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Game theory and water resources

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SUMMARY

Managing water resources systems usually involves conflicts. Behaviors of stakeholders, who might be willing to contribute to improvements and reach a win–win situation, sometimes result in worse conditions for all parties. Game theory can identify and interpret the behaviors of parties to water resource problems and describe how interactions of different parties who give priority to their own objectives, rather than system's objective, result in a system's evolution. Outcomes predicted by game theory often differ from results suggested by optimization methods which assume all parties are willing to act towards the best system-wide outcome. This study reviews applicability of game theory to water resources management and conflict resolution through a series of non-cooperative water resource games. The paper illustrates the dynamic structure of water resource problems and the importance of considering the game's evolution path while studying such problems.

Introduction

The conflicts over water issues are not limited to sharing of costs or benefits; a problem that have had many water scholars focused on. Conflicts also arise from social and political aspects of the design, operation and management of water projects. When analyzing, operating or designing a complex water project, a decision maker must ensure that the undertaking is not only physically, environmentally, financially and economically feasible, but also socially and politically feasible. This is challenging for engineers who conventionally measure performance in economic, financial, and physical terms. Optimization techniques, such as linear or dynamic programming, can find the optimal values of the decision variables in such terms. However, if not formulated correctly, they might fail to provide insights into the strategic behaviors of the local, regional, and policy decision makers to reach an optimal outcome and the attainability of such outcome from the status quo.

Interest in water resources conflict resolution has increased over the last decades (Dinar, 2004) and various quantitative and qualitative methods have been proposed for conflict resolution in water resources management, including, but not limited to Interactive Computer-Assisted Negotiation Support system (ICANS) (Thiessen and Loucks, 1992; Thiessen et al., 1998), Graph Model for Conflict Resolution (GMCR) (Kilgour et al., 1996; Hipel et al., 1997), Shared Vision Modeling (Lund and Palmer, 1997), Adjusted Winner (AW) mechanism (Massoud, 2000), Alternative Dispute Resolution (ADR) (Wolf, 2000), Multivariate Analysis Biplot (Losa et al., 2001), and Fuzzy Cognitive Maps (Giordano et al., 2005). Wolf (2002) presents some significant papers and case studies on the prevention and resolution of conflict (using descriptive methods) over water resources.

Game theory provides a framework for studying the strategic actions of individual decision makers to develop more broadly acceptable solutions. However, game theory is not yet well integrated into general systems analysis for water resources. Thus, game theory's value might remain unclear to the water resources community due to lack of understanding its basic concepts. As with other disciplines (e.g. economics, political science, social science, computer intelligence, etc.) water scholars will become more interested in game theory as they come to realize its novel and useful insights into water resources problems which are not obtainable from conventional systems engineering methods. In general, game theory results are closer to practice as this method better reflects the behaviors of the involved parties, something often neglected by conventional optimization methods for solving multi-criteria multi-decision-maker problems.

This paper illustrates the utility of game theory in water systems analysis and conflict resolution by discussing the basic concepts of game theory and presenting some simple two-by-two water resource games. It is also discussed how the dynamic structure of water resource problems and game evolution might affect the behaviors of stakeholders in different periods of the conflict.

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Game theory

Game theory is essentially the mathematical study of competition and cooperation. It illustrates how strategic interactions among players result in overall outcomes with respect to the preferences of those players. Such outcomes might not have been intended by any player (Stanford Encyclopedia of Philosophy, 2006). Games are defined mathematical objects, consisting of a set of players, a set of strategies (options or moves) available to them, and specification of players' payoffs for each combination of such strategies (possible outcomes of the game). The payoffs to players determine the decisions made and the type of the game being played. If the payoffs sum up to zero or a constant then the players have opposing interests and are playing a zero-sum-game or a constant-sum game; whatever one player wins, the other player loses. Non-zero-sum games, in which the sum of payoffs does not equal zero or a constant, have more complications, and sometimes more potential for cooperation.

Game theory can be used to predict how people behave, following their own interests, in conflicts. In a typical game, decision makers (players), with their own goals, try to outsmart one another by anticipating each other's decision. The game is resolved as a consequence of the players' decisions. Game theory analyses the strategies players use to maximize their payoffs. A solution to a game prescribes decisions the decision makers might make and describes the game's outcome. Game theory was established in 1944 with the publication of von Neumann and Morgenstern's "Theory of Games and Economic Behavior" book, which mainly dealt with quantitative game theory methods. After World War II, most scholars worked on developing quantitative game theory methods; and this trend still persists today (Hipel and Obeidi, 2005).

Why game theory?

A variety of methods have been proposed to handle strategic conflicts (Li et al., 2004), including metagame analysis (Howard, 1971), hypergame analysis (Bennett, 1980; Wang et al., 1988), conflict analysis (Fraser and Hipel, 1984), the Graph Model for Conflict Resolution (GMCR) (Kilgour et al., 1987; Fang et al., 1993), drama theory (Howard, 1999), and the theory of moves (Brams, 1994), all having game-theoretic roots (Kilgour, 1995). Game theory problems are often multi-criteria multi-decision-maker problems. To solve such problems by conventional optimization methods, usually the problem is converted ultimately to a single-decision-maker problem with a single composite objective for the whole system such as an overall economic or social welfare function or a weighted constrained multi-objective function. Typically, perfect cooperation among the decision makers to reach the system's optimal solutions is assumed. These decision makers are assumed to contribute to optimizing the objective function without giving priority to their own objectives. However, in game theory each decision maker plays the game to optimize his own objective, knowing that other players' decisions affect his objective value and that his decision affects others' payoffs and decisions.

Stable outcomes of the game predicted by game theory are not necessarily Pareto-optimal. The main concern of players is to maximize their own benefit in the game knowing that the final outcome is the product of all the decisions made. Game theory provides more realistic simulation of stakeholders' interest-based behavior. The self-optimizing attitude of players and stakeholders, represented in game theory, often results in non-cooperative stakeholder behaviors even when cooperative behavior is more beneficial to all parties. Game theory can help provide some planning, policy, and design insights that would be unavailable from other traditional systems engineering methods.

Another advantage of game theory over traditional quantitative simulation and optimization methods is its ability to simulate different aspects of the conflict, incorporate various characteristics of the problem, and predict the possible resolutions in absence of quantitative payoff information. Often non-cooperative game theory methods can help resolve the conflict based on the qualitative knowledge about the players' payoffs (i.e. how the players order (rank) different outcomes (ordinal payoffs)). This enables to handle the socio-economic aspects of conflicts and planning, design, and policy problem when quantitative information is not readily available.

Through some simple examples of water resources conflicts, this paper underscores the applicability of game theory for water resources conflict resolution and leads to insights into generic water resources problems.

Application of game theory to water resources conflict resolution

In a water conflict, different interest groups or individuals can be modeled as decision makers (players), where each decision maker can make choices unilaterally and the combined choices of all players together determine the possible outcomes of the conflict. Instead of unilaterally moving, decision makers also may decide to cooperate or form coalitions leading to Pareto-optimal outcomes. Game theory techniques provide an effective and precise language for discussing specific water conflicts. A systematic study of a strategic water dispute provides insights about how the conflict can be better resolved and may suggest innovative solutions.

Many researchers have attempted water conflict resolution studies in a game-theoretic framework. Carraro et al. (2005), Parrachino et al. (2006), and Zara et al. (2006) review game theoretic water conflict resolution studies. Game theory applications in water resources literature cover a range of water resource problems, locations, solution methods, analysis types, and classifications (Tables 1–5). It may be possible to place some studies in more than one table (under more than one category). However, the main aspect of the study was considered for categorization. So far, game theory has been applied for (1) water or cost/benefit allocation among users (Table 1); (2) groundwater management (Table 2); (3) water allocation among trans-boundary users (Table 3); (4) water quality management (Table 4); and (5) other types of water resources management problems (Table 5).

Non-cooperative game theory deals with non-cooperative games in which players compete and make decisions independently whereas cooperative game theory deals with cooperative games in which groups or coalitions of players make decisions together and involves allocation of benefits from cooperation. Based on previous game theory applications to water resource management problems in the literature and Tables 1–5, one concludes that cost/benefit allocation and cooperative game theory applications have been more common among water resource researchers than other applications and methods. This might be because bargaining and cost sharing in cooperative game theory is easily understandable by water engineers as the solutions are sometimes similar to solutions in optimization where the problem can be solved by having a single objective function, which tries to address the conflicting goals within the system, and a set of constraints. Nevertheless, the increasing number of game theory researches by water scholars in recent decades underscores the growing desire for application of this methodology in resolving water conflicts. However, there is still a lack of knowledge about the value of application of game theory in water resources management and many water scholars have not learned the basic concepts of game theory from the work published outside the water area.

Table 1
Selected game theory applications for water or cost/benefit allocation among users in water resources literature.

Category 1: Water or cost/benefit allocation among users					
Objective(s)	Location	Solution method	Analysis type	Game theory classification	Citation
Fair allocation of water resource development costs to urban and agricultural sectors	Japan	Cooperative solution concept	Quantitative	Cooperative	Suzuki and Nakayama (1976)
Allocation of costs of a water resource development project among 18 municipalities	Sweden	Cooperative solution concepts	Quantitative	Cooperative	Young et al. (1980)
Developing a method by Tennessee Valley Authority for apportioning costs of dam systems among users	USA	Cooperative solution concepts	Quantitative	Cooperative	Straffin and Heaney (1981)
Allocation of benefits of wastewater reuse for irrigation project and formation of a hypothetical inter-farm cooperation in water use for irrigation among farms	Israel	Cooperative solution concepts	Quantitative	Cooperative	Dinar et al. (1992)
Equitable distribution of income derived from regulated water after trade between farms	Australia	Cooperative solution concepts	Quantitative	Cooperative	Tisdell and Harrison (1992)
Analyzing the response of water supply organizations in Western U.S. (California) to rural-to-urban water transfers	USA	Cooperative solution concept	Quantitative	Cooperative	Rosen and Sexton (1993)
Developing solutions to find the noxious facilities location (allocation of disutility between the agents) based on equity principles	Hypothetical	Cooperative solution concepts	Quantitative	Cooperative	Lejano and Davos (1995)
Developing a framework for non-cooperative, multilateral bargaining and analysis of water policy negotiations in California	USA	Rausser–Simon non-cooperative model of multilateral bargaining	Quantitative	Non-cooperative	Adams et al. (1996)
Evaluating schemes for allocation of joint environmental control cost among polluters in California	USA	Cooperative solution concepts	Quantitative	Cooperative	Dinar and Howitt (1997)
Efficient and equitable allocation of impact fees for urban water systems among zones, user classes, and demand types	Hypothetical	Cooperative solution concepts	Quantitative	Cooperative	Lippai and Heaney (2000)
Modeling negotiations over irrigation quotas, water price, and reservoir sizes among seven aggregate players	France	Rausser–Simon non-cooperative model of multilateral bargaining	Quantitative	Non-cooperative	Thoyer et al. (2001) and Simon et al. (2007)
Efficient sharing of a river among satiable agents (countries)	Hypothetical	Cooperative solution concepts	Quantitative	Cooperative	Ambec and Ehlers (2008)
Equitable and efficient water allocation among users at the basin level	Canada	Cooperative solution concepts	Quantitative	Cooperative	Wang et al. (2008)

Table 2
Selected game theory applications for groundwater management in water resources literature.

Objective(s)	Location	Solution method	Analysis type	Game theory classification	Citation
Category 3: Groundwater management					
Providing insights into and resolution of the strategic conflict arose after discovery of carcinogen in the aquifer supplying water to Elmira, Ontario	Canada	Graph Model for Conflict Resolution (GMCR)/ non-cooperative solution concepts	Qualitative	Non-cooperative	Hipel et al. (1993) and Kilgour et al. (1996)
Examining strategic behavior in groundwater depletion within the setting of state governance and groundwater resources in the American West	USA	Non-cooperative solution concepts	Quantitative	Non-cooperative	Gardner et al. (1997)
Studying the roles of cooperation and non-cooperation on sustainability of groundwater extraction	USA	Non-cooperative solution concept	Quantitative/ analytical discussion	Non-cooperative	Loaiciga (2004)
Developing a socially acceptable resolution for a multi-objective problem and balancing economic benefits from agriculture against negative environmental impacts	Mexico	Cooperative solution concepts	Quantitative	Cooperative	Raquel et al. (2007)

Three common 2×2 games are presented (Prisoner's Dilemma, Chicken, and Stag-Hunt) and their equilibria are introduced. Then the corresponding water game is introduced and the insights suggested from game theory are discussed. Also, Pareto-optimal results are introduced to show how game theory results can differ from the results of system engineering methods. This paper focuses on non-cooperative game theory and pure strategies. Studying mixed strategies is out of the context of this paper (Mixed strategies are when a player randomly selects pure strategies, assigning probabilities to each strategy. A player who plays with a pure strategy knows what to do in different situations and selects a pure strategy with a probability of 1.).

Prisoner's dilemma game

In Prisoner's Dilemma two suspects have been put in prison by police. The police do not have sufficient conviction evidence, and so have separated the suspects to prevent them communicating. The suspects are given an incentive to cooperate with the police. Each prisoner has the option of confessing or remaining silent. If one prisoner confesses while the other remains silent, the betrayer will get a reward and goes free and the silent prisoner is convicted and sentenced based on the other prisoner's evidence. In this case, the silent prisoner should stay in jail for a long period because of the crime and his non-cooperative behavior. If both prisoners remain silent and do not confess they will be released after a short time because of insufficient evidence for conviction. However, if both parties confess they both serve sentences. In the latter case, the period each prisoner stays in jail is shorter than the case in which one prisoner should go to jail because of remaining silent while the other prisoner confesses. The fundamental prisoner's dilemma is whether to trust the silence of his colleague or to trust the reduced sentence the police offer from betraying his colleague.

Fig. 1a shows the Prisoner's Dilemma in a normal (matrix) form with cardinal payoffs, representing the number of years each prisoner should serve in jail. Each cell has two values. The first value (left) represents player 1's payoff and the second value represents player 2's payoff. The strategies which yield the payoffs of each cell are given in left of the table for the first player and on top of the table for the second player. In this example, the lower the payoff for a player, the better is the outcome for that player. Fig. 1b represents Prisoner's Dilemma in ordinal form. In this figure payoffs correspond to the rank of outcome (or payoff) for a given player. The higher the rank, the more desirable is the outcome.

In this game, the best payoff for a given player occurs when he defects (betrays) and his opponent cooperates (remains silent), providing the lowest payoff to the opponent. Both players prefer the case when they both cooperate to the case in which both defect and (C, C) is Pareto-inferior to (DC, DC) which is one Pareto-optimal resolution of the game. However, the strictly dominant strategy for each player is to confess (C), meaning that no matter if the other player selects to confess or not, it is always better to confess ($4 > 3$ and $2 > 1$). Therefore, the outcome (C, C) which has lower payoffs than the Pareto-optimal (DC, DC) for both players is the dominant strategy equilibrium and the most likely resolution of the game under the conditions of the game, most importantly no communication. The outcome (C, C) is also a Nash Equilibrium (Nash, 1950, 1951); given the options of other players, no player can do any better (improve his payoff) by changing his strategy. Nash stability differs from Pareto-optimality. The former is about what is good for an individual without considering what is good for the whole system and the latter is about what is good for the system without considering the interests of the individuals within the system. A state is Pareto-optimal where

Table 3
Selected game theory applications for water allocation among trans-boundary users in water resources literature.

Category 2: Water allocation among trans-boundary users					
Objective(s)	Location	Solution method	Analysis type	Game theory classification	Citation
International conflict over flooding of Ganges and Brahmaputra rivers	India and Pakistan	Mixed strategies and dominant strategy selection	Quantitative	Non-cooperative	Rogers (1969)
Characterizing the negotiations of Columbia and Lower Mekong river basin schemes	Canada, USA, Cambodia, Laos, Thailand, and Vietnam	Metagame theory	Quantitative	Non-cooperative	Dufournaud (1982)
Conflict over water diversions from the Great Lakes	Canada and USA	Dominant strategy selection	Quantitative	Non-cooperative	Becker and Easter (1995)
Deriving policy lessons useful for US–Mexico water negotiations and institutions	Mexico and USA	Cooperative solution concepts	Analytical discussion	Cooperative	Fisvold and Caswell (2000)
Developing a flexible water allocation rule which guarantees efficient (Pareto-optimal) distribution of river (Ganges in this paper) flows to countries in a river basin	Bangladesh and India	Cooperative solution concepts	Quantitative	Cooperative	Kilgour and Dinar (2001)
Wastewater pollution emissions by riparian countries into the shared river	Mexico and USA	Differential game model	Quantitative	Cooperative and non-cooperative	Fernandez (2002, 2009)
Determining the shares and prices of water to be supplied for environmental services in the Platte River	USA (Colorado, Nebraska, and Wyoming)	Second price sequential auction	Quantitative	Non-cooperative	Supalla et al. (2002)
Developing stable water allocations which encourage cooperation among the countries riparian to Euphrates and Tigris	Iraq, Syria, and Turkey	Cooperative solution concepts	Quantitative	Cooperative	Kucukmehmetoglu and Guldmen (2004)
Establishing baseline conditions for incentive-compatible cooperation regimes in the Nile basin	Burundi, Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania, and Uganda	Cooperative solution concepts	Quantitative	Cooperative	Wu and Whittington (2006)
Providing insights into the conflict between Israel and the Arab nations over the Jordan river and determining the most likely outcomes of the conflict	Israel, Jordan, Lebanon, Palestine, and Syria	Graph Model for Conflict Resolution (GMCR)/non-cooperative solution concepts	Qualitative	Non-cooperative	Madani and Hipel (2007)
Identifying the most likely outcome (division method choice) of the Caspian Sea conflict and proposing some possible allocations	Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan	Fallback bargaining/social choice rules/bankruptcy procedures/descriptive modeling	Qualitative/quantitative	Cooperative and non-cooperative	Sheikhmohammady and Madani (2008a,b,c)
Providing insights into the strategic behavior of the involved parties in the Nile river conflict and determining the most likely outcomes of the conflict	Burundi, Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania, and Uganda	Graph Model for Conflict Resolution (GMCR)/non-cooperative solution concepts	Qualitative	Non-cooperative	Elimam et al. (2008)

Table 4
Selected game theory applications for water quality management in water resources literature.

Category 4: Water quality management					
Objective(s)	Location	Solution method	Analysis type	Game theory classification	Citation
Determining the amount of contaminant removal and contaminant discharge by each pollutant such that the polluters have the least loss	Hypothetical	Non-cooperative solution concept	Quantitative	Non-cooperative	Bogardi and Szidarovsky (1976)
Management of an aquifer which a multi-objective management goal	Hungary	Cooperative solution concept	Quantitative	Cooperative	Szidarovszky et al. (1984)
Developing an approach for surface water quality management considering the complicated regulatory environment and the negotiations between the polluters and an authority	Czech Republic	Bargaining model/extensive form game	Quantitative	Non-cooperative	Sauer et al. (2003)
Modeling the strategies of phosphorus application, resulting in water contamination, by farmers of the Hopkins basin	Australia	Cooperative and non-cooperative solution concepts	Analytical discussion	Cooperative and non-cooperative	Schreider et al. (2007)

Table 5
Selected game theory applications for other types of water resources management problems in water resources literature.

Category 5: Other types of water resources management problems					
Objective(s)	Location	Solution method	Analysis type	Game theory classification	Citation
Analysis of the economic potential of regional collaboration in water use in irrigation, based on the efficiency and equitability conditions, under conditions characterized by a general trend of increasing salinity	Israel	Cooperative solution concepts	Quantitative	Cooperative	Yaron and Ratner (1990)
Systematic study of a conflict over the proposed bulk export of water from Canada	Canada	Graph Model for Conflict Resolution (GMCR)/non-cooperative solution concepts	Qualitative	Non-cooperative	Obeidi et al. (2002)
Analyzing the stability of agreements on river water allocation between riparian countries under climate change	Hypothetical	Infinite repeated games	Analytical discussion	Non-cooperative	Ansink and Rujis (2008)
Analysis of the interaction of participating companies in an eco-industrial park seeking to develop an inter-plant water integration scheme	Hypothetical	Non-cooperative solution concept	Quantitative	Non-cooperative	Chew et al. (2009)
Finding cooperative bargaining solutions to negotiations among hydropower generators and the environmentalists in the Federal Energy Regulatory Commission (FERC) hydropower re-licensing process in the USA and exploring the climate change effects on FERC negotiations	Hypothetical	Cooperative solution concept	Quantitative	Cooperative game theory	Madani (2009)

no other state exists where one player can do better without harming at least one other player. A state which is a Nash Equilibrium might not be Pareto-optimal and vice versa. In the Prisoner's Dilemma game at state (C, C), player 1 is not willing to change his strategy from C to DC as 2 > 1. Similarly, player 2 will be worse off by changing his strategy from C to DC. Given the strategy of the opponent, no player is willing to change his strategy and (C, C) is a Nash Equilibrium. However, state (C, C) is not Pareto-optimal as both players can do better at state (DC, DC) which is one of three Pareto-optimal outcomes of the game. (C, DC) and (DC, C) are the other two Pareto-optimal outcomes, but (C, C) is only Pareto-inferior to (DC, DC). State (DC, DC) is not a Nash Equilibrium because both players can do better by changing their strategies unilaterally (4 > 3).

As discussed, game theory solution might differ from the results of conventional system optimization as game theory considers the behaviors of the individuals in the problem and their self interests rather than an objective for the system. In real world, results gained by players are not always optimal for the whole system as each player makes his own decision based on individual information about the game and his own criteria. A player might be unwilling to contribute to an overall optimization of costs or benefits for the whole system. However, based on conventional system optimization methods, usually a cost minimization or utility maximization objective function might be defined for a system and the problem is solved as a single-decision-maker problem, assuming all players are willing to follow the prescribed optimal solution.

Fig. 2 shows the ordinal payoff matrix for a groundwater game with a Prisoner's Dilemma structure in which two farmers tap a shared a aquifer over a long period (say 25 years). A payoff (profit) for each farmer is his revenues from crop sales minus pumping costs. Each player must choose between the cooperative and non-cooperative pumping rates with the non-cooperative rate (pumping rate 2) exceeding (the cooperative rate (pumping rate 1). If both farmers pump at the lower rate the groundwater level will not drop and the farmers can enjoy long-term low pumping costs. However, both farmers pumping at the higher rate reduces groundwater levels, increases pumping costs, and reduces profit, eventually making pumping economically infeasible, and ending irrigation and profits. Cooperative pumping increases profits for both farmers. Getting "free ride" (letting others contribute and benefit from their contributions without paying oneself) would be the best outcome for each farmer. In that case, one farmer pumps at the higher rate while the other one has committed to pump at a lower rate. The free rider gains the highest payoff in this situation due to pumping costs lower than the case in which both farmers pump at the non-cooperative rate and higher crop sale revenues than the cases in which he decides to cooperate. On the other hand choosing a cooperative strategy while the other farmer is willing to cooperate, results in the lowest payoff due to high pumping costs and low crop revenues.

The optimal outcome of this game is (*PR 1*, *PR 1*) when both parties pump at the lower rate (Loaiciga, 2004). However, game theory suggests, each individual farmer finds the inferior *PR 2* option as a strictly dominant strategy. Therefore, (*PR 2*, *PR 2*) is the predicted outcome based on non-cooperative game theory and in fact such overpumping is typical for real unregulated aquifer systems. Lack of trust and cooperative strategy enforcement (by controlling pumping rates, metering, etc.) leads farmers prefer pumping at the higher rate to increase short-run profits, a "tragedy of the commons (Hardin, 1968)". Cooperation becomes more difficult with many pumpers from the aquifer.

In many water sharing problems around the world non-cooperative behaviors of the parties have lead to "tragedy of the commons" outcomes despite the existence of cooperative Pareto-optimal solutions. Game theory explains and predicts such situations, even without precise quantitative information. In the Prisoner's Dilemma example, the game theory prediction was the same for quantitative (Fig. 1a) and qualitative (Fig. 1b) values. Thus, the results for any water resource problem with the same structure will be the same as in non-cooperative game theory the ranking of the outcomes matters more than the actual payoff values associated with outcome.

If the Prisoner's Dilemma situation (game) is repeated more than few times, communication is allowed, and/or parties trust each other, the final resolution might be to cooperate (DC) to reach the Pareto-optimal resolution. Similarly, in water resources conflicts with a Prisoner's Dilemma structure, explaining the problem to the parties and binding contracts or other forms of trust might lead to cooperation and better solutions. Generally, in Prisoner's Dilemma games, the threat of defection by other players results in non-cooperative behavior. By understanding the structure of the game and predicting (or interpreting) the players' behaviors through game theory, it might be possible to find measures for enforcing better resolutions by changing the payoffs which change the structure of the game. For this groundwater game, if parties are assured that the extractions are monitored and supervised by a regulating agency and there is a penalty for defection from cooperation, the defection threat is small, as non-cooperation is no longer a strictly dominant strategy.

If the problem is changed so farmers who exceed the cooperative pumping rate after committing to cooperation at the beginning of the pumping period, lose their rights to pump, the groundwater game's structure changes to Fig. 3. Here, the payoffs are changed based on the new regulation (and its enforcement). Farmers can be assured that once they start cooperation the old payoffs are no longer valid and game's structure changes from Prisoner's Dilemma (Fig. 2) to that shown in Fig. 3. In the new game, cooperation is the strictly dominant strategy and state (*PR 1*, *PR 1*) is the both Pareto-optimal and game theoretic resolution of the game. The new game's structure is not attainable before both farmers agree to cooperate at the beginning, because regulation agencies might not have the authority to cut water rights and force the farmers to pump less than their rights.

Carraro et al. (2005) believe that many natural resource management issues have the characteristics of a Prisoner's Dilemma game: players' dominant strategy is not cooperative, and the resulting equilibrium is not Pareto-optimal. Similarly, most papers dealing with sharing natural resources problems have made the same assumption about the game to be the Prisoner's Dilemma. However, all common resource problems might not be Prisoner's Dilemmas (Sandler, 1992).

The conditions of a natural resource sharing problem might favor the possibility of cooperation (Taylor, 1987). Water resource games are not necessarily rival (there might be multiple users and usage by one user does not prevent simultaneous usage by other users). Thus, coordination among the parties might be beneficial to all and can create externalities. However, some water resources games can be treated as anti-coordination games in which the available resource is rival (the resource can only be consumed

Player 1 \ Player 2	DC	C
Don't Confess (DC)	1,1	10,0
Confess (C)	0,10	6,6

(a) cardinal payoffs

Player 1 \ Player 2	DC	C
DC	3,3	1,4
C	4,1	2,2

(b) ordinal payoffs

Fig. 1. Prisoner's Dilemma.

by one user), sharing the resource comes at a cost to users, and the resource is not excludable (it is not possible to prevent a player who does not pay for the resource from enjoying its benefits). Identifying the structure of water resource games is essential as the results can be misleading if wrong assumptions are made in conflict modeling. For instance, characteristics of an anti-coordination water game cannot be captured if the conflict is modeled as Prisoner's Dilemma. Bardhan (1993) believes that the literature usually jumps to the case of Prisoner's Dilemma in case of free-riders. Sometimes, the player might not be able to reach his objective on his own. Under that condition (Stag-Hunt game) a player cooperates when the other player also cooperates and defects when the other one defects. In some common resource examples consequences of defection might be so bad that a player prefers not to defect if the other player defects (Chicken game) (Bardhan, 1993). Here, two non-Prisoner's Dilemma water resource games, useful for understanding water conflicts, are introduced to support the fact that not all water resources games are Prisoner's Dilemmas.

Chicken game

In this game (Fig. 4) two drivers, heading toward a narrow bridge from opposite directions, are driving toward each other. The first driver to swerve ("chicken" out) yields the bridge to the other driver and loses. No driver entering the race wants to be the chicken, but if no driver chickens out, both drivers might suffer from the resulting crash. Being called a "chicken" is better than dying, but worse that winning, for both players. A tie occurs when both players swerve. Under a tie, the players do not gain anything and the fight is over protecting their prides. If their prides are more important than their lives to them, they might both die proudly! The payoff of each player in this game can be the value of the prize at the end of the game or the utility from winning or losing the game. The higher the payoff, the more preferred is the outcome.

The Chicken game has two Nash Equilibria in which one driver loses and one driver wins, (DS, S) or (Win, Lose) and (S, DS) or (Lose, Win), which are also Pareto-optimal. The third Pareto-optimal resolution (S, S) or a tie, a socially optimal resolution, occurs where the gain of each player exceeds the minimum gain in the other two possible states (3 > 2 = minimum {2, 4}). This socially and Pareto-optimal outcome (S, S) is not a Nash equilibrium and might not occur when players make decisions based on self interest.

In the Chicken game the strictly dominant strategy is to play exactly the opposite of what the other player does. Similar to the Prisoner's Dilemma game, each player wants to get a free ride and the cooperative or agreeable mutual solution ((S, S) in Chicken and (DC, DC) in Prisoner's Dilemma) is not stable since each player is willing to refrain from it. However, these two games differ in that if both players decide to get free ride, the resulting outcome is the worst for both players in Chicken (DS, DS) while the resulting outcome in Prisoner's Dilemma (C, C) is suboptimal, but not the worst for both players.

Chicken games are rare in the water resources literature as most water resources sharing problems have been treated as coordination games and modeled as Prisoner's Dilemma. An example of an anti-coordination water resources game is the Iran–Afghanistan Conflict on Hirmand (Helmand) River at time of the Taliban regime in Afghanistan. The Hirmand River flows from Afghanistan to Iran and is important for agriculture in both countries as well as the survival of Hamun (Hamoun) Lake, an internationally recognized marshland in Iran's Sistan-va-Balouchestan Province. Although there is an allocation agreement between the two countries since 1972, Iran is still struggling to receive its share from the river. The conflict between the two countries has not been resolved and the situation is sometimes exacerbated by droughts and political instability in Afghanistan. When the Taliban were in power in Afghanistan, this regime was unwilling (or could not afford) to pay the operations and maintenance (particularly sediment removal) costs for the Kajaki Reservoir in the Afghan territory. As a result Hrimad River dried up below the dam affecting agriculture and urban water supply in both sides of the border, and Hamoun's Lake and its ecosystem were dying. While the Afghans have responsibility to maintain the reservoir system and secure Iran's share of the river, since the Taliban was not doing so, the Iranians thought of fixing the system on the other side of their border. During this period, the conflict's structure was similar to a Chicken game (Fig. 5). Both sides could benefit from performing the required maintenance services. Payoffs for each country were equal to their urban, agricultural, and environmental benefits minus the maintenance cost paid. The values shown in Fig. 5 are ordinal. Apparently, each side was willing to get a free ride, and spend less (minimize costs) and make more (maximize revenues). The status quo of the game, (DP, DP), in which no party would pay for the maintenance was the worst outcome, due to high urban agricultural, and environmental losses. The two equilibria of this game were (DP, P) and (P, DP) in which one party would pay the maintenance costs. The game is a Chicken game, and although being socially and Pareto-optimal, the cooperative outcome (P, P) is not a Nash Equilibrium. In this conflict, the Iranians chose to chicken out and sent teams to bring the system back to operation. Although, the final result was not ideal for the Iranians (no free ride), the cost of defection (DP) for them was so high, that they preferred not to pay (P) when they found the Afghans were willing to defect (not paying).

A good tactic in a Chicken game is to reduce one's options and feasible outcomes of the game by signaling intentions (plans) clearly to the opponent(s) early in the game. The sent signal by a party should be strong, aggressive, and ostentatious to convince the other party that defection (DS or DP) is not the right choice. In the Chicken game one driver pretentiously can handcuff his hands behind his back before entering his car, lock his steering wheel in a straight position before the game starts, or throw the steering wheel out of the window early in the game, to force the other player to swerve. Other examples of such behavior within a Chicken's structure are a food striker who sews his lips shut, a protester who has locked himself to an object, a programmed security system which explodes the property it protects if someone tries to trespass, or a nuclear doomsday device which is programmed to

		Farmer 2	
		PR 1	*PR 2*
Farmer 1	*Pumping Rate 1 (PR 1)*	3,3	1,4
	Pumping Rate 2 (PR 2)	4,1	2,2

Fig. 2. Groundwater exploitation game with ordinal payoffs.

		Farmer 2	
		PR 1	*PR 2*
Farmer 1	*PR 1*	3,3	4,1
	PR 2	1.4	2,2

Fig. 3. Groundwater game with penalties for defection after starting cooperation.

explode in case of invasion (“Doctor Strangelove”). In case of the Iran–Afghanistan Conflict on Hirmand, it was obvious to the Iranians that the Taliban were unwilling or unable to cooperate under any condition. The Shia Muslim Iranians had never recognized the Sunni Muslim Taliban as the legal government of Afghanistan and the two governments had no political relations. The ongoing wars among Afghan parties also made the Taliban politically and economically unstable. The aggressive behavior of Taliban benefited the Afghans as a clear signal from the Taliban side, and the Iranians preferred to chicken out to pay for maintenance.

Unlike Prisoner’s Dilemma in which parties lose together, the Chicken game has one winner and one loser. The Chicken game’s structure and payoff values leave no incentive for cooperation. In water resources problems with a Chicken game structure, one might promote cooperation by increasing the penalty for defection (non-cooperation). For instance, for a conflict between two farmers over paying the maintenance costs of the pumps and irrigation channels which they both use (Fig. 6a), a higher authority with a superior power (such as a farmers union or an irrigation district) can impose extra charges on farmers who do not pay maintenance costs, and so promote cooperation and prevent defection (Fig. 6b). Without penalties (Fig. 6a), each farmer prefers to get a free ride and not pay, leading to the system’s demise. In that case, each farmer prefers not to defect prefers to cooperate when the other farmer defects (does not cooperate) and to defect when the other farmer does not defect. However, if defection has costs (high enough penalties) (Fig. 6b), a player is not interested in getting free ride, cooperation becomes a strictly dominated strategy, and the cooperative resolution (P, P) becomes a dominant strategy (and Nash) equilibrium.

Stag-Hunt (assurance) game

In this game (Fig. 7) two individuals who are out hunting can choose between hunting a stag together and a hare individually, without knowing the other player’s choice. A stag has the highest payoff for both players (half of a stag’s value goes to each hunter) but can be hunted only when both players cooperate. Instead, each player can choose to hunt a hare on his own which has a lower payoff. The worst case for a given player occurs when he chooses to hunt a stag (cooperation) and the other player chooses to hunt a hare (defection).

Table 6 reviews the characteristics of the three games introduced so far. Similar to Prisoner’s Dilemma, Stag-Hunt is a coordination game and the two games might be confused. In both games the cooperative resolution is Pareto-optimal and the non-cooperative Pareto-inferior resolution is a Nash Equilibrium. However, unlike Prisoner’s Dilemma, the Stag-Hunt has no strictly dominant strategy ($3 > 2$ but $1 < 2$) and the game has one more Nash equilibrium. Unlike Chicken, in which each player does the opposite of the other player, in the Stag-Hunt, each player’s interest is to do exactly as the other player. Although a Stag-Hunt does not look like a dilemma, game theory finds it as a dilemma and predicts that players do not always cooperate to reach the only Pareto-optimal resolution (S, S). In practice, sometimes, players might choose not to cooperate, perhaps due to lack of trust, which results in a Pareto-inferior result (H, H) for the game. So, the game can be also called a “Trust Dilemma (Grim et al., 1999)”.

A water resources example with a Stag-Hunt structure is shown in Fig. 8. In this game two littoral countries share a lake. Each country has one river flowing into the lake. As a result of high evaporation and reductions in seasonal flows of the two rivers from upstream consumptive use, the lake is drying up, becoming salty, and its ecosystem is deteriorating. For the lake and its ecosystem to survive, both countries must increase water releases to the lake by a specific amount (say 40%). Because of high evaporation, an increase in flow only by one country cannot solve the problem. The payoff of each country is the environmental benefit from increasing the inflow to the lake minus the revenue lost from decreasing upstream consumptive use (even if calculation of environmental benefits in monetary values is not possible, parties still are able to rank the possible outcomes). If both countries reduce consumptive use upstream and increase releases to the lake, the environmental benefits will exceed the revenue losses from reduced upstream consumption. However, if only one country increases its release to the lake, the lake’s problem is partially solved, the environmental benefits will be minimal, and that country’s payoff will decrease from revenue losses from decreased upstream use. The game has two equilibria, cooperative (I, I) and non-cooperative (DI, DI).

In the Trust Dilemma, if players trust each other, there is no risk of failed cooperation and the players will cooperate. However, in practice, non-cooperation is a risk-free strategy, leading to an outcome which is not the best, but better than the worst in absence of trust to the other players. Based on this finding within a Stag-Hunt structure: the rowers of a boat stop rowing or row slower to minimize their energy loss, when they suspect other rowers are not rowing effectively, although if everyone rows at the same rate, boat speed is higher; stockholders might sell their stocks individually when the company is not performing well and there is a risk of other stockholders selling their shares, although they could do better if they all keep their stocks or sell their shares together; or countries build nuclear weapons when there is a risk that other countries develop nuclear weapons, although they all agree and know that the world would be safer without nuclear weapons.

Generally, there is no tendency to free ride in a Stag-Hunt game as the payoff for non-cooperation is insensitive to what the other player does. Therefore, if one player observes signs of cooperation from the other party, he will cooperate. Similar to a Prisoner’s Dilemma, repetition of a Stag-Hunt game can help increase trust among the parties and leading to a Pareto-optimal resolution. In the presented water conflict, however, the parties might not have a chance to repeat the game many times to find if other players are trustworthy. Instead, negotiations and clear cooperative signals will be helpful in reaching the Pareto-optimal resolution (I,I).

Driver 1 \ Driver 2	S	DS
Swerve (S)	3,3	2,4
Don’t Swerve (DS)	4,2	1,1

Fig. 4. Chicken game with ordinal payoffs.

Iran \ Afghanistan	P	DP
Pay (P)	3,3	2,4
Don’t Pay (DP)	4,2	1,1

Fig. 5. Iran–Afghanistan Conflict on Hirmand (Helmand) River at the time of Taliban regime in Afghanistan.

(a) no penalty for defection

Farmer 1 \ *Farmer 2*	*P*	*DP*
Pay (P)	3,3	2,4
Don't Pay (DP)	4,2	1,1

(b) with penalty for defection

Farmer 1 \ *Farmer 2*	*P*	*DP*
P	3,3	2,2
DP	2,2	1,1

Fig. 6. Maintenance costs game.

Evolution of game structure (dynamic games)

Generally, in the course of modeling conflicts, modelers should be careful about identifying the game conditions and how these conditions could change. Changes in the conflict can change the payoff functions and values of players over time. Changing game conditions can alter the game's structure, its equilibria, and the results provided by game theory. Beside the modeler, players should be aware of the game's course of evolution and changing conditions. Early knowledge of changing game structure might lead to different behaviors by players to reduce risks of future lower payoffs.

Water problems often evolve over time. Knowledge of the changing payoff functions and water problem's structure is essential for finding reasonable solutions and useful insights into the problem. In a water resource example, two farmers share a newly built irrigation system and each has the options of paying the maintenance costs of the system and not paying. Fig. 9 shows how payoffs for each player change over time for the four possible outcomes of this game ((P, P), (P, DP), (DP, P), (DP, DP)). Since the example problem is symmetric, the payoffs are the same for both players. The first strategy in parentheses belongs to player i and the second belongs to player $j \neq i$ where $i, j \in N = \{Farmer\ 1, Farmer\ 2\}$. Table 7 shows how payoffs, varying with time, have been calculated. At the beginning (Period 1) the farmers can pay for the required system's minimal maintenance costs, but, there is no risk of failure at this stage, so the payoff of the player who pays the maintenance cost is equal to his share from the maintenance cost (if both players pay, the cost is divided equally). Since there is no risk of irrigation system failure, the player who pays nothing, has a payoff of zero during the first period. If no maintenance is performed over time, maintenance costs and the risk of system failure increase. In Period 2, risk of failure grows and the risk of revenue losses for each player is less than half of the maintenance cost if no farmer pays the maintenance cost. When one farmer alone pays the maintenance cost, his payoff is the entire maintenance cost while the other farmer has a zero payoff because the system gets fixed and there will be no risk of failure. If no farmer spends on maintenance, the risk of economic loss becomes more than half of the maintenance costs in the third period and more than the total maintenance costs in the fourth period. The risk of economic loss is half of the maintenance cost at Point A and equal to the total maintenance cost at Point B.

Table 6
Characteristics of the introduced two-by-two games.

	Prisoner's Dilemma	Chicken	Stag-Hunt
Strictly dominant strategy	Non-cooperation	–	–
Dominant strategy	Non-cooperation	–	–
Nash equilibrium	Non-cooperative	Non-cooperative	Cooperative Non-cooperative
Dominant strategy equilibrium	Non-cooperative	–	–
Pareto-optimal outcome	Cooperative	Cooperative Non-cooperative	Cooperative
Classification	Coordination game	Anti-coordination game	Coordination game

Fig. 10 and Table 8 show how the structure of the irrigation system's maintenance game evolves over time. As a result of the changing problem structure, the equilibria and the Pareto-optimal outcomes of the game change. During Periods 1 (Fig. 10a) and 2 (Fig. 10b) and at Point A (Fig. 10c) DP is a strictly dominant strategy and (DP, DP) is the dominant strategy equilibrium, the only Nash equilibrium, as well as a Pareto-optimal outcome. In Period 2 and at Point A, the problem has other Pareto-optimal outcomes, but since they are not equilibria, game theory suggests that farmers are unwilling to share the maintenance costs at this point. At point A (P, P) and (DP, DP) are socially optimal outcomes. However, based on a Nash solution (stability definition) outcome (P, P) is not a possible resolution of the conflict. In Period 3 (Fig. 10d) the problem finds a Prisoner's Dilemma structure. DP is still the strictly dominant strategy and (DP, DP) is the dominant strategy and Nash equilibrium as well as the Pareto-inferior outcome. Although (DP, DP) is Pareto-inferior to (P, P) where the farmers share the cost, parties might decide not to pay any cost in this period. At point B (Fig. 10e), DP is a dominant (not strictly dominant) strategy ($3 > 2$ and $1 = 1$) and there are three Nash equilibria ((DP, P),(P, DP), and (DP, DP)), two of which are Pareto-optimal ((P, DP) and

Hunter 1 \ *Hunter 2*	*S*	*H*
Stag (S)	3,3	1,2
Hare (H)	2,1	2,2

Fig. 7. Stag-Hunt Game with ordinal payoffs.

Country 1 \ *Country 2*	*I*	*DI*
Increase (I)	3,3	1,2
Don't Increase (DI)	2,1	2,2

Fig. 8. Neighboring countries with a common environmental problem game.

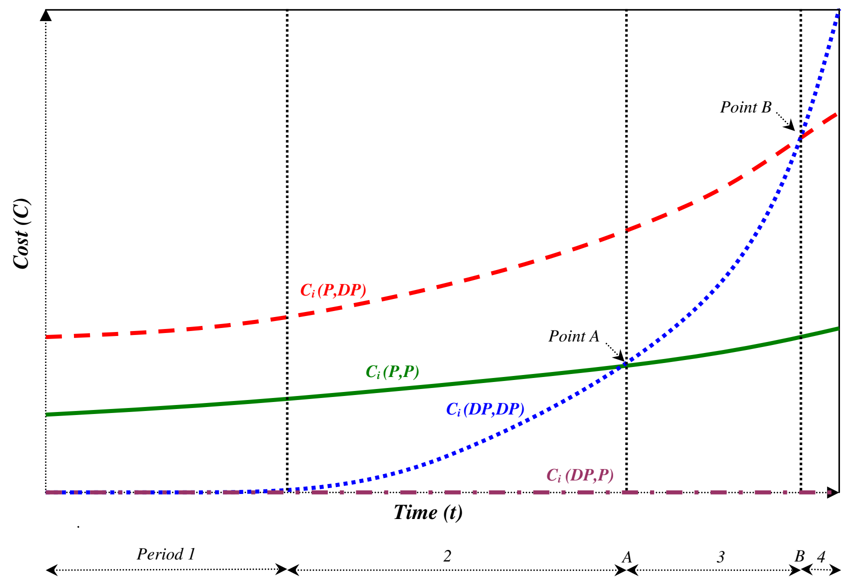

Fig. 9. Payoff of player *i* during the irrigation system's maintenance conflict.

(DP, P)). (P, P) is another Pareto-optimal outcome of the game. (DP, DP) is Pareto-inferior to all three Pareto-optimal outcomes. Game theory suggests that a player with a lower risk tolerance might decide to take care of the maintenance costs at this stage. If the players have the same risk tolerance, they will end up in not paying any cost and enter Period 4 of the game (Fig. 10f), which has the Chicken structure. In this period one player will chicken out and take care of the maintenance costs to avoid high revenue losses from system failure.

The conflict problem changes significantly with each state. If the evolution of the problem is considered, game theory provides useful insights to explain players' behavioral changes. Thus, it is important to recognize the correct stage of the problem for modeling. If the problem is not modeled correctly and the problem's evolution is not considered, results might be wrong or misinterpreted. By analyzing different stages of the irrigation system's conflict it was found why players might avoid paying or sharing the maintenance costs at the early stages for not ending up in paying high amounts later on, something which might be interpreted as irrational behavior if the conflict's evolution path is not considered.

The optimal solution of the irrigation system's game is to share the maintenance cost from the start. However, players may not have a clear understanding of the problem, how the structure of the game might evolve, how long they will be involved, and the risk tolerance of other players. Sometimes, players have short foresight and make their decisions based on the current conditions, without considering the future changes. If a player is aware of the changing structure of the game and sure that he will eventually chicken out because the opponent has a higher risk tolerance or is more aggressive, he might decide to pay all maintenance costs from the start to avoid high costs in the future. On the other hand, a player with perfect foresight about the future and a high-risk tolerance might be willing to prolonging the game and reach the last period (Chicken stage) to force the other player to chicken out and take care of the maintenance cost.

Table 7
Possible outcomes and descriptions of payoffs in the irrigation system's maintenance conflict.

Outcome (S_i, S_j) $S_i, S_j \in S = \{P, DP\}$	Payoff $C_i(t)$, $C_j(t)$
(P, P)	$C_i(t)$ = Half of the total maintenance cost $C_j(t)$ = Half of the total maintenance cost
(P, DP)	$C_i(t)$ = Total maintenance cost $C_j(t) = 0$ (There is no risk of revenue loss to player *j* due to the system's failure when player *i* pays for the maintenance)
(DP, P)	$C_i(t) = 0$ $C_i(t)$ = Total maintenance cost
(DP, DP)	$C_i(t)$ = Risk of revenue loss to player i due to the system's failure $C_j(t)$ = Risk of revenue loss to player j due to the system's failure

Conclusions

Game theory can provide insights for understanding or resolving water conflicts which often are multi-criteria multi-decision-makers problems. It sometimes can reflect and address different engineering, socio-economic, and political characteristics of water resources problems even without detailed quantitative information and without a need to express performances in conventional economic, financial, and physical terms. Game theory can predict if the optimal resolutions are reachable and explain the decision makers' behavior under specific conditions. The stakeholders' decisions and behaviors might seem to be irrational from the system engineering perspective, but game theory can explain how decision makers' rational behavior, trying to maximize their own objectives, might result in overall Pareto-inferior outcomes.

By simple examples of 2×2 water resources games, it was discussed how game theory results might not be optimal for the whole system and how decision makers can make decisions based on self interests and the problem's current structure. The examples presented here are very simple. The water resource conflicts may not be so simple in practice. However, understanding the basic concepts of game theory allows for modeling complicated water resource problems to gain valuable insights into strategic behaviors of the stakeholders. Non-cooperative game theory can handle real world conflicts in absence of accurate quantitative information, where only ordinal information is available, which is a great advantage of game theory over conventional systems engineering methods.

Although, most water conflicts (games) have been previously modeled as Prisoner's Dilemma, simple presented examples of games with different structures and characteristics (i.e. Chicken and Stag-Hunt) support the idea that not all water resources games are Prisoner's Dilemma. It was also discussed how the structure of the games might be changed by third parties and regulating agencies to promote Pareto-optimal resolutions to water conflicts considering the non-cooperative behaviors of the stakeholders.

Water resource problems often change over time. The evolution of a game's structure should be considered while studying water resource conflicts. By understanding a game's evolution, a more realistic interpretation of the stakeholders' behaviors can be provided. An example showed how the structure of the problem evolves from the status quo based on decisions made by stakeholders in different stages of the game. In that example, the self-optimizing and non-cooperative characteristics of the players over time resulted in a final undesirable structure under which even the cost of cooperative resolution was much higher than the cost of non-cooperation (losing or paying all the costs individually) early in the game. Sometimes, decision makers have imperfect foresight and an unclear understanding of the game's conditions and other players' characteristics (e.g. risk attitude, cooperative tendency, aggression level, etc.). Providing information about the evolving structure of the problem and the risk of undesirable future outcomes (high costs) in the future might help change behavior and decisions to reduce overall losses.

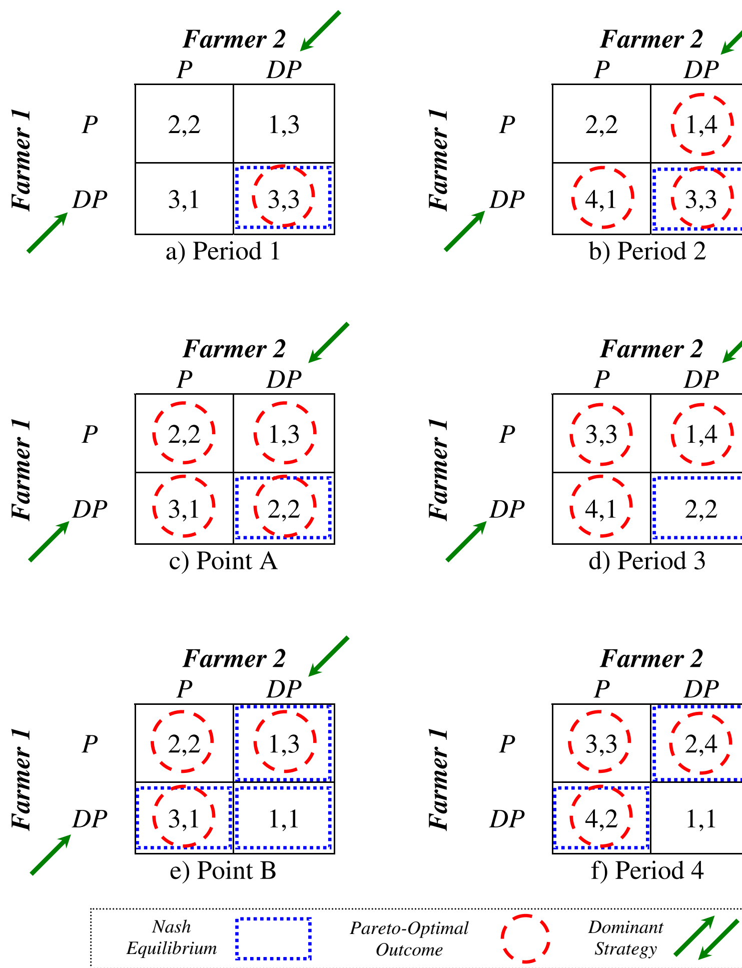

Fig. 10. Irrigation system's maintenance game.

Table 8
Characteristics of the irrigation system's maintenance game at different stages.

	Period 1	Period 2	Point A	Period 3	Point B	Period 4
Strictly dominant strategy	DP	DP	DP	DP	–	–
Dominant strategy	DP	DP	DP	DP	DP	–
Nash equilibria	(DP, DP)	(DP, DP)	(DP, DP)	(DP, DP)	(P, DP), (DP, P), (DP, DP)	(P, DP), (DP, P)
Dominant strategy equilibrium	(DP, DP)	(DP, DP)	(DP, DP)	(DP, DP)	(DP, DP)	–
Pareto-optimal outcomes	(DP, DP)	(P, DP), (DP, P), (DP, DP)	(P, P), (P, DP), (DP, P)	(DP, DP)	(P, P), (P, DP), (DP, P)	(P, P), (P, DP), (DP, P)	(P, P), (P, DP), (DP, P)

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