Chapter 3.

Figure 7.2: Effects of Full Improvement in Headworks When Water is Sufficient

(a) Effects on the Group Payoffs



(b) Effects on the Efficiency Losses



solution is maximized when the improvement index is 5. Which of these two levels is the "optimal improvement level"?

The efficiency loss in payoff measures the ratio of outcomes that can actually be achieved to the best outcomes. Efficiency losses in payoffs can be reduced by an improvement in engineering works even when the group payoff declines. This happens when the group payoff of the social optimum solution declines to a greater extent than the group payoff of the closed-loop solution declines. For this reason, the efficiency loss in payoff is not a good measure of the effectiveness of an improvement in engineering work. The increase in the group payoff should be the guide for evaluating an improvement in engineering works. The optimal improvement level, then, should be "I"", the score that maximizes the group payoff (5 when T=2 and 4 when T=4).

Imagine that one faces a choice between two improvement projects: one that increases the group payoff and the efficiency loss in payoff; and the other which decreases both the group payoff and the efficiency loss in payoff. In this case, the former should be regarded as a better project than the latter. The crucial criterion for the improvement in engineering works is not whether or not the group payoff of individual rationality increases to a greater extent than the group payoff of social optimum solution, but whether or not the group payoff of individual rationality increases.

In summary, partial improvements in headworks always increase the group payoff of the myopic solution, but do not always increase the group payoff of the closed-loop solution. Until the improvement index reaches I", partial improvements in headworks increase the group payoff of the closed-loop solution; after that point, partial improvements in headworks decrease the group payoff. Full improvements in headworks, on the other hand, always increase the group payoff both in the closed-loop solution and in the myopic solution. Adding more iterations increases the gap between the group payoff of the closed-loop solution and the group payoff of the myopic solution, but it does not change the relationship between improvements in headworks and outcomes of this game in any meaningful way.

Improvement in Lining

When water is sufficient, the effects of full and partial improvements in lining on the outcomes of this game are identical to the effects of partial improvements in headworks. Thus, the relationships are exactly same as those shown in Figure 7.1, which implies that making the water delivery efficiency less sensitive to appropriation and maintenance is redundant when water is sufficient. The level of water delivery efficiency already exceeds the threshold value, so an additional increase in the level of water delivery efficiency cannot bring any more benefits. This suggests that improvements in lining, partial or full, do not always increase the group payoff to an irrigation system where appropriators behave as the closed-loop solution prescribes when water is sufficient. The optimal investment level (I*) will be identical to that of partial improvement in headworks. When water is not sufficient, however, improvements in lining can bring additional benefits to the system. The efficiency losses in both full and partial improvements in lining also mirror those of improvements in headworks; improvements always reduce the efficiency losses in the payoff.

Improvement in Headworks and Lining

The effects of partial improvements in headworks and lining are always identical to the effects of partial improvements in lining, no matter whether water is sufficient or not. This is because these two type of improvements are represented by the same parameter configuration. As shown in Table 7.1, both types are represented by changes in the same nine parameters.[8]

When water is sufficient, partial improvement in lining has the same effect as partial improvement in headworks, as shown in Figure 7.1. This means that partial improvement in headworks and lining always have the same I* as partial improvement in headworks. Partial improvements in headworks and lining, thus, do not always increase the group payoff even though they always reduce the efficiency loss in the closed-loop solution.

Full improvement in headworks and lining has the same impact on the outcomes of this game as full improvement in headworks only when water is sufficient. If water is already sufficient at appropriators' field gates, increases in water delivery efficiency cannot bring additional benefits. Thus, the relationship between the improvement index and the group payoffs is identical in Improvement Type 2 and Improvement Type 6. Full improvement in headworks and lining always increase the group payoffs and decrease the efficiency loss in payoffs in both the closed-loop and myopic solutions.

Summary

When appropriators behave as the closed-loop solution prescribes, only Improvement Types 2 and 6 always increase the performance of irrigation systems. When appropriators behave as prescribed by the myopic solution, all types of improvement always increase performance of irrigation systems.

When water is sufficient, improvement in lining has no appreciable effect on the outcome of this game because water is already abundant at

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[8] We can differentiate them from each other by assigning them separate sets of values which differ from that of Table 7.1. Using different sets of values in representing a certain type of improvement, though, will not change the basic pattern of relationship between the improvement and the outcomes of this game. Therefore, I use the same set of values in representing these two types, and they consequently share the same relationships.

appropriators' field gates. Making water delivery efficiency less sensitive to appropriation and maintenance has no extra effect on the outcome of this game when water is sufficient. When water is sufficient, enhancing the performance of an irrigation system is not accomplished by changing the amount of water at the source (Q^s) or the sensitivity of efficiency to appropriation and maintenance, but only by changing the sensitivity of the reliability of water supply to appropriation and maintenance.

Effects of Improvements in Engineering Works When Water is Insufficient

In the previous Chapter, I define four water scarcity cases: Water Scarcity I (Q^s=155); Water Scarcity II (Q^s=165); Water Scarcity III (Q^s=180) ; and Water Scarcity IV (Q^s=185) . These four cases were possible because all of the parameters except the amount of water at the source were held constant. In this analysis, however, we allow other variables to vary so the distinctions between the four cases no longer possible. The differences between Water Scarcity I and Water scarcity II, and the difference between Water Scarcity III and Water scarcity IV blur. Thus, I use only two of the water scarcity cases, Water Scarcity I and Water Scarcity IV in the analysis of the water scarcity cases.[9]

Improvement in Headworks

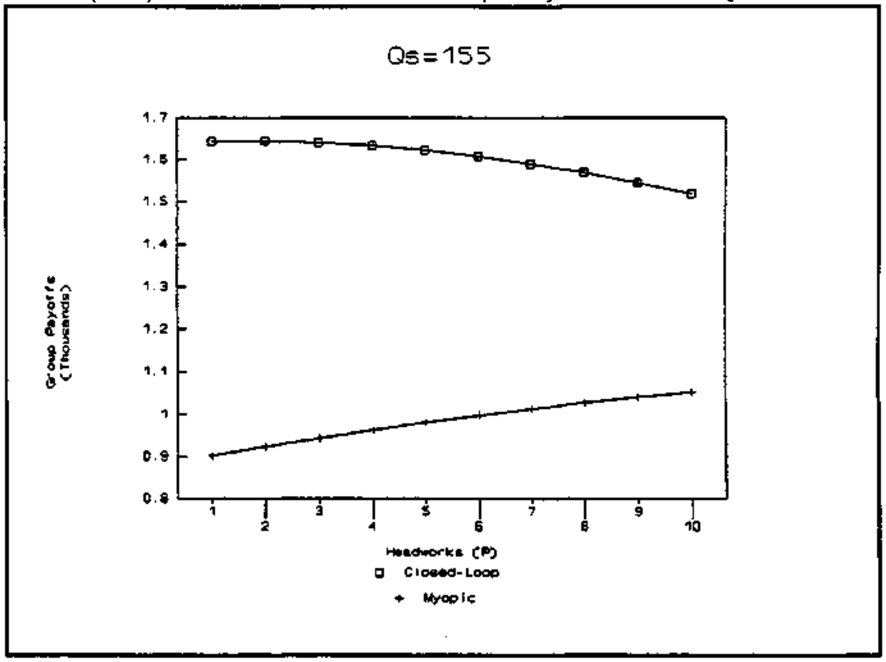
The effects of partial improvement in headworks are shown in Figure 7.3. Once again, partial improvement in headworks increases the

[9] The values for the amount of water at the source (Q^s) for the two scarcity cases are shown in the following Table.

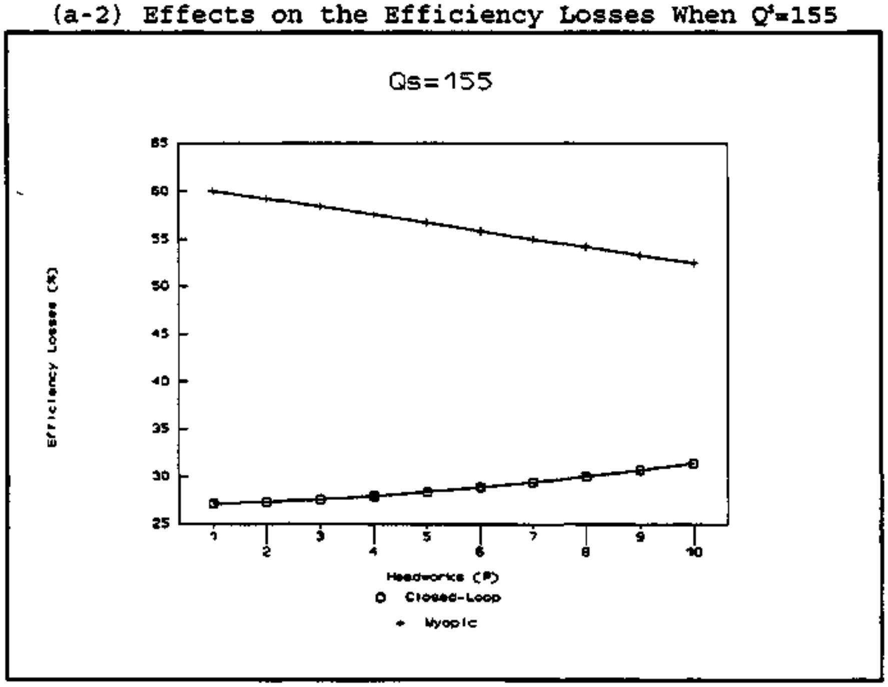
W.S	1	2	3	4	5	6	7	8	9	10
I	152.5	153	153.5	154	154.5	155	155.5	156	156.5	157
IV	182.5	183	183.5	184	184.5	185	185.5	186	186.5	187

Figure 7.3: Effects of Partial Improvement in Headworks When Water is Insufficient

(a-1) Effects on the Group Payoffs When Q^s=155



(a-2) Effects on the Efficiency Losses When Q^s=155



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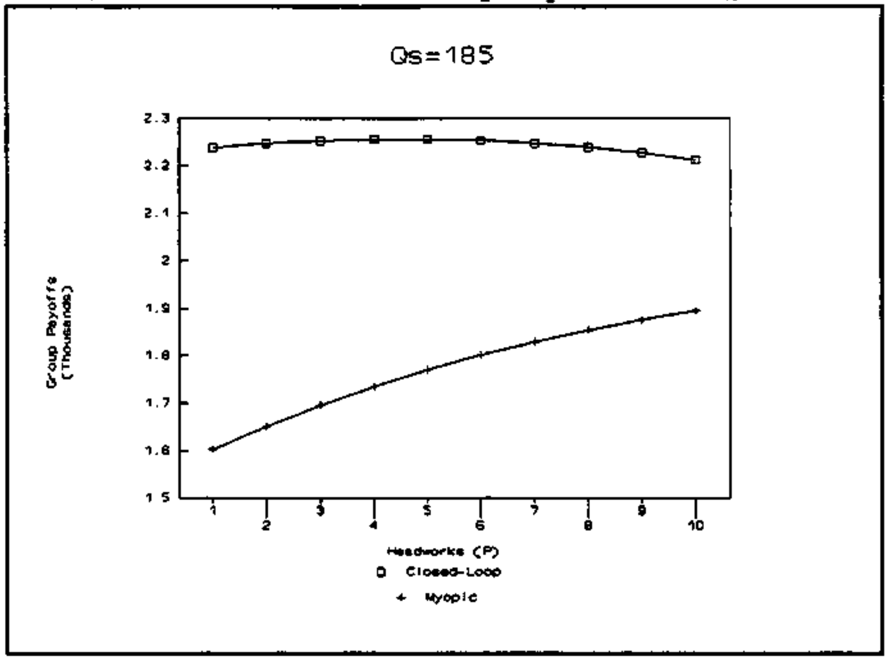
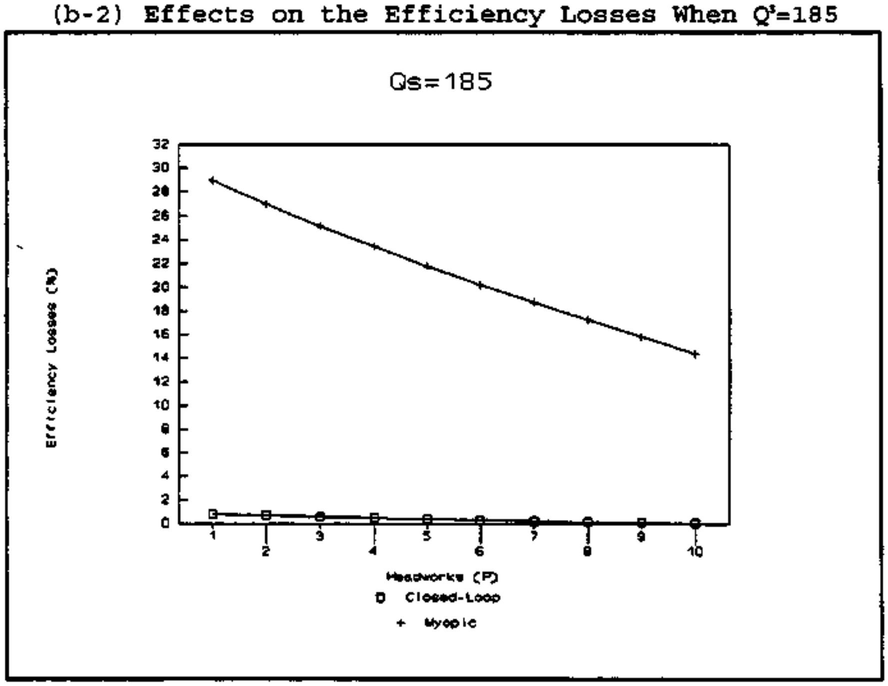
(b-1) Effects on the Group Payoffs When Q^s=185



(b-2) Effects on the Efficiency Losses When Q^s=185



group payoff of the myopic solution, but does not always increase the group payoff of the closed-loop solution. In Water Scarcity I (Q^s=155), partial improvement in headworks maximizes the group payoff of the closed-loop solution when the improvement index score equals 2, when T=2, as shown in Figure 7.3(a-1). When the improvement index is 3 or higher, partial improvement in headworks reduces the group payoff of the closed-loop solution when T=2. When T=4, the optimal improvement level (I*) becomes 3.

Contrary to the water abundance case, the efficiency loss in the payoffs of the closed-loop solution in this case are increased by the partial improvement in headworks, as shown in Figure 7.3(a-2). The optimal improvement level is not 1, however, which minimizes the efficiency loss in payoff, but I*, which maximizes the group payoff (2 when T=2, and 3 when T=4). As explained earlier, the target of improvement projects should be the maximization of group payoffs, rather than minimization of the efficiency loss.

In Water Scarcity IV (Q^s=185), the pattern of the relationships between the improvement index and the closed-loop group payoff, as well as between the index and the efficiency losses in the closed-loop payoff, become identical to those of water abundance cases because water is scarce only in the myopic solution in Water Scarcity IV. Water is not scarce any more in the closed-loop solution. In Water Scarcity I, on the other hand, water is scarce both in the closed-loop solution and in the myopic solution. Figure 7.3(b-1) shows that the group payoffs of the closed-loop solution in Water Scarcity IV are maximized when the improvement index reaches the score of 5 when T=2. The efficiency losses in payoff are, again, reduced by partial improvement in headworks both in Water Scarcity I and Water Scarcity IV (Figures 7.3(a-2) and 7.3(b-2)).

These findings implies that the optimal investment in partial improvement in headworks is larger when water is sufficient than when water is scarce. When water is scarce, it is more likely that investment in improvement type 1 can be a failure since it can easily go beyond I*, causing the improvement index to have a negative relationship with the group payoff of the closed-loop solution. When water is as scarce as in Water Scarcity I, partial improvement in headworks can be successful only at the low level of improvement in headwork, especially when T=2 .

In the closed-loop solution, water is scarce in Water Scarcity I, but not in Water Scarcity IV. In Water Scarcity IV, the optimal amount of investment in maintenance is always the maximum that appropriators can afford. As the improvement index of partial improvement in headworks gets larger, the negative effects of increasing amounts of appropriation cannot be canceled out by the positive effects of increasing amount of investment in maintenance because investment is fixed at the maximum that appropriators can afford. Consequently, the level of the physical conditions begins to deteriorate and the payoffs for both the headender and the tailender begin to decrease.

In Water Scarcity I, water is not sufficient for the tailender. Thus, the optimal amount of investment in maintenance for the tailender is less than the maximum that he/she can afford. As the improvement index of partial improvement in headworks gets larger, the optimal amount of appropriation for the headender gets larger since more water can be appropriated without hurting the level of physical conditions of the irrigation system. The optimal amounts of appropriation and investment in maintenance for the tailender, on the other hand, decrease as the improvement index of partial improvement in headworks gets larger. Water becomes more and more scarce for the tailender as the headworks improve so that the headender gets more water. Since less is invested in maintenance, the point at which the effect of the amount of appropriation cannot be canceled out by the investment in maintenance comes earlier in Water Scarcity I than in Water Scarcity IV. Therefore, I* of partial improvement in headworks is larger when water is sufficient than when water is scarce.

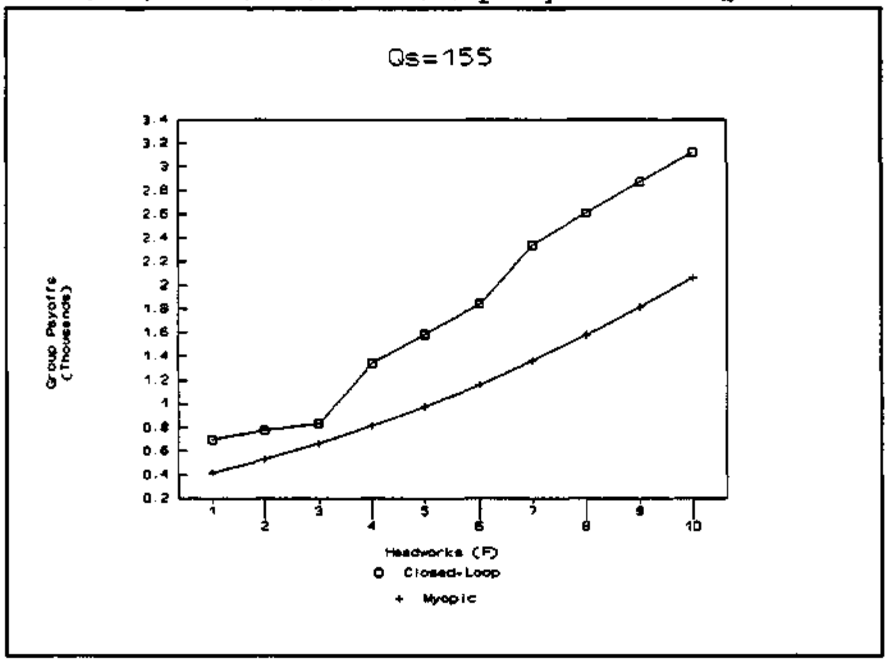
In Water Scarcity I, the payoff for the tailender always decreases as the improvement index of partial improvement in headworks gets larger, even before improvement index reaches I*. This relationship does not occur in Water Scarcity IV. A partial improvement in headworks can make tailenders worse off, while it makes headenders better off. The efficiency loss of the closed-loop solution still has a positive relationship with the improvement index.

Again, full improvement in headworks always increases the group payoffs of both the closed-loop and the myopic solutions, as shown in Figure 7.4. However, the tailender's payoffs can be worsen with full improvement in headworks, especially when water is as scarce as in Water Scarcity I. In Water Scarcity I, the payoff for the tailender decreases as headworks are improved until water becomes sufficient to entice the tailender to invest in maintenance. Contrary to the case of partial improvement in headworks, once this point has been reached, the optimal amount of investment in maintenance for the tailender increases as headworks improve; and the payoff for the tailender increases. Before this point, however, the tailender's optimal amount of investment in maintenance is zero and the payoff for the tailender has a negative relationship with the improvement index while the efficiency loss in payoff has a positive relationship with the improvement index (see Figures 7.4(a-1) and 7.4(a-2)). Note that the group payoff of the closed-loop always increases with full improvement in headworks. Thus, the optimal improvement level is I", which equals 10. The efficiency loss in payoff is also minimized when the improvement index score is 10.

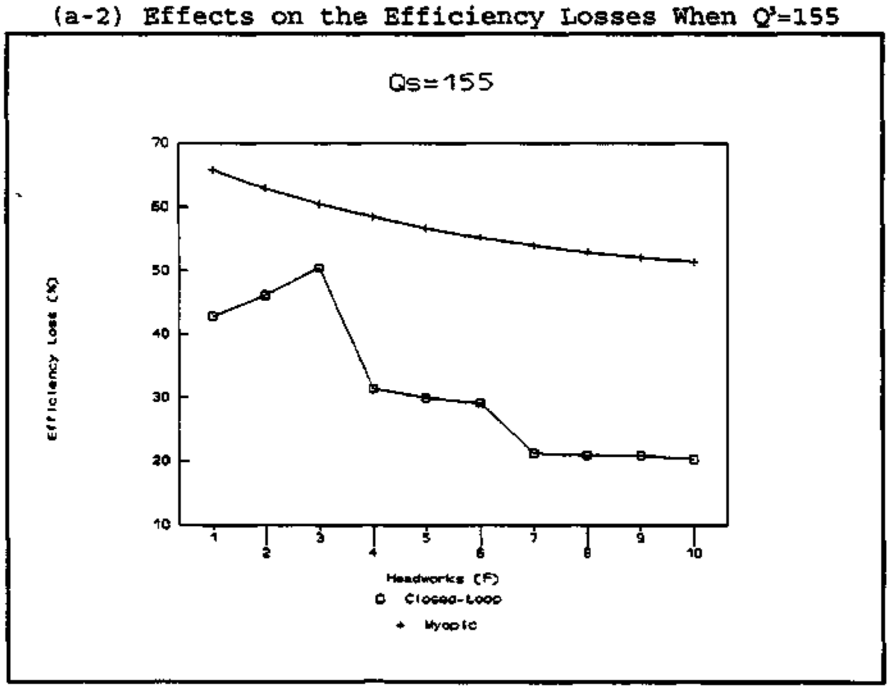
In Water Scarcity IV, full improvement in headworks always increases the group payoff and usually decreases the efficiency losses in payoff in the closed-loop solution. Occasionally, full improvement in headworks increases the efficiency loss in payoffs. The efficiency

Figure 7.4: Effects of Full Improvement in Headworks When Water is Insufficient

(a-1) Effects on the Group Payoffs When Q^s=155



(a-2) Effects on the Efficiency Losses When Q^s=155



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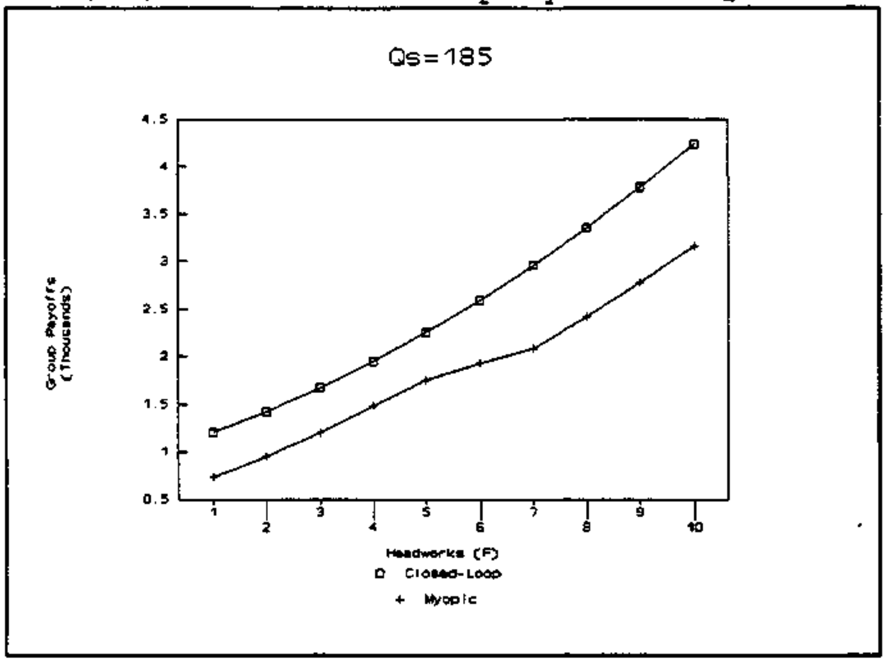
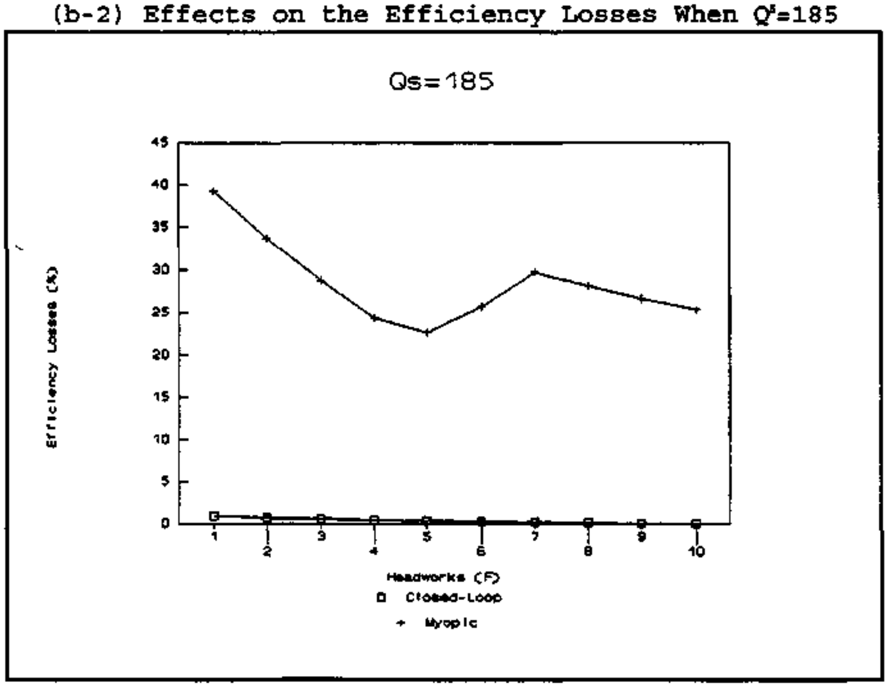
(b-1) Effects on the Group Payoffs When Q^s=185



(b-2) Effects on the Efficiency Losses When Q^s=185



loss in the payoff is minimized when the improvement index score equals 5 in the myopic solution. The optimal improvement level, however, should be "I*", as explained just earlier.

Improvement in Lining

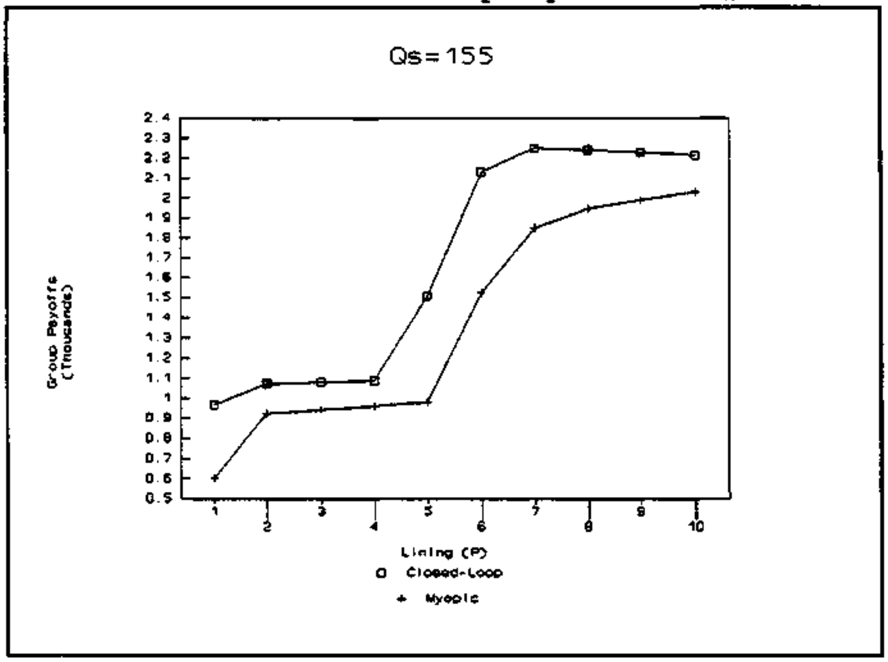
When water is sufficient, the optimal investment levels of both partial and full improvements in lining are identical to optimal investment level of partial improvement in headworks. When water is scarce, this is no longer the case because the amount of water at the appropriators' field gate is no longer abundant, so improvements in lining can bring additional benefits.

Partial improvement in lining still does not always increase the group payoff of the closed-loop solution. As shown in Figure 7.5, in Water Scarcity I, partial improvement in lining maximizes the group payoff of the closed-loop solution when the improvement index equals 7 when T=2. Note that there is a big leap in group payoffs when the improvement index score is 5. This is the point at which the tailender begins to invest in maintenance and get water at the second round. This increases marginal benefit of partial improvement in lining to a great extent in the closed-loop solution. The efficiency loss in payoff also drastically decreases at this point (Figure 7.5(a-2)). Partial improvement in lining always decreases the efficiency loss in payoff. Again the optimal improvement level in lining should be the "I*" that maximizes the group payoff, not 10 which minimizes the efficiency loss in payoff.

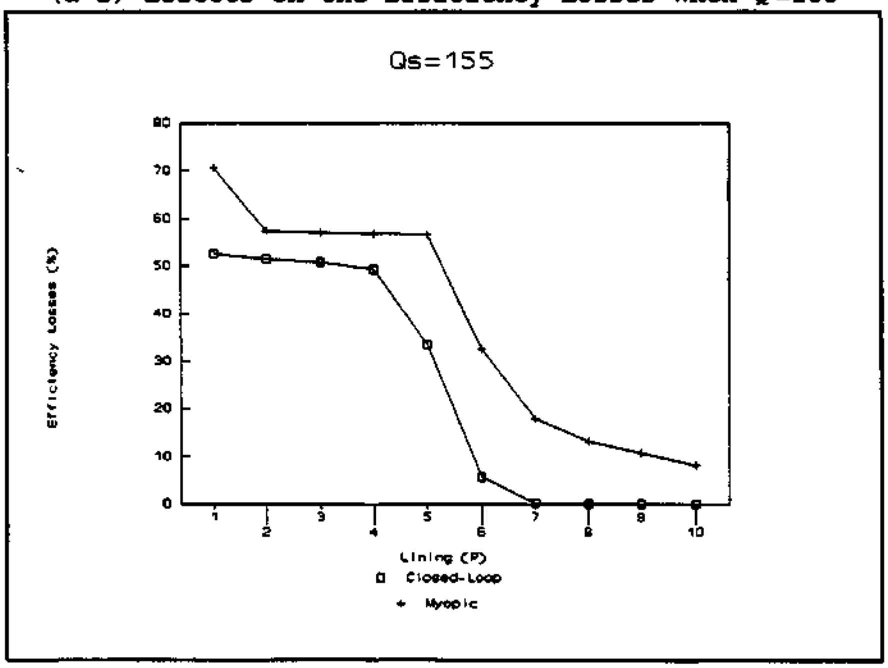
This kind of change does not happen when water is sufficient. This is why when water is scarce, we cannot find a smooth line that can be found in water abundance case. When water is sufficient, the marginal benefit of improvement tends to not change much. When water is not sufficient, on the other hand, the marginal benefit of improvement changes a great deal because the payoff for the tailender changes

Figure 7.5: Effects of Partial Improvement in Lining When Water is Insufficient

(a-1) Effects on the Group Payoffs When Q^s=155



(a-2) Effects on the Efficiency Losses When Q^s=155



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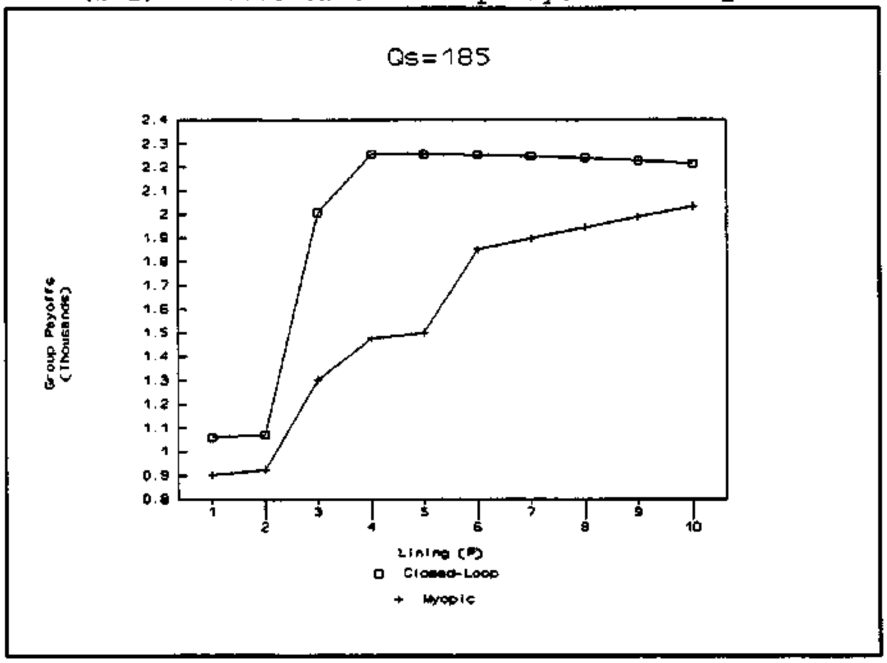
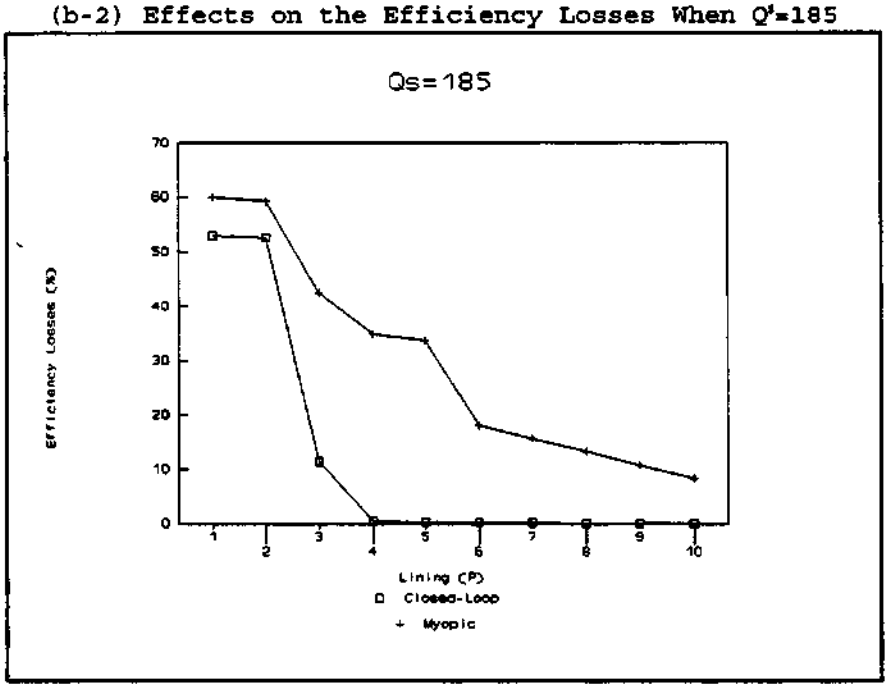
(b-1) Effects on the Group Payoffs When Q^s=185



(b-2) Effects on the Efficiency Losses When Q^s=185



drastically as the physical conditions change.

In Water Scarcity IV, partial improvement in lining affects the group payoff of the closed-loop solution in a way similar way to that in Water Scarcity I. There is a big leap when the improvement index score reaches 3 (Figure 7.5(b-l)). Partial improvement in lining always reduces the efficiency loss in payoff (7.5(b-2)). Partial improvement in lining maximizes the group payoff of the closed-loop solution when the improvement index score equals 5, when T=2.

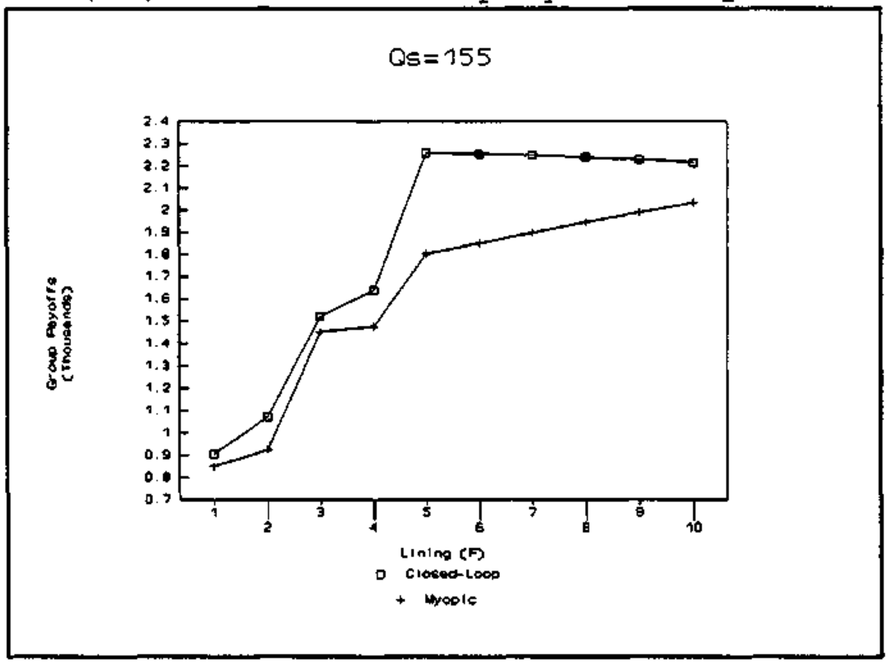
Note that the relationship between the improvement index and the group payoff of the closed-loop solution shows a big leap, it becomes identical to the relationship between the improvement index and the group payoff of the closed-loop solution of the water abundance case in both Water Scarcity I and Water Scarcity IV. After the big leap, water becomes abundant in both Water Scarcity cases in the closed-loop solution so that additional increases in the level of water delivery efficiency fail to bring additional benefits.

Full improvement in lining shows patterns similar to those for partial improvement in lining. Figure 7.6 shows the results of full improvement in lining. The optimal improvement level is 5 in both water scarcity cases. The relationship between the index and group payoffs of the closed-loop solution again shows a big leap, and after that big leap the relationship between the improvement index and the outcomes of the closed-loop solution becomes identical to that of the closed-loop solution of water abundance for both Water Scarcity I and Water Scarcity IV.

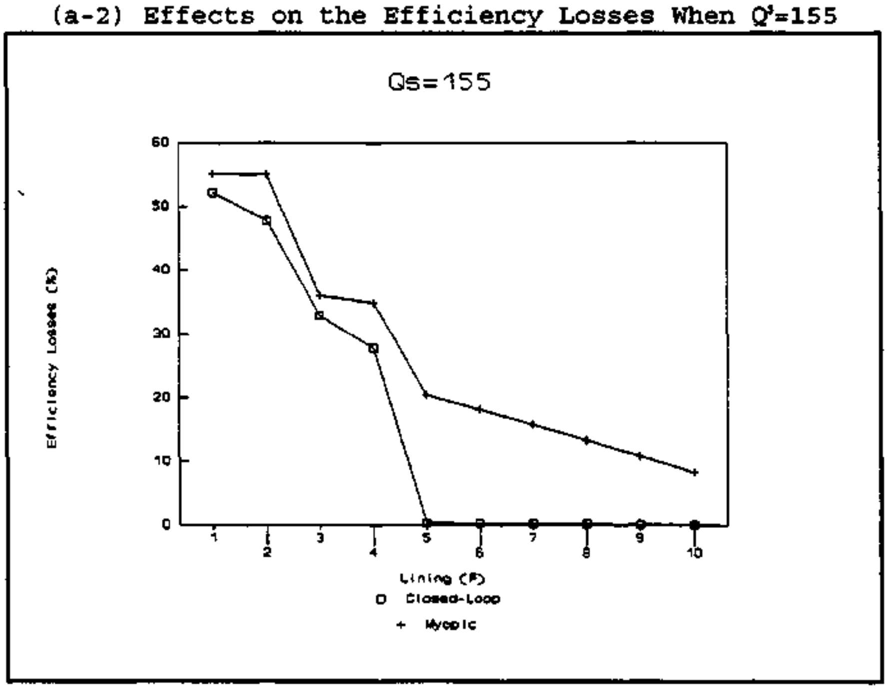
Both partial and full improvements in lining always increase the group payoff of the myopic solution. Unlike in the case of improvement in headworks, however, full improvement in lining cannot always increase the group payoff of the closed-loop solution. In the closed-loop solution, the optimal level of improvement in lining tends to be higher when water is scarce than when water is sufficient. When water is

Figure 7.6: Effects of Full Improvement in Lining When Water is Insufficient

(a-1) Effects on the Group Payoffs When Q^s=155



(a-2) Effects on the Efficiency Losses When Q^s=155



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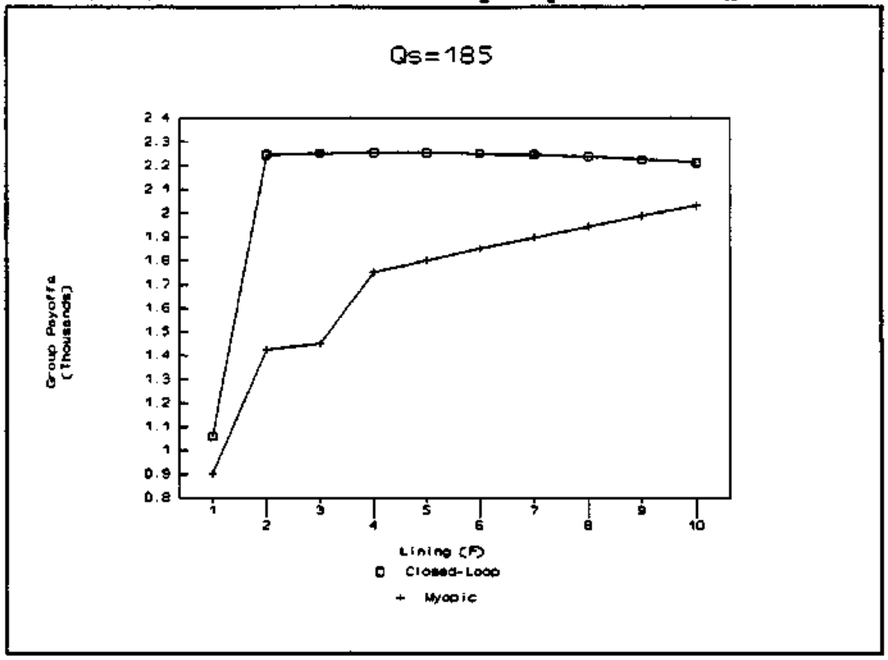
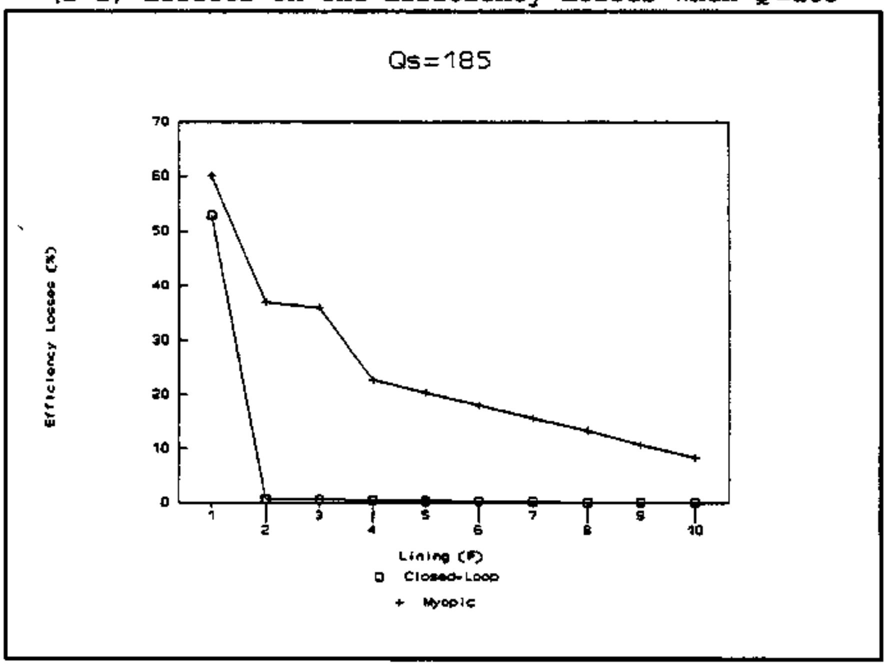
(b-1) Effects on the Group Payoffs When Q^s=185



(b-2) Effects on the Efficiency Losses When Q^s=185



sufficient, it is more likely that investments in partial improvement of lining fail because they easily exceed the optimal improvement level. When water is relatively abundant, as in the Water Scarcity IV case, the marginal benefit of full improvement in lining can be positive only at the very low levels of improvement project in lining.

The improvement index for both partial and full improvements in lining have positive relationships with the optimal amount of investment in maintenance. The optimal amount of investment in maintenance increases as lining improves. Since water becomes abundant earlier in Water Scarcity IV than in Water Scarcity I, the optimal amount of investment in maintenance reaches its upper limit earlier in Water Scarcity IV than it does in Water Scarcity I. Consequently, the point at which the positive effect of investment in maintenance on physical conditions cannot counteract the negative effect of appropriation comes earlier in Water Scarcity IV than in Water Scarcity I.[10] For this reason, I* for improvements in lining is smaller when water is sufficient than when water is scarce.

Improvement in Headworks and Lining

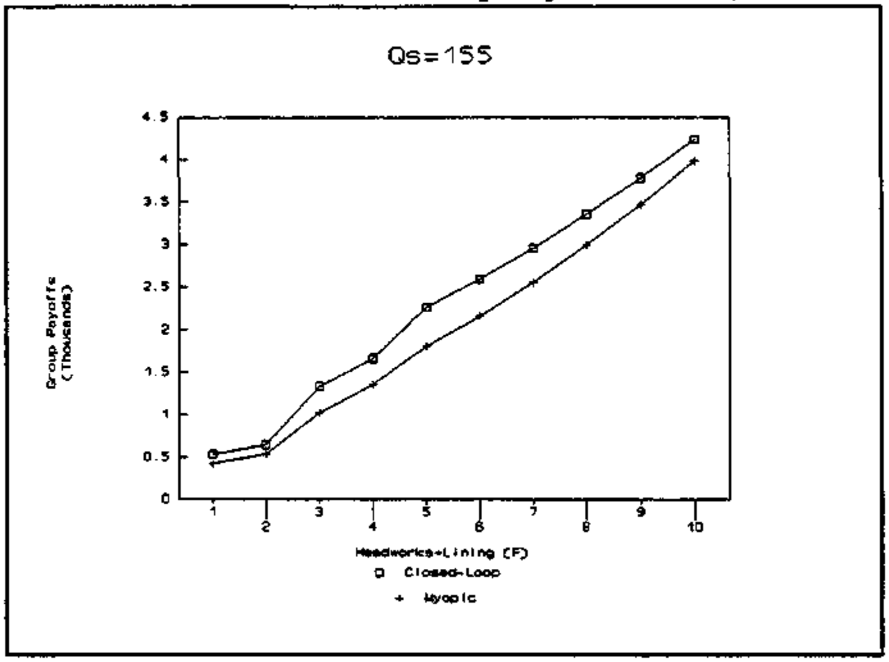
The relationships between the improvement index and the outcomes of the game in partial improvement in headworks and lining are identical to those for partial improvement in lining, as discussed earlier. This section, therefore, examines only full improvement in headworks and lining.

Figure 7.7 shows the effects of full improvement in headworks and lining. As was the case in water abundance, full improvements in

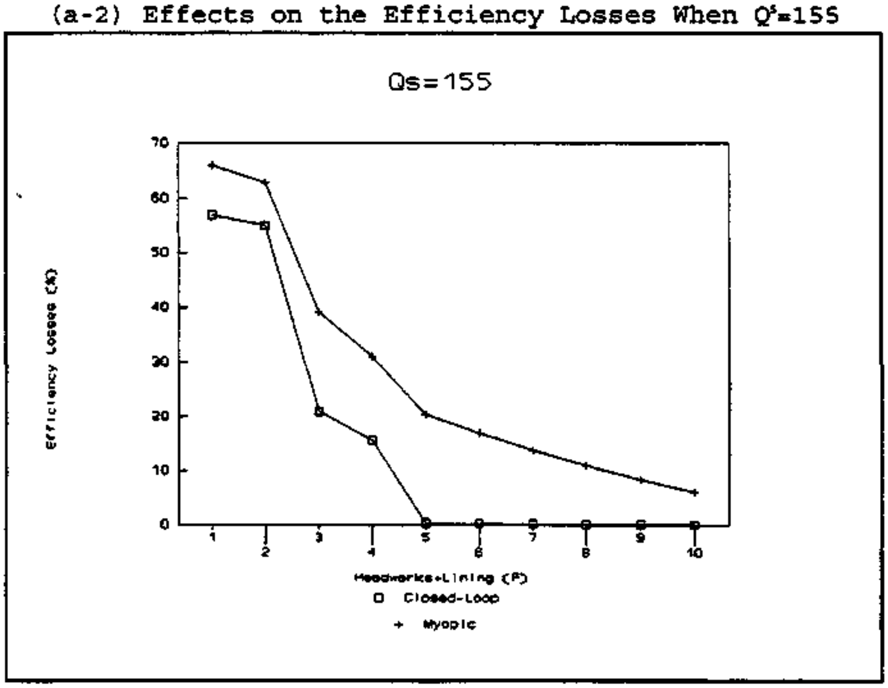
[10] Before this point, the positive effect of maintenance on physical conditions and the negative effect of appropriation on physical conditions are balanced so that physical conditions do not deteriorate. After this point, the positive effect of maintenance on physical conditions cannot cancel out the negative effect of appropriation on physical conditions, so physical conditions deteriorate. This point occurs because the amount of investment in maintenance cannot exceed the upper limit on it.

Figure 7.7: Effects of Full Improvement in Headworks and Lining When Water is Insufficient

(a-1) Effects on the Group Payoffs When Q^s=155



(a-2) Effects on the Efficiency Losses When Q^s=155



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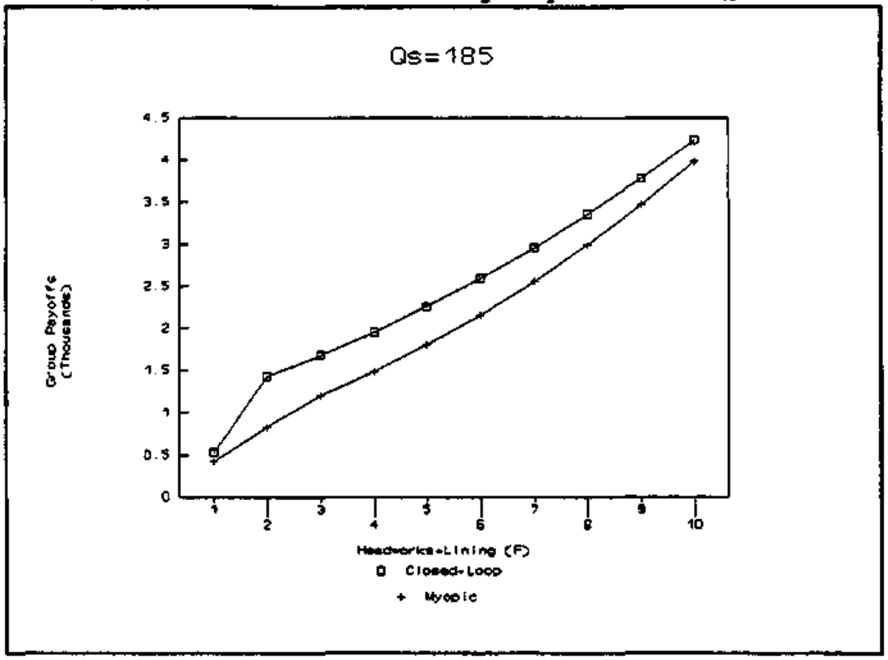
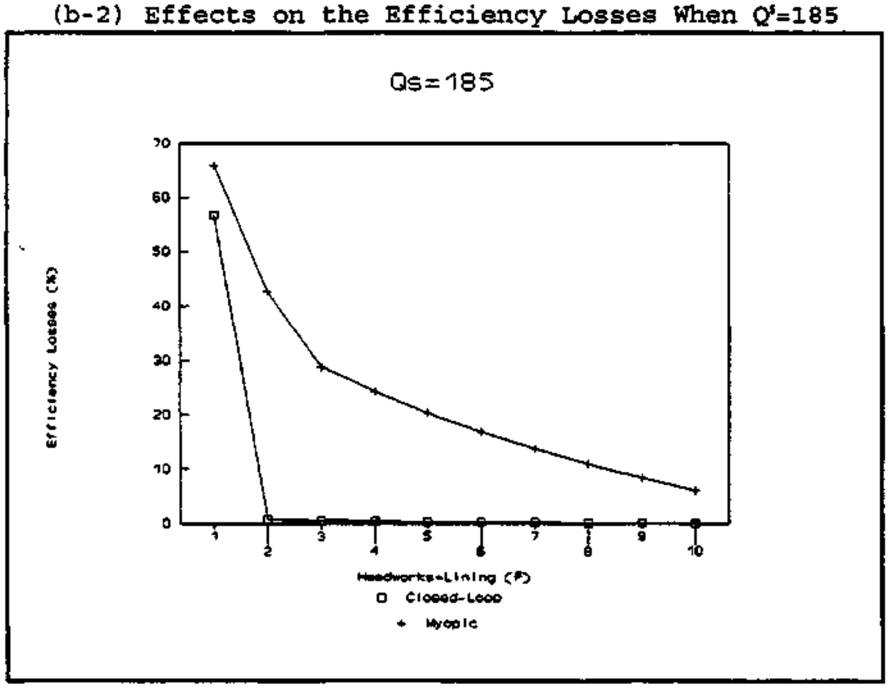
(b-1) Effects on the Group Payoffs When Q^s=185



(b-2) Effects on the Efficiency Losses When Q^s=185



headworks and lining always increase the group payoff of the closed-loop solution (Figures 7.7(a-1) and 7.7(b-l)), and always decrease the efficiency loss in payoff (Figures 7.7(a-2) and 7.7(b-2)). Unlike the water abundance case, however, full improvement in headworks and lining does not have the same impact on the outcomes of this game as does full improvement in headworks. In Water Scarcity I, full improvement in headworks and lining brings more benefits than full improvement only in headworks when the improvement index has a score of 3 or higher. The improvement in lining that makes water delivery efficiency less sensitive to appropriation and maintenance brings additional benefit from this point on. When the improvement index scores 5 or higher, the relationship between the improvement index and the outcomes of the game becomes identical to the relationship between the improvement index and the outcomes of the game in water abundance case.

In Water Scarcity IV, making water delivery efficiency less sensitive to appropriation and maintenance cannot bring any extra benefit once the improvement index reaches 2, which has the water delivery efficiency greater than or equal to 0.58.[11] After this point, water is abundant at the appropriators' field gates and improvement in lining cannot bring additional benefit. Thus, the relationship between the improvement index and the outcomes of the closed-loop solution, becomes identical to that of the water abundance case after the improvement index reaches 2.

Summary

Partial improvements in headworks, lining, and headworks and lining, and full improvement in lining, do not always increase the group payoff of the closed-loop solution when water is insufficient. When water is insufficient and water is no longer abundant at appropriators'

[11] This is the second value for the water delivery efficiency in Table 7.2.

field gates, improvement in lining has significant effects on the outcomes of this game because the additional improvement in lining brings additional benefits. A full improvement in lining, however, does not consistently increase the group payoff of the closed-loop solution. It cannot increase the amount of water at the source (Q^s) nor the initial value of the reliability of water supply (R_1), both of which play a pivotal role in determining the size of the payoffs.

Improvements in engineering works almost always reduce the efficiency loss in payoff, the exception being the three cases of improvement in headworks.[12] The efficiency loss in payoffs of the closed-loop solution is always increased by partial improvement in headworks in Water Scarcity I and increased in some range by full improvement in headworks in Water Scarcity I. The efficiency loss in payoff of the myopic solution is increased in some range by full improvement in headworks in Water Scarcity IV.

It also turns out that when water is insufficient, any kind of improvement can increase the group payoff of the myopic solution. Appropriators, who behave as the myopic solution prescribes do not invest in maintenance, so the levels of the reliability of water supply and the water delivery efficiency always deteriorate as the game repeats. Any kind of improvement increases the levels of these two state variables, and consequently increases the group payoff of the myopic solution.

Increasing the number of iterations has no significant effect on the outcomes of this game. It changes the size of the group payoffs of closed-loop and myopic solutions as well as the optimal improvement level; but does not change general patterns in the relationship between the improvement index and the outcomes of this game.

The findings in this Chapter indicate the following: (i) an

[12] See Figures 7.3(a-2), 7.4(a-2), and 7.4(b-2).

improvement project that is successful in an irrigation system with myopic appropriators can fail in an irrigation system with appropriators who behave as the closed-loop solution prescribes, even if all the other attributes of the two systems are identical; (ii) in an irrigation system with appropriators who behave as the closed-loop solution prescribes, an investment in an engineering improvement project that is successful in low levels of improvement can fail in high levels of improvement; and (iii) in an irrigation system with appropriators who behave as the closed-loop solution prescribes, an investment in an improvement project that is successful in water abundance cases, can fail in water shortage cases.

Conclusion and Policy Implications

Improving engineering works has been a major policy tool. Policy makers presume that constructing permanent headworks and fully lined canals enhances the performance of irrigation systems and increases the benefits to farmers. This Chapter shows that this presumption is justified only when appropriators behave as the myopic solution prescribes. When appropriators make decisions without foresight, investments in engineering work always increase the group payoffs.

This analysis does not consider the cost of improvement. Once costs becomes a factor, one cannot determine whether an improvement is effective or not without considering cost. It may not be efficient to make an improvement that increases the group payoff when its cost exceeds its net gain. When appropriators act without foresight, therefore, any improvement is efficient, only if costs are not too high.

An improvement cannot increase the group payoffs when appropriators make decisions by taking the future into account, just as the closed-loop solution prescribes. In the closed-loop solution case, only improvements that accompany an increase in the amount of water at the source (Q^s) and the initial value of the reliability of water supply (R_1)can guarantee increase in the group payoff. We can speculate that the costs of investment in improvement rise in a non-linear fashion as they go from partial improvements to full improvements. Given that, full improvements which do enhance the performance of irrigation systems are extremely expensive to build. Optimal improvement levels are less than 10 and vary situation by situation in improvements other than Improvement Type 1 and 2. This suggests that investing in the improvement of engineering works is not always the best policy. Spending money for improvements that produce minor results will not be an efficient solution. One can even reduce the performance of an irrigation system by improving engineering works when appropriators behave as the closed-loop solution prescribes. That kind of improvement is nothing but a waste of money no matter how small the cost.

Sometimes it is better to encourage appropriators to behave as the closed-loop solution prescribes rather than to spend resources on improving engineering works. Even though improvements in engineering works always increase the group payoff of the myopic solution, the group payoff of the myopic solution always falls short of the group payoff of the closed-loop solution. Policy alternatives that are based on the pessimistic assumption about the possibility of collective action in CPR situations and could be successful when appropriators act as the myopic solution or one-shot PD game prescribes, therefore, may reduce the performance of an irrigation system when appropriators act with foresight as the closed-loop solution prescribes.

According to Lam, Lee, and E. Ostrom (1994), irrigation systems that lack permanent headworks or even partial lining perform better than those that have permanent headworks and full lining. The results in this Chapter demonstrate that systems with permanent headworks and lining could perform worse than systems without permanent headworks and lining. These two findings seem mutually supporting. Unfortunately, we cannot determine whether the headworks and lining studied by Lam, Lee and Ostrom change the values of Q^s, R_1, and E_l; so we do not know if the improvements in headworks and ling are full or partial. Given that rivers in Nepal shift their courses drastically so that headworks cannot capture water efficiently, even if they are permanent, improvements in headworks are not likely to increase Q^s or R_1. In other words, it is reasonable to assume that building permanent headworks in Nepal more likely yields Improvement Type 1 than Improvement Type 2.

Note that even a partial improvement in headworks always increases the performance of an irrigation system if the appropriators behave as the myopic solution prescribes. If the appropriators behave as the myopic solution prescribes, systems with permanent headworks and lining should perform better than systems without permanent headworks and lining, even if the improvements are partial. Therefore, the findings of Lam, Lee, and E.Ostrom suggest that appropriators in Nepal behave as the closed-loop solution prescribes rather than as the myopic solution prescribes. In Nepal, irrigation policy, which could be successful if appropriators acted as the one-shot PD game suggests, turns out to be a failure since appropriators do not behave that way. The Nepal study, therefore, offers empirical support for the theoretical findings in this Chapter.

The findings of this Chapter imply that the degree of water scarcity is an important factor to be considered when determining irrigation policy. When water is sufficient and appropriators consider the future in decision making, investment in lining no longer seems a good policy tool; improvements in lining cannot bring extra benefits. When water is scarce, on the other hand, investment in lining could be a useful policy tool; it can bring additional benefits and its marginal benefit can be large.

In both partial and full improvements in headworks, the tailender can be made worse off by an improvement project, which makes the headender better off, especially in the early stages when water is scarce. This asymmetry does not occur when water is abundant, which means that we face equity problems more often in water scarcity cases than in water abundance cases.

The major finding of this Chapter is that the <u>same</u> intervention has different effects, depending on whether or not farmers make decisions based on estimates of the future and on whether or not water is scarce. Throughout, we have assumed that the myopic behavior solely stems from a lack of foresight. The myopic solution, however, can be the inevitable choice for rational individuals, even those with foresight when no proper institutional arrangement exists. This will be explored in the next Chapter.

Chapter 8

Effects of Institutional Arrangements and Attributes of Community

Previous Chapters examine the effects of physical attributes on the performance of irrigation systems in situations in which a minimal level of institutional arrangements exists. This Chapter shifts to analyses of the effects of institutional arrangements and attributes of the community on outcomes.

First, I examine the effect of a minimal level of institutions by comparing the results of an action situation with a minimal level of institutions to those of an action situation without it. It has been assumed so far that there exists at least a minimum level of institution that enables appropriators to have information about transformation functions and to expect iterated interactions. Given these assumptions about the action situation, the closed-loop solution has been used as a portrayal of individual rationality with foresight and the myopic solution has been treated as a depiction of individual rationality without foresight. In an action situation without a minimal level of institutional arrangements, the myopic solution can portray rational individuals with foresight, which we do in this Chapter. This allows us to examine the importance of a minimal level of institutional arrangement in an action arena.

Secondly, I examine the effect of an action situation with institutional arrangements that regulate appropriators' behavior more strictly than the minimal level of institutions. To examine the effects of a stricter institutional arrangement on the outcomes of this game, I change assumptions about the action situation to create another institutional arrangement and analyze the effect of this change on the outcomes of this game. We can portray many potential institutional arrangements by changing assumptions about the action situation. However, changing the assumptions about the action situation often completely changes the way the game is played, which means that we need an entirely different simulation program. We, therefore, cannot depict many action situations in one dissertation. For this reason, I look at only one additional action situation, one in which appropriators lose their right to water when they appropriate more than the amount that they are assigned.

Finally, I examine the impacts of attributes of community on outcomes at the end of this Chapter. The effects of the number of repetition (T), the discount parameter (to), the number of appropriators (n), and the maximum amount of investment appropriators can afford (mB_i) all reflect attributes of the community.

Effects of a Minimal Level of Institutional Arrangement

Myopic Solution as a Portrayal of Rationality in Stark Institutions

The myopic solution can be an appropriate solution concept for action situations in which players possess foresight but do not have proper institutional arrangements that enhance their capabilities.

Table 8.1: Four Possible Action Arenas and Appropriate Solution Concepts

	No Foresight	Foresight
No Institution	Action Arena I (Myopic Solution)	Action Arena II (Myopic Solution)
Institution	Action Arena III (Myopic Solution)	Action Arena IV (Closed-Loop Solution)

Table 8.1 illustrates four possible combinations of the assumptions about the existence of a minimal level of institutional arrangements and the foresightedness of individuals. Each of the four cells represents a different action arena. The bracketed entries in each cell lists the

appropriate solution concepts for the particular action arena. Notice that the closed-loop solution is only appropriate in action arena IV, where players have foresight <u>and</u> proper institutional arrangements. Even when players have foresight, they cannot use the closed-loop solution in arenas without proper institutional arrangements (action arena II). If players are assumed to have no foresight, institutional arrangements have no impact on their selection of a proper solution concept (action arenas I and III); the myopic solution is always appropriate regardless of whether institutional arrangements exist or not. Proper institutional arrangements, thus, play a pivotal role in establishing the appropriate solution concept only when players have foresight.

The finding in earlier Chapters assume that the myopic solution represents individual rationality without foresight in action situations with institutions (action arena III). The myopic solution to this game, however, can also depict a situation in which individuals have foresight <u>but</u> repeated interactions among them cannot be expected and information about transformation function is not accessible due to the lack of proper institutional arrangements (action arena II). Most of the results of the prior Chapters that compare the myopic and closed-loop solutions`can be interpreted as demonstrating the positive effects of moving from an arena of no institutional arrangements in which the only rational solution is myopic decision making to an arena with at least a minimal level of institutions, which makes closed-loop decision process a rational solution. In this section, I treat the myopic solution as a portrayal of action arena II and the closed-loop solution as a portrayal of action arena IV to examine the effects of the minimal level of institutional arrangement on outcomes of this game.

<u>Minimal Level of Institutional Arrangement</u>

Institutional arrangements are rules, which "are potentially linguistic entities that refer to prescriptions commonly known and used by a set of participants to order repetitive, interdependent relationships" (E. Ostrom 1986, 22). Several rules, such as boundary rules and information rules, are particularly important in determining whether or not a minimum level of proper institutional arrangement exists.[1] Without effective enforcement of a set of boundary rules that specify how players enter or leave positions, the closed-loop solution cannot be available as a solution to this game. Without boundary rules, the players cannot expect repeated interactions. Consequently, it becomes individually rational for them to choose actions that set a single period marginal benefit equal to a single period marginal cost.

Information rules specify the information available to each position. In order for the closed-loop solution to be available to players, information about transformation functions must be accessible. It may be extremely difficult for players to know the transformation functions in the absence of information rules that requires generating and recording of necessary information.[2]

A minimal level of institutional arrangement is, then, requires at least minimum boundary rules and information rules. According to E.Ostrom's (1990) interesting study, all robust CPR institutions share eight "design principles." They are: (1) clearly defined boundaries; (2) congruence between rules and local conditions; (3) collective choice

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[1] Position rules also play important roles in our model. Position rules enable players to choose a rational way of interacting with other players by adopting to others' rational choice. Without these rules, the action arena cannot be modelled as a game. These rules are even necessary in the myopic solution. Thus, position rules can be considered as the minimum level of institutional arrangement that is required to model the action arena as a game. These rules, however, are not important for determining proper solution concepts since these rules are necessary in both closed-loop and myopic solutions.

[2] To play the myopic solution, appropriators need to know information about a single time period game tree. Without knowing the transformation functions that map actions into intermediate outcomes in a single time period, even the myopic solution cannot be a rational solution to this game. Knowing a single time period game tree is, thus, one of presumptions of this game.

arrangements; (4) monitoring; (5) graduated sanctioning; (6) conflict resolution mechanisms; (7) a minimal recognition of rights to organize; and (8) nested enterprises. She maintains that each design principle is "an essential element or condition that helps to account for the success of [robust CPR] institutions in sustaining the CPRs and gaining the compliance of generation after generation of appropriators to the rules in use" (E.Ostrom 1990, 90).

The first design principle (clearly defined boundaries) coincides with the first component of the minimal level of institutional arrangements (boundary rules). The second component of the minimal level of institutional arrangements (information rules) appears to not fit any of the design principles. The omission of information rules probably occurs because the dynamic features of the situation are not considered. However, the fourth principle (monitoring) could refer to the existence of information rules. Monitoring requires gathering detailed information about the conditions of CPRs and the behavior of others. Detailed information about the conditions of CPRs permits appropriators to obtain information about the transformation function.

Having these rules makes the closed-loop solution available for players. In other words, minimal level of institutional arrangement makes the closed-loop solution to be available, and enhances appropriators' abilities to allocate water and maintain an irrigation system effectively.

Summary of the Effects of a Minimal Level of Institutional Arrangement

As shown in previous Chapters, the group payoff of the closed-loop solution always exceeds the group payoff of the myopic solution. A minimal level of institutional arrangements (the closed-loop solution) can make it individually rational to appropriate less and to invest in maintenance in earlier rounds, which provides more benefits to appropriators in later rounds and, consequently, more total benefits.

When water is sufficient, it is individually rational to invest nothing in maintenance in an irrigation system without a minimal level of institution (i.e., in the myopic solution). In an irrigation system with a minimal level of institution (i.e., in the closed-loop solution), it is always individually rational for appropriators to invest up to the maximum that they can afford in maintenance when water is sufficient,[3] which suggests that a minimal level of institutional arrangement alone can enhance appropriators' abilities to maintain an irrigation system effectively to a great extent in some situation.

When water is scarce, the group payoff of the closed-loop solution still always exceeds the group payoff of the myopic solution. As water gets scarcer, the gap in efficiency losses between the closed-loop solution and the myopic solution probably increases. This implies that having a minimal level of institutional arrangements reduces efficiency losses more when water is scarce than when water is abundant. However, when water is scarce, a minimal level of institutional arrangements cannot achieve the result that is possible when water is abundant.[4] Thus, we can achieve more of the socially optimal outcome when water is abundant than when water is scarce, even though we can reduce efficiency losses in payoff to a greater extent when water is scarce than when water is sufficient.

The existence of a minimal level of institutional arrangements also plays a critical role in determining the success or failure of improvement projects in engineering works, as demonstrated in Chapter 7.

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[3] When the maximum that appropriators can afford is too large, it is not rational to invest up to the maximum they can afford. For example, in our base line parameter configuration, it is not rational to invest more than 28.6, which is $mB_i^{\#}$, even though the maximum they can afford may exceed 28.6. Investing up to the maximum that they can afford is not always rational because the state transition functions of this model are linear, not continuous. This is inevitable in a "linear-quadratic game". For more detail, see Chapter 5.

[4] The efficiency losses of the closed-loop solution are 29.62% in Water Scarcity I, 9.30% in Water Scarcity II, and 0.23% when water is sufficient.

When no minimal level of institutional arrangement exists (action arena II), investments in improvement of engineering works always enhance the performance of the irrigation systems. Conversely, when a minimal level of institutional arrangement exists (action arena IV), investments in engineering works do not always enhance the performance of irrigation systems; Investments in improvement can even reduce the performance of irrigation systems. This implies that the performance of an irrigation system can be maximized at lower levels of improvements in engineering works, especially when they are partial, when a minimal level of institutions exists. An improvement project that is successful in an irrigation system without sufficient institutions (the myopic solution), therefore, could be a failure in an irrigation system with sufficient institution (the closed-loop solution).

A comparison of systems with the same level of improvements in engineering works finds that an irrigation system with a minimal level of institution always performs better than systems without a minimal level of institution. Thus, the existence of a minimal level of institutional arrangement itself can be an effective policy tool. In an irrigation system without a minimal level of institutional arrangement, we can enhance the performance of an irrigation system more effectively by crafting a minimal level of institutional arrangements than by investing in improving works.[5]

A fundamental precondition for successful collective action in a CPR is, thus, to have a minimal level of institutional arrangements that causes players to anticipate repeated interactions and that generate and record information about transformation functions. Note that authority rules -- such as allocation rules, input rules, and penalty rules -- can be at their default condition in a minimal level of institutional

[5] In Improvement Type 1 (partial improvement in headworks), for example, an irrigation system with a improvement index score of 1 and with a minimal level of institution performs better than an irrigation system with an improvement index score of 10 but without a minimal level of institutions.

arrangements required for the closed-loop solution. Appropriators are allowed to get as much water as possible and to invest as little as they want.[6] The next section examines how an alternative institutional arrangement affects the outcome of this game.

Effects of An Alternative Institutional Arrangement

A Strong Exclusion Rule

In the games explored above, appropriators can obtain and invest whatever they want as long as it is physically possible. In this section, I change the assumptions about the action situation and examine the effects of this change on the outcome. Assumptions about the actors remain unchanged. In the original game, appropriators choose any physically possible level of appropriation and of investment in maintenance in every round. In the new game, they still choose any physically possible level of appropriation and of investment in maintenance, but they lose their right to appropriate water in the next round if they obtain more water than the institutionally allowable quantity. I assume that appropriators know the socially optimal level of appropriation and set this quantity as the allowable amount of water. Appropriators now have two strategies: F (to follow the rule and get only what is socially optimal) and NF (to not follow the rule and appropriate what is individually optimal). For simplicity, I only deal with the case where T=2.

The contingency matrix of this new game is shown in Table 8.2. The column player is the headender and the row player is the tailender. The outcomes of the game are identical in the closed-loop solution and in the myopic solution when both headender and tailender choose NF (see Table 8.2 (a)); no one gets water in the second round in either

[6] Physical constraints on appropriation and maintenance exist, but there have been no institutional constraint on them so far in this analysis.

Table 8.2: The Strong Exclusion Game

(a) Water Sufficiency

	NF	F
NF	**Closed-loop** u_j: (7.73453, 0) u_k: (7.72681, 0) m_j: (0,0) m_k: (0,0) Π_{CL}: 1197.66 Π_H: 599.426 Π_T: 598.23 %Δ: 46.41% **Myopic** u_j: (7.73453, 0) u_k: (7.72681, 0) m_j: (0,0) m_k: (0,0) Π_{MY}: 1197.66 Π_H: 599.426 Π_T: 598.23 %Δ: 46.41%	**Closed-Loop** u_j: (6.71842, 7.31329) u_k: (7.72783, 0) m_j: (5,0) m_k: (0,0) Π_{CL}: 1611.2 Π_H: 1012.81 Π_T: 598.387 %Δ: 27.91% **Myopic** u_j: (6.71842, 6.53991) u_k: (7.72681, 0) m_j: (0,0) m_k: (0,0) Π_{MY}: 1530.32 Π_H: 931.929 Π_T: 598.387 %Δ: 31.53%
F	**Closed-Loop** u_j: (7.73453, 0) u_k: (6.71842, 7.31277) m_j: (0,0) m_k: (5,0) Π_{CL}: 1611.14 Π_H: 599.426 Π_T: 1011.14 %Δ: 27.91% **Myopic** u_j: (7.73453, 0) u_k: (6.71842, 6.53279) m_j: (0,0) m_k: (0,0) Π_{MY}: 1539.25 Π_H: 599.426 Π_T: 930.827 %Δ: 31.13%	**Closed-loop** u_j: (6.71842, 8.16482) u_k: (6.71842, 8.15667) m_j: (5,0) m_k: (5,0) Π_{CL}: 2234.95 Π_H: 1118.46 Π_T: 1116.49 %Δ: 0.000024% **Myopic** u_j: (6.71842, 6.61789) u_k: (6.71842, 6.61129) m_j: (0,0) m_k: (0,0) Π_{MY}: 1878.71 Π_H: 940.156 Π_T: 938.552 %Δ: 15.94%

(continued on the next page)

(b) Water Scarcity (Q^S=160)

	NF	F
F or NF	**Closed-Loop** u_j: (7.73453, 0) u_k: (2.26547, 7.65719) m_j: (0,0) m_k: (5,0) Π_{CL}: 1363.8 Π_H: 599.426 Π_T: 764.369 $\%\Delta$: 38.98% **Myopic** u_j: (7.73453, 0) u_k: (2.26547, 0) m_j: (0,0) m_k: (0,0) Π_{MY}: 898.797 Π_H: 599.426 Π_T: 299.371 $\%\Delta$: 59.95%	**Closed-Loop** u_j: (6.71842, 8.43064) u_k: (3.28158, 8.42222) m_j: (5,0) m_k: (5,0) Π_{CL}: 2117.73 Π_H: 1153.82 Π_T: 963.907 $\%\Delta$: 5.25% **Myopic** u_j: (6.71842, 8.15668) u_k: (3.28158, 0) m_j: (0,0) m_k: (0,0) Π_{MY}: 1369.23 Π_H: 968.925 Π_T: 400.301 $\%\Delta$: 38.76%

Key

u_j	: Optimal amount of appropriation for the headender (t=l, t=2)
u_k	: Optimal amount of appropriation for the tailender (t=l, t=2)
m_j	: Optimal amount of maintenance for the headender (t=l, t=2)
m_k	: Optimal amount of maintenance for the tailender (t=l, t=2)
Π_{CL}	: Group payoff for the closed-loop solution
Π_{MY}	: Group payoff for the myopic solution
Π_H	: Payoff for headender
Π_T	: Payoff for tailender
$\%\Delta$	: Efficiency loss in payoff

solution. In Table 8.2 (b), the row player has no reason to choose NF since the individually optimal amount of appropriation in the first round is smaller than the rule assigned amount. Table 8.3 shows the payoff matrix of this strong exclusion game. The first entry of each cell is the payoff for the headender and the second entry is the payoff for the tailender.

Effects of A Strong Exclusion Rule

(1) **Group Payoffs and Efficiency Losses:** In the strong exclusion game, (F,F) is always the equilibrium in all cases because F is the dominant strategy for both players. The group payoffs of this new game will be 2234.95 for the closed-loop solution and 1878.71 for the myopic solution when water is sufficient. Note that, according to Table 5.2 in Chapter 3, the group payoffs of the original game were 2229.8 for the closed-loop solution and 1866.3 for the myopic solution. When water is scarce, the group payoffs of this new game is 2117.73 for the closed-loop solution and 1369.23 for the myopic solution. The group payoff of the original game were 2027.15 for the closed-loop solution and "1278.64" for the myopic solution (see Table 6.2 in Chapter 6). The strong exclusion rule, thus, always increases the group payoffs regardless of whether water is scarce or not in both the closed-loop solution and the myopic solutions. Efficiency losses in payoffs in both closed-loop and myopic solutions are also reduced by having a strong exclusion rule.

Another interesting finding is that when water is sufficient, the payoffs for both the headender and the tailender are increased by having a strong exclusion rule. On the other hand, when water is scarce, the payoff for the headender decreases while the payoff for the tailender increases in both the closed-loop and the myopic solutions with a strong exclusion rule. As a result, the ratios of the payoff for the tailender to the payoff for the headender increase from 0.74 to 0.84

Table 8.3: Payoff Matrix of the Strong Exclusion Game

(a-1) Water Sufficiency:Closed-Loop

	NF	F
NF	(599.426, 598.23)	(1012.81, 698.387)
F	(599.426, 1011.14)	(1118.46, 1116.49) *

(a-2) Water Sufficiency:Myopic

	NF	F
NF	(599.426, 598.23)	(931.929, 598.387)
F	(599.426, 930.827)	(940.156, 938.552) *

(b-1) Water Scarcity:Closed-Loop

	NF	F
NF/F	(599.426, 764.369)	(1153.82, 963.907) *

(b-2) Water Scarcity:Myopic

	NF	F
NF/F	(599.426, 299.371)	(968.925, 400.301) *

Key

* : equilibria

in the closed-loop solution and from 0.23 to 0.41 in the myopic solution. This suggests a new strong exclusion institution may be effective in solving equity problem.

So far, we have presumed that (i) appropriators will <u>always</u> lose their right to water at the next round whenever they break the rule; and (ii) having a strong exclusion rule adds no cost. Now, let us change these assumptions, and examine their impacts on the outcomes of this game.

(2) The Effect of Less Than Perfect Enforcement (P_N) : First, let us assume that when appropriators breaking the rules, they lose their right to water with the probability of p_N, which is smaller than 1, and keep their right to water in the second round with the probability of $(1-p_N)$. The probability p_N, then, can be thought of as the effectiveness of strong exclusion rule.

When water is sufficient, less than perfect enforcement does not have any impact on the outcome of the game. In the original strong exclusion game, where $p_N=0$, the payoffs of the strategy (F,F) for both the headender and the tailender always exceeds the payoffs of the other strategies for both the headender and the tailender. Any convex combination of the payoffs of any combination of strategies other than (F,F) for both the headender and the tailender cannot be greater than the payoffs of (F,F). When water is sufficient, therefore, (F,F) is always the equilibrium of this game, irrespective of the size of p_N.

When water is scarce, on the other hand, less than perfect enforcement could impact the outcome of the strong exclusion game (see Table 8.4). The first row of each cell represents the payoff for the headender and the second row of each cell represents the payoff for the tailender. As is the case in the strong exclusion game in Table 8.3, the tailender has no reason to choose NF and the change in this game has no effect on the tailender's strategy. p_N affects the headender's strategy, however. The payoff of strategy NF exceeds the payoff of

Table 8.4: The Strong Exclusion Game with P_N Smaller Than 1 When Water is Scarce

(a) Closed-Loop

	NF	F
NF/F	P_N*599.426 + $(1-P_N)$*1164.17 P_N*764.369 + $(1-P_N)$*862.977	1153.82 963.907

(b) Myopic

	NF	F
NF/F	P_N*599.426 + $(1-P_N)$*979.271 P_N*764.369 + $(1-P_N)$*299.371	1153.82 963.907

strategy F when P_N is smaller than 0.0183 in the closed-loop solution or 0.0272 in the myopic solution. This implies that we only need a relatively very small p_N in order for (F,F) to be an equilibrium in the strong exclusion game both in the closed-loop the myopic solutions. In other words, the strong exclusion rule could induce appropriators to follow the rule even when it is enforced with a probability of as low as 0.0183 (in the closed-loop solution) or 0.0272 (in the myopic solution).

(3) Enforcement Cost (ϵ): What happens when having strong exclusion rule costs something? Let the enforcement cost (ϵ) greater than or equal to zero in the strong exclusion game. This means that ϵ refers to the cost of having a strong exclusion rule.

First, let us examine the effects of ϵ on whether the outcomes of the strong exclusion rule are socially desirable. If ϵ is too large, then the outcome of the strong exclusion game (F,F) cannot be socially desirable. When water is sufficient, the group payoff of the strong exclusion game can exceed the group payoff of the original game only if ϵ is smaller than 1.34 in the closed-loop solution or 3.45 in the myopic solution. Higher values of ϵ decreases the group payoffs as a results of a strong exclusion rule. When water is scarce, a strong exclusion rule can be desirable with a much larger ϵ; the group payoff of the strong exclusion game can exceed the group payoff of the original game when ϵ is smaller than 25.16 in both the closed-loop and the myopic solutions. In other words, a strong exclusion rule enhances the performance of an irrigation system to a much greater extent in situations with water scarcity cases than those with abundant water.

Now, let us examine the impact of ϵ on the appropriators' individual payoffs and individual optimality of a strong exclusion rule. The maximum values of ϵ that make the individual payoff of the strong exclusion game greater than the individual payoff of the original game (ϵ^*) are shown in Table 8.5. The individual payoffs of the strong exclusion game surpass the individual payoffs of the original game for both the headender and the tailender when ϵ falls short of ϵ^*. Notice that the headender needs a smaller ϵ than the tailender, and that both appropriators need a smaller ϵ in the closed-loop solution than in the myopic solution because the strong exclusion rule increases individual payoffs more when a player is a tailender and has no foresight.

Table 8.5: Maximum ϵ That Can Make the Strong Exclusion Rule Provide Individual Payoffs Higher Than Those of the Original Institution

Water Availability	Solution Concepts	Appropriator	ϵ^*
Abundant	Closed-Loop	Headender	1.38
		Tailender	1.48
	Myopic	Headender	3.37
		Tailender	3.52
Scarce	Closed-Loop	Headender	NA
		Tailender	56.07
	Myopic	Headender	NA
		Tailender	56.07

When water is scarce, the headender's individual payoffs are always smaller with the strong exclusion rule than with the original institution, even when $\epsilon=0$. The tailender's individual payoff with the strong exclusion rule, on the other hand, surpasses the individual payoff of the original game as long as ϵ falls short of 56.07, in both the closed-loop and the myopic solutions. When water is scarce, the headender's payoff decreases with a strong exclusion rule, while the tailender's payoff increases to a great extent with a strong exclusion rule.

The enforcement cost (ϵ) could be a criterion for institutional choice at the collective choice level (E. Ostrom 1990).[7] If so, then appropriators choose a strong exclusion rule if they obtain a higher expected payoffs with the strong exclusion rule (i.e., the strong exclusion rule will be adopted as long as ϵ is smaller than the ϵ^* shown in Table 8.5). When water is sufficient, the headender and the tailender need relatively similar ϵ's in order for a strong exclusion rule to be chosen in either the closed-loop or the and myopic solution. Thus, the headender and the tailender will likely agree on whether or not to select a strong exclusion rule. When water is scarce, however, the headender will never agree to choose a strong exclusion rule since it decreases his/her payoffs, even when $\epsilon=0$. This implies that reaching an agreement on institutional choice among appropriators will be more difficult when water is scarce than when it is sufficient.

Conclusion

A strong exclusion rule enhances the performance of an irrigation system. It always increases the group payoffs of the game; it always reduces efficiency losses in the payoffs; and it always enhances the levels of physical conditions in the final round.

The group payoff of each strategy in the closed-loop solution always surpasses (or at least equals) the group payoff of each strategy in the myopic solution. The efficiency loss in payoff of each strategy

[7] There are two major costs in an institutional choice situation: the transformation costs and monitoring and enforcement costs. In our game, ϵ is assumed to represent both of the two majors costs even though it is called "enforcement cost". For more details, see E.Ostrom (1990; 198-205).

in the closed-loop solution is also always smaller than or equal to the efficiency loss in payoff of each strategy in the myopic solution. This implies that a minimal level of institutional arrangements enhances the performance of an irrigation system with the strong exclusion rules. This evinces again that the minimal level of institutional arrangements is an effective policy tool.

Effects of Community Attributes

Community attributes also influence the action arena. This section examines how the homogeneity of the community, the size of community, and the maximum amount of maintenance that appropriators can afford affect the outcomes of this game.

Homogeneity of the Community

As the community grows more homogeneous, appropriators discount the future less (ω increases). As ω increases, appropriators take less water and invest more resources in maintenance in earlier rounds. Thus, the group payoffs will increase as ω gets larger (i.e., as the community becomes more homogeneous). If a community is extremely heterogeneous, it could be extremely difficult to expect repeated interactions and ω could become zero. When ω equals 0, the outcomes of the myopic solution and the closed-loop solution are identical. Thus, a minimum level of institutional arrangements may not enhance the appropriators' abilities to overcome collective action problems when the community is extremely heterogeneous.

The number of repetitions (T) also increases as the community becomes more homogeneous. As T becomes larger, in the closed-loop solution, efficiency losses in the payoffs increase when water is sufficient and decrease when water is scarce. In the myopic solution, efficiency losses in payoffs always decrease as T gets larger. If a community is extremely heterogeneous, then T approaches 1, and the difference between the closed-loop solution and the myopic solution could disappear completely. As T gets larger, the minimal level of institutions will be able to generate more benefits.

Therefore, in order for the minimal institutional arrangements to enhance the appropriators' ability to solve collective action problems, T must be greater than 1 and ω should be greater than 0. If these conditions are not met due to extreme heterogeneity, the closed-loop solution brings no more benefit than the myopic solution; and the appropriators would not be able to escape the traps of collective action problems without external help.

Size of Community

The size of community also impacts the outcomes of this game. By changing n, we portray the effects of changes in the size of community on the outcomes of this game. However, as Umino (1989) points out, "it is impossible to change the N [in our case, n] while other conditions are held constant". Changing n while holding other parameters constant in our game is likely to produce outcomes that are not meaningful. Thus, I make only small enough changes in n to still produce meaningful results without changing other parameter values in the base line parameter configuration.

When water is sufficient, an increase in n enhances the appropriators' ability to solve collective action problems. As n gets larger, the total investment in maintenance and the total amount of appropriation increase. Since physical conditions are assumed to be more sensitive to maintenance than to appropriation, physical conditions improve as n gets larger. For this reason, an increase in n enhances the performance of an irrigation system.

When n is so large that water is no longer abundant, though, an increase in n cannot bring more benefits to the appropriators. For example, when water is scarce, as in Water Scarcity II and T=2, tailenders get water in both rounds even though they can only get a limited amount of water in the first round. However, as n increases further, tailenders cannot get water in both rounds; and when n is greater than or equal to 10, tailenders cannot get water in both rounds; and even the amount of water at headenders' field gate in the second round becomes limited.

In summary, an increase in n enhances the appropriators' ability to solve collective action problems when water is abundant, but reduces the appropriators' ability to overcome collective action problems when water is scarce. However, examining the exact effects of the size of the community on the outcomes of this game is impossible due to the difficulties of changing n while other parameters are held constant.

<u>Maximum Amount of Maintenance That Appropriators Can Afford</u>

The maximum amount that appropriators can afford to invest in maintenance (mB_i) also affects the outcomes of this game. Once water sufficiency makes the optimal amount of investment in maintenance equal to mB_i, an increase in mB_i always increases the optimal amount of investment in maintenance. Increases in mB_i enhance the performance of an irrigation system until mB_i is not too large. Note that it is not individually optimal for appropriators to invest up to the maximum that they can afford when mB_i is too large even in the water abundance case.[8]

When water is scarce, on the other hand, an increase in mB_i does not always increase the total amount of investment in maintenance. An Increase in mB_k can reduce the optimal amount of investment in maintenance (m_{jt}* and m_{kt}*) in some cases. For example, when water is as scarce as in Water Scarcity I, and T=2, m_{k1}* and m_{j1}* are 2.05755 and 5, respectively. As mB_i increases from 5 to 6, m_{j1}* also increases from 5 to

[8] This is the case when mB_i is greater than $mB^{\#}$. For more detail, see Chapter 5.

6. m_{k1}*, on the other hand, decreases from 2.05755 to 1.05755. The increase in m_{j1}* is large enough to allow the tailender to get the same amount of water with a smaller m_{k1}*, but not large enough to encourage the tailender to invest more. As a result, the total amount of investment in maintenance, and the resulting group payoffs, remain unchanged. This implies that the headender's payoff decreases while the tailender's payoff increases as mB_i gets larger in some cases in which water levels approximates Water Scarcity I. When mB_i is large enough (e.g., 10 in Water Scarcity I), however, m_{k1}* also becomes mB_i. The amount of investment in maintenance made by the headender is large enough to make it optimal for the tailender to increase the level of investment in maintenance up to the maximum. In this case an increase in mB_i again improves the performance of an irrigation system.

In general, increases in mB_i enhance the performance of an irrigation system, but only with the closed-loop solution. In the myopic solution, changes in mB_i have no impact at all on the outcomes of this game.

Conclusion and Policy Implications

The nature of the institutional arrangements can determine the appropriate solution concept to this game. In most cases, a minimum level of institutional arrangements greatly enhances the ability of appropriators to resolve collective action problems. When no minimum level of institutional arrangements exists, the myopic solution becomes the individually rational choice, even for appropriators with foresight. Although present behavior affects the future physical condition of an irrigation system as well as its future incentive structure, rational individuals with foresight can only try to maximize their present payoffs (i.e., set the present marginal benefits equal to the present marginal costs) in the absence of a minimum level of institutions.

The findings in this Chapter shows that a strong exclusion rule enhances the appropriators' ability to solve the collective action problems effectively, even when appropriators have no foresight. This strong exclusion rule is also effective in resolving equity problems by reducing the gaps between the payoffs for the headender and the tailender.

The strong exclusion rule improves <u>group</u> payoffs, but the headender becomes worse off while the tailender becomes better off. Even though the strong exclusion rule is socially desirable when water is scarce, there will undoubtedly be more conflicts over adopting the rule between the headender and the tailender as water becomes scarcer.[9]

Community attributes also affect the outcomes of this game. Without certain community attributes, the closed-loop solution cannot be the appropriate solution to this game. If a community is extremely heterogeneous so that either ω equals zero or T equals 1, then the myopic solution becomes the only rational solution. In this case, a minimal level of institutional arrangements or a strong exclusion rule will not have any impact on outcomes, even if appropriators have foresight.

Without proper institutional arrangements and community attributes, it is impossible for rational individuals with foresight to behave as the closed-loop solution prescribes. Even though physical attributes greatly impact the appropriators' ability to manage CPRs effectively, institutional arrangements and community attributes determine the effectiveness of self-governing solutions to CPR dilemmas. Therefore, without knowing the institutional arrangements and the community attributes, it is extremely difficult to design a policy that will achieve its intended purpose.

[9] Since the benefits that the tailender can get in the strong exclusion game are relatively large, there could be a side-payment contract between the headender and the tailender. A cooperative game theoretic model will help us to understand this possibility. This issue is, however, beyond the scope of this study.

Chapter 9

Conclusions

This study began with the need for a new formal model that could explain anomalies of the earlier models. Drawing upon IAD framework and dynamic game theory, I develop a new game model of collective action problems in irrigation systems to explore the possibility of self-governing solutions to collective action problems and to examine how physical attributes and institutional arrangements impact on the possibility of self-governing solutions. A computer simulation uses the Mathematica program to solve the game. This model shows that in some conditions appropriators can escape the trap of collective action problems; and that institutional arrangements as well as physical attributes affect the appropriators' capability of resolving collective action problems by themselves.

In this final Chapter, I first highlight how my model explains anomalies that the earlier models could not explain. Second, I review the relationship between institutional arrangements and the possibility of self-governing solutions to collective action problems. Third, I discuss how physical attributes impact the possibility of self-governing solutions. Fourth, I examine the policy implications as well as the theoretical implications of this study. Finally, I address the limitations of this study and suggest some directions for future research.

Puzzles of Self-Governing Solutions and a New Model

The collective action problems that arise in managing CPRs have frequently been regarded as too difficult for appropriators to resolve without external help. The presumption that an external Leviathan is necessary to escape the traps of the collective action problems leads to the policy recommendation that central governments should control most CPRs. Other scholars have argued that the management problems of CPRs can easily be solved by improving the physical conditions of CPRs. They presume that making a physical system easier to operate and maintain automatically enables the appropriators to maintain the CPRs more effectively. This logic also concludes that the central government is necessary since improving the performance of systems is seen largely as a technical problem that requires "technical expertise...best located in a powerful state bureaucracy" (Barker et.al., 1984, 26). According to these two arguments, effective CPR management requires central government intervention.

The results generated by the new model show that appropriators can achieve higher levels of efficiency on their own, as opposed to the pessimistic predictions based on earlier formal models. The main difference between earlier models of collective action problems and the new model developed in this study stems from the dynamic nature of the new model. Some of the former models, such as the iterated game model, allow a game to repeat over time, but they are still not dynamic because the payoff structure remains unchanged over time. According to the findings of this study, appropriators in adynamic setting who take the future into account can achieve higher levels of efficiency than they can obtain without doing so. As Hardin (1982) points out, collective action problems are typically ongoing rather than one-shot. It is therefore reasonable for rational individuals to consider the future when making decisions about the use of CPRs.

Some details of real life must be sacrificed when developing a formal model of a complex social phenomena, as no model can portray all the details of such phenomena. When what is sacrificed in a model is essential in the sense that it has significant impact on the interactions among rational individuals in that setting, however, the predictions deduced from that model cannot be valid. The details that are sacrificed in most earlier models -- that appropriators interact with each other more than once and that present patterns of interactions among appropriators affect future payoff structure -- are essential features. Predictions based on models that sacrifice these essential modelling features, therefore, cannot be robust. This implies that pessimistic predictions about the possibility of self-governing solutions to collective action problems are not robust because these predictions are based upon models that do not contain essential modelling features.

The myopic solution results of this game can be thought of as a proxy for the outcomes of models that do not include these two essential features. The group payoffs of the myopic solution always fall short of the group payoffs of the closed-loop solution. This suggests that predictions based on earlier models <u>understate</u> the possibility of self-governing solutions to collective action problems, hence the anomaly that self-governing solutions found in the real world are not explained by the models.

The closed-loop solution, of course, cannot achieve 100 percent of the socially optimal, even though it achieves as high as 99.99 percent under some conditions. The degree to which the closed-loop solution approaches the social optimum depends on the physical and the community attributes of a system as well as on its institutional arrangements. In other words, physical and community attributes along with institutional arrangements impact rational appropriators' ability to resolve collective action problems and to manage CPRs effectively without external help. Given the empirical evidence that some appropriators manage CPRs effectively by themselves while others do not,[1] this result appears reasonable. The varying degrees of success in CPRs produce another anomaly that this model can address better than the earlier

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[1] For examples of successes and failures in managing CPRs, see E.Ostrom 1990.

models.

Institutional Attributes and the Possibility of Self-Governing Solutions

This study asserts that rational and forward-looking appropriators can escape the traps of collective action problems to some extent under some conditions. This assertion is based on the finding that the closed-loop solution to the dynamic irrigation game can obtain more efficiency than the myopic solution. The simulations show that parameters representing physical attributes affect the optimal behavior of appropriators and the resulting outcomes of the game. In an irrigation system, the amount of water at the source has a crucial impact on the outcomes of the game. Other physical attributes that affect water availability, such as headworks and lining of the canals, are also important.

Does this mean that physical attributes have a greater impacts on the possibility of self-governing solutions than institutional arrangements have? No, because the closed-loop solution cannot even be a solution to this game unless a minimum level of institutional arrangements exists. As illustrated in Table 8.1, the myopic solution also depicts the situations in which appropriators have foresight, but cannot expect repeated interactions among them and/or cannot have information about the transformation functions due to the lack of institutional arrangements. In other words, rational, forward-looking appropriators cannot avoid acting as the myopic solution prescribes in the absence of a minimal level of institutional arrangements.

The alternative institutional arrangement discussed in Chapter 8 shows that the institutional arrangements chosen have a substantial impact on the optimal behavior of appropriators and on the outcomes of this game. As rules concerning appropriation become stricter, appropriators take less water and achieve more efficiency.

A minimal level of institutional arrangements exists when at least the following exist: (1) boundary rules that enable appropriators to expect repeated interactions among them; and (2) information rules that allow appropriators to have information about transformation functions. The first component (boundary rules) coincides with the first of E.Ostrom's "design principles" (clearly defined boundaries). Her fourth principle (monitoring) is related to the second component of a minimal level of institutional arrangements (information rules). Detailed information about the conditions of CPRs permits appropriators to obtain information about the transformation function. In order for the strong exclusion rule, discussed in Chapter 8, to be feasible, CPR institutions need to satisfy additional design principles, such as principle 3 (collective choice arrangements), principle 5 (graduated sanctioning), principle 6 (conflict resolution mechanisms), and principle 7 (a minimal recognition of rights to organize). The findings of this study illustrate that E. Ostrom's design principles can be preconditions for self-governing solutions to collective action problems in CPRs that enables rational individuals to achieve more efficiency than earlier models predict.

Engineering Works and the Possibility of Self-Governing Solutions

Improving engineering works, such as headworks and lining, has frequently been used as a major policy tool. Its use is based on the presumption that betterment in engineering works makes it easier for appropriators to manage CPRs, which in turn enhances the performance of CPRs. Empirical studies of Nepal's irrigation system dispute this presumption. They show that farmer-managed irrigation systems with poorer engineering works achieve higher levels of performance than irrigation systems operated by the central governmental agencies with better engineering works. Earlier models cannot successfully explain this anomaly.

The major findings of this study about the effects of engineering works are: (i) improvements in engineering works do not guarantee an increase in the performance of an irrigation system with appropriators who use foresight when they make decisions, as the closed-loop solution prescribes; and (ii) improvements in engineering works do guarantee an increase in the performance of an irrigation system when appropriators do not or cannot take the future into account when they make decisions, as the myopic solution prescribes. These findings of this study could answer the puzzle raised by the anomaly of better performance of an irrigation system with poorer engineering works (Ostrom, Lam, and Lee 1994). The improvement in engineering works can even reduce the performance of an irrigation system if: appropriators behave as the closed-loop solution prescribes; the improvement in engineering work is partial, as defined in Chapter 8; and the investment in improvement in maintenance is higher than the investment level that yields the optimal improvement level (I*) .

Although the findings suggest that improvements in engineering works always enhance the performance of an irrigation system with appropriators who behave as the myopic solution prescribes, the more important finding is that the performance levels of irrigation systems with the same level of improvement are always higher in the closed-loop solution than in the myopic solution. In some cases, an irrigation system with a lower level of improvement performs better in the closed-loop solution than an irrigation system with higher level of improvement does in the myopic solution.

Policy and Theoretical Implications

The above discussions conclude that (i) rational individuals can resolve collective action problems to some extent, under some conditions, without external help; and (ii) institutional, community, and physical attributes impact the ability of appropriators of CPRs to resolve collective action problems by themselves. Several policy implications as well as theoretical implications can be drawn from these conclusions.

First, we enhance the performance of CPRs by simply ensuring a minimal level of institutional arrangements that clearly define the boundary of appropriators and that provide information about the transformation functions. Encouraging appropriators to organize themselves could be an appropriate policy tool in cases where appropriators currently cannot take the future into account because they lack the minimum institutions that allow future-regarding behavior.

Second, policy recommendations that focus on improving the physical structure of a CPR without paying proper attention to appropriators' community and organizational structure are likely to be improper. Expensive policy interventions that improve physical structures of CPRs, can even potentially <u>reduce</u> the performance of CPRs when institutional arrangements are not taken into consideration. This study shows that this could be the case when improvement projects are partial and appropriators behave as the closed-loop solution prescribes.

When an improvement project <u>decreases</u> the performance of an irrigation system, it is clearly inefficient, regardless of its cost. When an improvement project could <u>increase</u> the performance of an irrigation system, on the other hand, we should take its costs into account in order to determine whether or not it is efficient. Improvement projects always increase the performance of an irrigation system when appropriators behave as the myopic solution prescribes and/or when the improvements meet the requirements of full improvements set out in Chapter 7. However, even in these cases, the improvement projects are not necessarily desirable for one of two reasons: (i) we could possibly increase the performance of the irrigation system more by encouraging appropriators to organize themselves rather than by improving engineering works; and (ii) it is likely that the cost of full improvement projects exceed their benefits.

Third, although appropriators can potentially manage their CPR effectively, we cannot take for granted that they can resolve every collective action problems or that they will manage the CPRs as effectively as the social optimum solution. There is always an efficiency loss, even though it could be extremely small in some cases, which means there is always room for improvement through policy intervention, even when appropriators resolve collective action problems extent by themselves. The size of efficiency loss depends on physical as well as institutional attributes. By being more fully informed of the dynamic nature of the incentive structure of appropriators, one can target interventions to improve the performance of CPRs more effectively.

Fourth, the success of a policy tool in one irrigation system does not necessarily guarantee its success in other irrigation systems. Since the incentive structures of appropriators in different systems are not the same, there exists no single policy tool that can work in every system. To resolve collective action problems effectively, therefore, it is necessary to obtain detailed knowledge of the particular circumstances of a particular CPR. Appropriators of that particular CPR are more likely to have this detailed knowledge than are policy analysts. Thus, information from appropriators of CPRs should be included in policy analyses.

Finally, the model in this study can be generalized and applied to the collective action problems of a wide variety of CPRs. The model in this study is specific to one CPR, an irrigation system, but, the main features of this dynamic game theoretic model can be used when modelling collective action problems in other CPRs. The essential modelling features are: (i) there are at least two control variables -- one for appropriation problems and one for provision problems; (ii) choices on these two control variables impact the state variables that portray the physical conditions of the CPR; and (iii) changes in the state variables are followed by changes in the incentive structure of appropriators in the next round.

The forms of payoff functions and state transition functions will vary across CPRs. If the main modelling features of this game are used to depict the incentive structures of CPR situations, the prediction that rational, and forward-looking individuals may achieve efficiency to a greater extent under some conditions without external help than expected in earlier static games, will probably remain unchanged.

By incorporating the dynamic context into the collective action theory, we can develop a richer theory of collective action, which can explain anomalies that the earlier theory of collective action fails to explain.

Directions for Future Research

In this study, I employ the IAD framework and dynamic game theory to model the incentive structure of appropriators of CPRs. The predictions deduced from this game show that appropriators can escape the trap of collective action problems under some circumstances without external help. I use computer simulations to obtain the solutions for several variant of this game. This study, however, has several limitations. Addressing these limitations leads toward a richer collective action theory.

First, this study relies on an initial parameter configuration and its variants. This is inevitable for two reasons: it is almost impossible to discover the boundaries of each parameter in which the game yields meaningful results; and it is difficult to obtain empirical data concerning the parameters. The first reason causes me to limit the range of the parameter values for analyzing the effects of changes in parameters on the outcomes of this game. For example, I do not include cases where a large number of appropriators interact with each other because it is impossible to change n while holding other parameters constant. Increasing n to a large number requires another initial line parameter configuration. In this study, I have limited n to 10 because this model cannot yield meaningful results when n is greater than 10. However, this does not necessarily means that a self-governing solution is possible only when n is smaller than 10. By having another initial parameter configuration, this model could generate meaningful results when n is greater than 10. The simulation results with this parameter configuration will be close to those with the parameter configuration of this study, which suggests that a self-governing solution can be possible when n is large under some conditions.

It is extremely difficult to get precise empirical data for the parameters used in this study, especially for the parameters used in state transition equations. By doing empirical studies, however, we may obtain at least indirect information about the parameter values and thus restrict the boundaries for parameter values in more systematic ways. This effort will help to explore the impact of n and to produce more reliable and richer results of this game.

Second, the solution process of this game is specific to a particular institution. The strong exclusion rules are only one of a wide variety of institutional arrangements that can possibly affect the game outcomes. The dynamic model developed in this study may be used as a base model to portray various institutional arrangements and their effects on the possibility of self-governing solutions. By modelling as many institutional arrangements as possible with a dynamic game model, we could make a contribution to the development of collective action theory.

Third, this study analyzes only the cases where the game is repeated less than 6 times. The branching method is required in the process of solving this game to deal with upper and lower limits on control variables. Due to this branching, it takes a long time to calculate the solutions. For example, when T equals 5, it took about 12 hours to get results. Limitations on T do not seem to have any meaningful impacts on the outcomes of this game, but we can test the effects of larger Ts if we improve the simulation program and run it on a faster computer. A large T (i.e., 60 or larger), can approximate infinite iterations and remove the final round effects on the outcomes of this game.[2]

Fourth, state transition equations of this game are linear, which is inevitable in this model because state transition equations must be linear in order for a dynamic game to be "linear-quadratic",[3] The dynamic game needs to be linear-quadratic in order to generate a unique solution (Papavassilopoulos and Cruz 1979). Non-linear state transition equations might be more reasonable in this game. To approximate this non-linearity with linear state transition equations, I assume that the two types of thresholds used in the state transition equations -- the minimum investment required to maintain the previous levels of state variables and the maximum appropriation allowed to maintain the previous levels of`state variables -- are linear functions of the previous state variables[4]. I suspect that using non-linear state transition equations will unduly complicate the solution process of this game. If one can handle such complexity successfully, however, a game with non-linear state transition equations could provide more reliable results.

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[2] As mentioned in Chapter 5, the discount factor for payoff in the 61st round is 0.00000153 when ω is 0.8.

[3] Linear-quadratic game is a game for which "[state transition equations] are linear in the state and control variables and the objective functions are quadratic in state and control variables" (Fudenberg and Tirole 1991, 523).

[4] For reference, see equation (12) in Chapter 3.

Finally, this study focuses only on the operational level. Choices at the collective choice level, such as a choice about whether or not to adopt a strong exclusion rule, are also very important for understanding the possibility of self-governing solutions to collective action problems in CPR situations. The Incorporation of cooperative game theoretic modelling techniques into the dynamic game theoretic approach of this study, therefore, will enable us to provide a more comprehensive analysis about the problems of collective actions in CPR situations.

The findings of this study can guide future empirical studies by suggesting the kinds of empirical data needed to determine the values of parameters in these types of formal models. They can also benefit future formal modelling by identifying the essential modelling features that usually have been overlooked in the earlier formal models <u>but</u> are so critical because they change the predictions of formal models drastically. New studies, both empirical and formal, that are guided by these considerations will expedite knowledge accumulation for a theory of self-organized collective action, which is broader and still-evolving, rather than completed (E.Ostrom 1990).

Myopic Solution Process

```
T = 2; q = 310; r = 20; c = 0; U = 0; d=0; M = 0; R1 = .7; E1 =.7; m = 4; n = 8; e = .02; ep = 4; w = 0.8;
alp = 0.004;  gam = 5000;  alpp = 0.004;  gamp = 5000;  alppp = 0.004;  gampp = 5000;  the = 0.004;
gamppp = 5000;  mB = 5;  Qs = 30;  a = 0.05; I = 400;  Ip = 200;

Pijm: =  (R q uj - 0.5 r uj^2 - e m uj^2 - (c (uj - U)  + d M) - ep);

Pikm: =  (R q uk - 0.5 r uk^2 - e (m uj + (n-m) uk) uk - (c (uk - U)  + d M) - ep);

R11 = R1; E11 = E1;

ujp: = (-c  +  q*R)/(2*(e*m  +  0.5*r));
ukp:= -(-c  +  q*R-(e*m*(-c  +  q*R))/(2*(e*m  +  0.5*r)))/(2*(e*m  - e*n  - 0.5*r));

ujpp = Min[0, (ujp /.  R-> R11), ((Qs-a (1-Ee)  1)/m /.  Ee-> E11)];
ukpp = Min[0, (ukp /.  R-> R11), ((Qs-a(1-Ee)  (I  +  Ip) - m ujpp)/(n-m) /.  Ee-> E11)];

pijP = Pijm /.  {uj ->ujpp, uk -> ukpp, R -> R11};
pikP = Pikm /.  {uj ->ujpp, uk -> ukpp, R -> R11};

Ujpp = {ujpp};  Ukpp = {ukpp};  PijP = {pijP};  PikP = {pikP};  PR = {R11};  PE = {E11};


Do[

Rp  =  (R11  - alp (gam R11)  +  alpp( gamp R11  - m ujpp - (n-m) ukpp));
Ep  =  (E11  - alp (gam E11)  +  alpp( gamp E11  - m ujpp - (n-m) ukpp));

R11 = .;  E11  = .;

Rff = If[0<=Rp<=1,  Rp, If[Rp>1,  1,0]];
Eff = If[0<=Ep<=1,  Ep, If[Ep>1,  1, 0]];

ujpp = .;  ukpp = .;  pijP = .;  pikP = .;

ujpp = Min[(ujp /.  R-> Rff),  ((Qs-a  (1-Ee)  1)/m /.  Ee -> Eff)];
ukpp = Min[(ukp /.  R-> Rff),  ((Qs  - a(1-Ee)  (I  +  Ip)  - m ujpp)/(n-m) /. Ee -> Eff)];

pijP = Pijm /.  {uj ->ujpp, uk -> ukpp, R -> Rff};
pikP = Pikm /.  {uj ->ujpp, uk -> ukpp, R -> Rff};

Ujpp = Insert[Ujpp, ujpp, -1];
Ukpp = Insert[Ukpp, ukpp, -1];
PijP = Insert[PijP, pijP, -1];
PikP = Insert[PikP, pikP, -1];
PR = Insert[PR, Rff, -1];
PE = Insert[PE, Eff, -1];

R11=Rff;  Rff = .; E11= Eff;  Eff = .;
```

```
,{T-1}];

Myopj = Sum[(w^(i-1))*PijP[[i]], {i, 1, T}];
Myopk = Sum[(w^(i-1))*PikP[[i]], {i, 1,-T}];
```

Closed-Loop Solution Process

```
UUJ = {}; UUK = {}; MMJ = {}; MMK = {}; PPJ = {}; PPK = {}; RRR = {}; EEE = {};

Dot

B = Table[IntegerDigits[kk,2]];
len = Length[B];
CC = Table[0, {ii, 2T-len}];
A = Join[CC,B];

Pij: = (R q uj - 0.5 r uj^2 - e m up^2 - mj - (c (uj - U) + d(M -mj)) - ep);
Pik: = (R q uk - 0.5 r uk^2 - e (m uj + (n-m) uk) uk - mk - (c (uk - U) + d(M -mk)) - ep);

ujs = Replace[uj, Solve[ D[Pij, uj]= =0, uj] ] [[1]];
ujc = If[A[[1]]= =0, ujs, If[(Qs-0.05a l)<0, 0, (Qs - a (1-Ee) l)/m] ];

ukz = Replace[uk, Solve[ D[Pik, uk]= =0, uk] ] [[1]];
uks = ukz /. uj -> ujc;

ukc = If[A[[2]]= =0, uks,If[(Qs-0.05a(l + lp)-(Qs-0.05a l/m))<0,0, (Qs-a (1-Ee) (l + lp)-m ujc)/(n-m)] ];

Saij = Pij /. {uj -> ujc, mj -> 0};

Saik = Pik /. {uj -> ujc, uk -> ukc, mk -> 0};

TPij = {Saij}; TPik = {Saik}; Tmj = {0}; Tmk = {0}; Tuj = {ujc}; Tuk = {ukc};

ujs = .; ujc = .; uks = .; ukc = .; ukz = .;

Do[

aj = Saij; Saij =.; ak = Saik; Saik = .;

bj = aj /. {R -> Rb, Ee -> Eb}; bk = ak /. {R -> Rb, Ee -> Eb};

R = .; Ee = .; aj = .; ak = .;

Saij = bj /. {Rb -> (R - alp (gam R - m mj - (n-m) mk) + alpp( gamp R - m uj - (n-m) uk)),
          Eb -> (Ee - the (gampp Ee - m mj - (n-m) mk) + alppp( gamppp Ee - m uj - (n-m) uk))};
Saik= bk /. {Rb -> (R - alp (gam R - m mj - (n-m) mk) + alpp( gamp R - m uj - (n-m) uk)),
          Eb -> (Ee - the (gampp Ee - m mj - (n-m) mk) + alppp( gamppp Ee - m uj - (n-m) uk))};

Rb = .; Eb = .;
Obj = Pij + w Saij; Obk = Pik + w Saik;
```

```
Saij = .; Saik = .;

mkzs = If[Coefficient[Obk, mk, 2] > = 0, mB,
        Simplify[Replace[mk,Solve[D[Obk, mk]==0, mk]] [[1]]] ];
mjzs = If[Coefficient[Obj, mj, 2] > = 0, mB,
     Simplify[Replace[mj, Solve[D[Obj, mj]= =0, mj]] [[1]]] ];

mks = If[Coefficient[Obk, mk, 2] > =0, mB,
    Replace[mk, Solve[(mkzs /. mj->mjzs)= = mk, mk]] [[1]] ];
mjs = If[Coefficient[Obj, mj, 2] > =0, mB, mjzs /. mk->mks];

Obkk = Simplify[Obk] /. mk->mks;
Obkkk = Simplify[Obkk] /. mj->mjs;
ukz = If{A[[2 + 2i]]  = = 0 ,
    Simplify[Replace[uk, Solve[D[Obkkk, uk]= =0, uk]][[1]] ],
    If[(Qs-0.05a (l + lp) - (Qs-0.05a l/m))<0, 0,
    (Qs - a (1 - Ee) (l + lp) - m uj)/(n-m) ] ];

Objj = Obj /. mj->mjs;
Objjj = Simplify[Objj] /. mk->mks;
Objjjj = Simplify[Objjj] /. uk->ukz;
ujs = If[A[[1+2i]]  = =0,
    Simplify[Replace[uj, Solve[D[Ob]jjj, uj]= =0, uj]][[1]] ],
    !f[(Qs-0.05a l)<0, 0, (Qs - a (1 -Ee) l)/m ] ];

uks = ukz /. uj -> ujs;

mksz = mks /. {uj -> ujs, uk -> uks};
mjsz = mjs /. {uj -> ujs, uk -> uks};

mkss = If[Coefficient[Coefficient[mksz,R,0],Ee,0] + Coefficient[mksz,Ee,1]
       + Coefficient[mksz,R,1]<0, 0,
            If[Coefficient[Coefficient[mksz,R0],Ee,0]
            + Coefficient[mksz,Ee, 1 ] + Coefficient[mksz,R, 1 ] > mB,
                mB,mksz]];
mjss = If [Coefficient[Coefficient[mjsz,R,0],Ee,0] + Coefficient[mjsz,Ee, 1 ]
       + Coefficient[mjsz,R,1]<0, 0,
            If [Coefficient[Coefficient[mjsz,R,0],Ee,0]
            + Coefficient[mjsz,Ee, 1 ] + Coefficient[mjsz,R, 1 ] > mB,
                mB,mjsz]];

Saij =  Simplify[Obj /. {uj -> ujs, uk -> uks, mj -> mjss, mk -> mkss}];
Saik=  Simplify[Obk /. {uj -> ujs, uk -> ujs, mj -> mjss, mk -> mkss}];

TPij = Insert[TPij, Saij, 1]; TPik = Insert[TPik, Saik, 1];
Tuj = Insert[Tuj, ujs, 1]; Tuk = Insert[Tuk, uks, 1];
Tmj = Insert[Tmj, mjss, 1]; Tmk = Insert[Tmk, mkss, 1];

mjs = .; mjz = .; mjzs = .; mjss = .; mjsz = .; mks = .; mkz = .; mkzs = .; mkss = .; mksz = .;
ujs = .; ujz = .; uks = .; ukz = .; aj = .; ak = .; bj = .; bk = .; Obj = .; Obk = .; Objj = .; Objjj = .; Objjjj =.;
Obkk = .; Obkkk = .;
```

```
, {i, (T-1)}];

ujN = Tuj[[1]] /. {R -> R1, Ee -> E1};
ukN = Tuk[[1]] /. {R -> R1, Ee -> E1};
mjN = Tmj[[1]] /. {R -> R1, Ee -> E1};
mkN=Tmk[[1]] /. {R -> R1, Ee -> E1};

PikN = Pik /. {uj ->ujN, uk -> ukN, mj -> mjN, mk -> mkN, R -> R1};
PijN = Pij /. {uj ->ujN, uk -> ukN, mj -> mjN, mk -> mkN, R -> R1};

Nuj = {ujN}; Nuk = {ukN}; Nmj = {mjN}; Nmk = {mkN}; NPij = {PijN};
NPik = {PikN}; Rp = R1; Ep = E1;

RD= ( Rp - alp (gam Rp - m mjN - (n-m) mkN) + alpp( gamp Rp - m ujN - (n-m) ukN));

Rf = If[0<=RD<=1, RD, If[RD>1, 1, 0]];

ED= ( Ep - alp (gam Ep - m mjN - (n-m) mkN) + alpp( gamp Ep - m ujN - (n-m) ukN));

Ef = If[0<=ED<=1, ED, If[ED>1, 1, 0]];

Rp = .; RD = .; Ep = .; ED = .; ukN = .; ujN = .; mjN = .; mkN = .; PikN = .; PijN = .;

NR = {R1}; NE = {E1};

Do[

ujN=Tuj[[i + 1]] /. {R-> Rf, Ee-> Ef};
ukN = Tuk[[i +1 ]] /. {R -> Rf, Ee -> Ef};
mjN = Tmj[[i + 1]] /. {R-> Rf, Ee-> Ef};
mkN = Tmk[[i + 1]] /. {R -> Rf, Ee -> Ef};

PikN = Pik /. {uj ->ujN, uk -> ukN, mj -> mjN, mk -> mkN,
      R-> Rf};
PijN = Pij /. {uj ->ujN, uk -> ukN, mj -> mjN, mk -> mkN,
      R-> Rf};

Nuj = Insert[Nuj, ujN, -1]; Nuk = Insert[Nuk, ukN, -1];
Nmj = Insert[Nmj, mjN, -1]; Nmk = Insert[Nmk, mkN, -1];
NPij = Insert[NPij, PijN, -1]; NPik = Insert[NPik, PikN, -1];
NR = Insert[NR, Rf, -1]; NE = Insert[NE, Ef, -1];

Rp = Rf; Rf = .; Ep = Ef; Ef = .;

RD = ( Rp - alp (gam Rp - m mjN - (n-m) mkN) + alpp( gamp Rp - m ujN - (n-m) ukN));
Rf = If[0<=RD<=1, RD, If[RD>1, 1, 0]];

ED= ( Ep - alp (gam Ep - m mjN - (n-m) mkN) + alpp( gamp Ep - m ujN - (n-m) ukN));
Ef = If[0<=ED<=1, ED, If[ED>1, 1, 0]];

Rp = .; RD = .; Ep = .; ED = .; ukN = .; ujN = .; mjN = .; mkN = .; PikN = .; PijN = .;
```

```
, {i, (T-1)}];

UUJ = Insert[UUJ, Nuj, -1];
UUK = Insert[UUK, Nuk, -1];
MMJ = Insert[MMJ, Nmj, -1];
MMK = Insert[MMK, Nmk, -1];
PPJ = Insert[PPJ, NPij, -1];
PPK = Insert[PPK, NPik, -1];
RRR = Insert[RRR, NR, -1];
EEE = !nsert[EEE, NE, -1];

Nuj = .; Nuk = .; Nmj = .; Nmk = .; NPij = .; NPik = .; NR = .; NE = .;

, {kk, 0, 2^(2T)-1, 1}];

Aux = Table[ii, {ii, 2^(2T)}];
Temp = {};

Do[
    Do[
    Temp = If[ UUK[[Aux[[k]], x]] < =UUK[[Aux[[(k+1)]], x]],
        !nsert[Temp, Aux[[k]], -1],
        Insert[Temp, Aux[[k + 1]], -1] ],
    {k, 1, 2^(2T-2x + 2), 2 } ];

    Aux = {};

    Do[

    Aux = If[ UUJ[[Temp[[k]], x]] < =UUJ[[Temp[[(k + 1)]], x]],
        Insert[Aux, Temp[[k]], -1],
        Insert[Aux, Temp[[k + 1]], -1] ],
    {k, 1, 2^{2T-2x + 1),2}];

    Temp = {};

, {x, T}];

UUJX = UUJ[[Aux[[1]] ]];
UUKX = UUK[[Aux[[1]] ]];
MMJX = MMJ[[Aux[[1]] ]];
MMKX = MMK[[Aux[[1]] ]];
PPJX = PPJ[[Aux[[1]]]];
PPKX = PPK[[Aux[[1]]]];
RRRX = RRR[[Aux[[1]] ]];
EEEX = EEE[[Aux[[1]] ]];

Dynapj = Sum[(w^(i-1))*PPJX[[i]], {i, 1, T}];
Dynapk = Sum[(w^(i-1))*PPKX[[i]]/ {i, 1, T}];
```

Social Optimum Solution Process

```
B = .; CC = .; A = .; len = .; Aux = .; Temp = .;

QJ: = (Qs - a (1-Ee) I)/m;

QK: = (Qs - a (1-Ee) (I+Ip) - m QJ)/(n-m);

UUS = {}; MMS = {}; PPP = {}; RRRS = {}; EEES = {};

Do[
B = Table[IntegerDigits[kk,2]];
len = Length[B];
CC=Table[0, {ii, T-len}];
A = Join[CC,B];

P:= 2*(-ep - d*M - ms + d*ms - c*u + q*R*u - (e*m*u^2)/2 - (e*n*u^2)/2 - 0.5*r*u^2 + c*U);

us = Replace[u, Solve[D[P, u]= =0, u]][[1]];

usc = If[A[[1]]==0, us,
       If[((Qs-0.05a I + Qs -0.05a (I +Ip) - Qs +0.05a I)/n <0),
       0, (m QJ + (n-m) QK)/n] ];

Sai = P /. {u -> usc, ms -> 0};

TP = {Sai}; Tms = {0}; Tu = {us};

us = .;

Do[

as = Sai; Sai = .; bs = as /. {R -> Rs, Ee-> Es}; R = .; Ee = .; as = .;
Sai= bs /. {Rs ->  <R - alp (gam R - m ms - (n-m) ms) + alpp( gamp R - m u - (n-m) u)),
           Es ->  (Ee - alp (gam Ee - m ms - (n-m) ms) + alpp( gamp Ee - m u - (n-m) u))};
Rs = .; Es = .;

Ob = P + w Sai; Sai = .;

msz = If[Coefficient[Ob, ms, 2]>=0, mB, Simplify[Replace[ms, Solve[D[Ob, ms] = =0, ms]] [[1]] ] ];

Obb = Ob /. ms->msz;

us = If[A[[i + 1]]==0,
   Simplify[Replace[u, Solve[D[Obb, u]= =0, u]][[1]] ],
    If[((Qs-0.05a I + Qs -0.05a (I +Ip) - Qs + 0.05a I)/n <0),
    0, (m QJ + (n-m) QK)/n] ];

msz2 = msz /. u->us;

mss = If[Coefficient[Coefficient[mszz,Ee,0],R,0] + Coefficient[mszz,Ee,1]
       + Coefficient[mszz,R, 1 ] <0,0,
```

```
        If [Coefficient[Coefficient[mszz,Ee,0],R,0] + Coefficient[mszz,R, 1} +
              Coefficient[mszz,Ee,1]>mB,  mB,  mszz] ];

Sai=  Simplify[Ob /. {u -> us, ms -> mss}];

TP = Insert[TP, Sai, 1];
Tu = Insert[Tu, us, 1];
Tms = Insert[Tms, mss, 1];

mss = .; msz = .;  mszz = .; us = .; uz = .; as = .; bs = .; Ob = .; Obb = .;

, {i, (T-1)}];

uN=Tu[[t]] /. {R -> R1, Ee -> E1};
msN = Tms[[1]] /. {R -> R1, Ee -> E1};
PN = P /. {u ->uN, ms -> msN, R -> R1};

Nu = {uN}; Nms = {msN}; NP = {PN};

Rs = R1; Es = E1;

RDD= ( Rs - alp (gam Rs - m msN - (n-m) msN) + alpp( gamp Rs - m uN - (n-m) uN));
Rfff = If[0 < = RDD < = 1, RDD, If[RDD > 1, 1, 0]];

EDD= ( Es - alp (gam Es - m msN - (n-m) msN) + alpp( gamp Es - m uN - (n-m) uN));
Efff = If[0 < = EDD < = 1, EDD, If[EDD > 1, 1, 0]];

Rs = .; RDD = .; Es = .; EDD = .; uN = .; msN = .; PN = .;

SR = {R1}; SE= {E1};

Do[

uN=Tu[[i + 1]] /. {R-> Rfff, Ee-> Efff};
msN = Tms[[i + 1]] /. {R -> Rfff, Ee -> Efff};
PN = P /. {u ->uN, ms -> msN, R -> Rfff};

Nu = Insert[Nu, uN, -1];
Nms = Insert[Nms, msN, -1];
NP = Insert[NP, PN, -1];
SR = Insert[SR, Rfff, -1];
SE = Insert[SE, Efff, -1];

Rs = Rfff; Rfff =.;  Es = Efff; Efff =.;

RDD = ( Rs - alp (gam Rs - m msN - (n-m) msN) + alpp( gamp Rs - m uN - (n-m) uN));

Rfff = If[0<=RDD<=1, RDD, If[RDD>1, 1,0]];

EDD= ( Es - alp (gam Es - m msN - (n-m) msN) + alpp( gamp Es - m uN - (n-m) uN));

Efff = If[0<=EDD< =1, EDD, If[EDD>1, 1,0]];
```

```
Rs = .; RDD = .; Es = .; EDD = .; uN = .; msN = .; PN = .;

, {i, (T-1)}];

UUS = Insert[UUS,Nu, -1];
MMS = Insert[MMS,Nms, -1];
PPP = Insert[PPP,NP,-1];
RRRS = Insert[RRRS,SR, -1];
EEES = Insert[EEES,SE, -1];

Nu = .; Nms = .; NP = .; SR = .; SE = .;

, {kk, 0, 2^(T)-1, 1}];

Aux = Table[ii, {ii, 2^(T)}];
Temp = {};

Do[
    Do[
    Temp = If[ UUS[[Aux[[k]], x]] <= UUS[[Aux[[(k+1)]], x]],
        Insert[Temp, Aux[[k]], -1],
        Insert[Temp, Aux[[k + 1]], -1] ],
    {k, 1,2^(T-x + 1), 2} ];

, {x, T}];

UUJS = UUS[[Temp[[1]] ]];
MMJS = MMS[[Temp[[1]] ]];
PPKS = PPP[[Temp[[1]]]];
RRRSS = RRRS[[Temp[[1]] ]];
EEESS = EEES[[Temp[[1]] ]];

Socip = (Sum[(w^(i-1))*PPKS[[i]], {i, 1, T}])/2;
```

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