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Application of game theory in water resource management

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ABSTRACT

With this research paper, we aim to analyse the effectiveness of Game Theory in Water Resource Allocation through simple two-by-two symmetric water resource games. The results of examples using three kinds of game theory icons are scanned to compare cooperative and non-cooperative game players. The highest payoff is achieved when both the players cooperate hence this paper explains how decision makers' rational behaviour, who are trying to maximize their own objectives, might result in overall Pareto-inferior outcomes.

Keywords— Game Theory, Prisoner's Dilemma, Chicken game, Stag Hunt

1. INTRODUCTION

The activity of designing, developing, dispersing and managing the optimum use of water resources under blueprints and regulations is called Water Resource Management. The major objective of water resource management is to modify the use of water and to minimize the environmental impact of water use on the natural environment. Ideally, water resource management planning considers the competing demands for water and aims at allocating water on an equitable basis to satisfy all uses and demands (International, 2014)

A 40% scarcity in the water supply is estimated to arise by 2030 owing to the increasing rate of global population. Presently, 148 countries share 276 Trans-Boundary basins, which accounts for 60% of the global freshwater flow. The global dependency on groundwater is 2 billion people owing to 300 aquifers systems being Trans boundary in nature. (Hagbrink, 2017). Countries now have to improve their water resource management and associated services to deal with such complexities.

A study known as "Game Theory" can be applied to develop policies for water resource allocation. "Game theory is the study of mathematical models of strategic interaction between rational decision-makers" (Wikipedia). Since water resource management usually involves conflict, Game Theory identifies and interprets the behaviours of the parties who aim for their own objectives rather than the system's objective.

We have considered three-game theory icons, namely: prisoner's dilemma, chicken and stag hunt. Both the players benefit in each game when they cooperate. If one player does not cooperate, the payoff decreases. Although there is always a temptation to defect, each player covers for the other's cooperation.

2. OVERVIEW

Water is fundamental to human life. Although it covers 71% of our world, it is scarce. Global demand for freshwater has been growing exponentially as a result of the population explosion and greater affluence. In addition to this, climate change and environmental degradation are altering the regional and seasonal availability and quality of water. The inefficient governance and management of this scarce resource have led to en number of conflicts and even violence. A few examples of these conflicts are listed below:

- The dispute at the Cauvery Basin in India
- The dispute at the Nile Basin
- The dispute in Turkey, Syria, and Iraq over the Euphrates-Tigris
- The Security Implications of growing water scarcity in Egypt

(Adrien Detges, 2017)

Complex societies and economies have evolved and grown in many regions, with water resource infrastructure having been significantly developed. More complex water management problems have arisen that go beyond the optimal operation of a single component or class of water system components (reservoirs or prices). These contemporary water management problems call for a more integrated and comprehensive optimization of water management within a much larger and more diverse economy, and within an institutional structure which is far more de-centralized than traditionally assumed. This is where operations research comes into the picture; this paper applies game theory to produce a better approach to an optimal solution. (Lund, 2008)

3. WHY GAME THEORY?

What is a 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."

The objective is to predict how people behave, trying to achieve their goals while in conflict. It includes decision makers (players) trying to outsmart one another by anticipating each other's decision. The game is resolved as a byproduct of the players' decisions. The resolution of the 'game' leads to optimal decision making and describes the game's outcome.

In the industry being discussed, game theory could result in a revolutionary change in efficiency and optimality. Saving significant amounts of the essential scarce resource- water.

- Game theory creates a realistic simulation of stakeholders' interest-based behavior. The self-optimizing behavior of players and stakeholders, often results in non-cooperative behaviors, although cooperative competition could be a win-win situation.
- The model can create planning, policy, and design insights that would be unavailable from other traditional systems and engineering methods.
- Another advantage of game theory over traditional 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. This enables to handle the socio-economic aspects of conflicts and planning, design, and policy problem when quantitative information is not readily available. (Madani, 2009)

3.1 The challenges

- The complexity in the economics that comes with large-scale water resources projects are challenging; the industry impacts different strata of the society and varied geographical locations differently.
- The unpredictability of natural and climatic conditions makes creating forecasts even more challenging. However, the implications would be significant in extent and variety.
- The large number of decision variables involved, stochastic nature of the inputs, and multiple objectives makes this sector an obstacle course towards optimality using the given model. (Bithin Datta, 2005)

Therefore, we can see the relevance, challenge, and important resource incorporating operations research into the management of water resources.

4. LITERATURE REVIEW

A number of models have been applied to the management of water resources given its importance and one such is System dynamics. A study (Chen & Wei, 2014) by Zhihe and Shuai collected literature on the application of the SD method in water security over the past 20 years. It verified research for water security systems and discussed the progress of research on flood control, disaster mitigation, water resource security, and water environment security which focused on water quality management, water pollution control, early warning systems, and water ecology. The study of water ecological security had primarily focused on the bearing capacity of water ecology. The study concluded SD method can properly solve the complicated relations in the water security system; however, has deficiencies in the following aspects: research on large systems; the influence of social environment changes; uncertainties in water security; and the methods, means, and influence of natural environment changes on water security. Roozbahani, Abbasi, Schreider proposed_(Roozbahani, Abbasi, & Schreider, 2015)_a mixed-integer multi-objective model for sustainable water allocation of a multi-stakeholder river basin. The proposed model maximized the profits of stakeholders simultaneously, while, water requirement of the environment in the entire basin was satisfied. The approach, first, finds the highest possible profits for the stakeholders (the HPP model) and then maximizes sequentially the minimum ratio of stakeholders' profits achieved by their water shares to their highest possible profits in each time step until obtaining a non-dominated solution (Highest ratio of highest possible profit model). A study by Muhammad and Pfug (Muhammad & Pflug, 2014) compared the stochastic programming model and the Deterministic model for the Indus Basin Irrigation system considering the vast network of rivers and canal system which resulted in a huge model. The study concluded that the stochastic model could be used as a great administrative tool for decision making, formulating the cropping policies and scheduling the reservoir's release. It also noted the flexibility a stochastic approach has over a deterministic one which increased when decisions were managed over a shorter period. In the 200 scenarios generated for hydrologic parameters, a stochastic model showed a highly significant improvement over the deterministic one. The study also provided a reconciliation among the provinces of Pakistan over surface water was provided by incorporating a political constraint. Researchers have suggested optimization models balance the conflicts among water users regarding the allocation of water recourses (Heydari, Othman, & Qaderi, 2015). One of those models is Linear Programming. Significant advantages of the LP method are its ability to solve large scale problems in the best possible way, easy to perform sensitivity analysis and uncomplicated problem solving. One of the drawbacks with LP formulation in reservoir operation and management is that reservoir storage continuity equation cannot explicitly control spillway, whereas perhaps when the reservoir is not full in optimized solutions some values are considered for the spillway (Heydari, Othman, & Qaderi, 2015). Another study (Sechi, Zucca, & Zuddas, 2013) proposed CGT (cooperative game theory) approach to solving the cost allocation problem for a water resources system. The developed methodology allowed a cost-sharing policy definition by water authorities that should be accepted more easily by stakeholders. The methodology provided an adequate justification of the adopted sharing criteria and promoted cooperation among the users in order to maximise the efficiency of water use, satisfying rationality and marginality principles in the management of the system.

Various studies and researches have also focused on game theory and its applications. A study by Shubik (Shubik, 1955) did a detailed study of the model of 'game theory' and its applications in the world of management. It studied two types of theories, the two-person zero sum game, and Non-zero-sum game. The study concluded that the problems that have a direct application in the first theory have certain aspects of a duel; in a duel, the goals of the opponents are diametrically opposed. An example given was that of a market constricted by the government where demand is constant, a gain by one firm will mean that loss by the other. Game theory has also been applied to supply chain management. A study by Fiala (Fiala, 2016)explores the possible correlation between the components of the supply chain and the decision-making tool – Game theory. The study focused on the supply chain participants having an integration of Cooperative behaviour and Non-Cooperative behaviour.

Game theory has played and continues to play a large role in the social sciences. Beginning in the 1970s, game theory has been applied to animal behaviour, including evolutionary theory. Many games, especially the prisoner's dilemma, are used to illustrate ideas in political science and ethics. Game theory has recently drawn attention from computer scientists because of its use in artificial intelligence and cybernetics (Sindik & Vidak, 2008).

5. OBJECTIVES

- To determine how the concept of Game Theory can be used to discuss specific water conflicts.
- To display how a systematic study of a strategic water dispute provides an insight into how the conflict can be better resolved.
- To emphasize how Game theory applications in water resource literature cover a range of water resource problems, solutions, analysis types, and classifications.
- To show how Game Theory results differ from the results of system engineering methods.
- To provide innovative solutions to complex water disputes using the concept of Game Theory.

6. ANALYSIS

6.1 Prisoner's dilemma

In Prisoner's Dilemma, two suspects are put in prison by police. The police do not have sufficient evidence, and so have separated the suspects to prevent them from interacting. The suspects are given an incentive to collaborate with the police. Each prisoner has the option to confess or remain silent. If one prisoner confesses to the police while the other remains silent, the traitor will get a reward and goes free and the silent prisoner is convicted. In this scenario, the silent prisoner should stay in jail for a long period because of the crime and his non-cooperativeness. If both suspects remain silent and do not confess they will be released after a short period because of lack of evidence. However, if both suspects confess they both serve sentences (fig 1). 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 suspect confesses (Madani, 2009). The fundamental prisoner's dilemma is whether to have trust in the silence of his colleague or to have trust in the reduced sentence the police offers from betraying his fellow colleague (Madani, 2009).

		PRISIONER 1	
		D	C
PRISIONER 2	D	G,G	L,G
	C	G,L	L',L'

D- Don't confess
C- Confess
L- Loss
L'- a lower loss lower than L
G- Gain

Let us take an example of a groundwater game with a Prisoner's Dilemma (Madani, 2009) a structure in which two farmers tap a shared aquifer over a long period (say 20 years). A payoff (profit) for each farmer is his revenues from crop sales minus pumping costs (Madani, 2009). Each farmer (player) must choose between the cooperative pumping rate (PR1) and non-cooperative pumping rates (PR2) with the NCR exceeding the CR. If both farmers pump at the lower rate the groundwater level will not go down and the farmers can enjoy a long-term low cost of pumping. However, both farmers pumping at the higher rate decreases groundwater levels, increases the cost of pumping, and hence reduces profit, eventually making pumping economically infeasible. Cooperative pumping increases profits for both farmers. Getting ''free ride" that is letting others contribute and benefit from their contributions without paying oneself would be the best outcome for each farmer (Madani, 2009). In that case, one farmer pumps at the higher rate while the other farmer has committed himself to pump at a lower rate. The free rider gains a payoff which is highest in this situation due to pumping costs which are lower than in the scenario/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 (Madani, 2009). On the other side, selecting a cooperative strategy while the other farmer is also willing to cooperate, results in the lowest payoff due to high pumping costs and low crop revenues (Madani, 2009). 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 predicted outcome which is 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 leads farmers to prefer pumping at the higher rate to increase short-run profits which are called ‘‘tragedy of the commons” (Hardin, 1968). Cooperation becomes harder with a lot of pumpers from the aquifer. In many water sharing problems around the world, non-cooperative behaviours of the player/parties have led to ‘‘tragedy of the commons” outcomes despite the existence of cooperative solutions. Game theory explains and predicts such situations, even without precise quantitative information (fig 1 and fig 2). Thus, the results for any water resource problem with the same structure will be the same as in non-cooperative game theory where the ranking of the outcomes matters more than the actual payoff values associated with outcome (Madani, 2009). 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 (Madani, 2009) 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 behaviour. By understanding the structure of the game and by predicting (or interpreting) the players’ behaviours 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 will be monitored and supervised by a regulating body and there is a penalty for defection from cooperation to non-cooperation, the defection threat is small, as non-cooperation is no longer a strictly dominant strategy. Carraro (Carraro, 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, not all common resource problems are Prisoner’s Dilemma (Sandler, 1992).

		Farmer 1	
		PR1	PR2
Farmer 2	PR1	G,G	L,G
	PR2	G,L	L,L

6.2 Chicken game

In this game (Fig. 4) two drivers driving a vehicle are heading towards a narrow bridge from opposite directions (they are driving towards each other). The first driver to swerve or ‘‘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 will suffer from the resulting crash. However, Being called a ‘‘chicken” is better than dying but worse than 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 pride. If their pride are more important than their lives, 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 (Madani, 2009). The Chicken game has two 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. 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)(fig 3) while the resulting outcome in Prisoner’s Dilemma (C, C) is suboptimal, but not the worst for both players.

		Driver 1	
		S	DS
Driver 2	S	L,L	L,G
	DS	G,L	HL,HL

S – Swerve
DS – don’t swerve
HL – a loss much higher than L

Chicken games are mostly rare in the water resources literature as most of the water resources sharing problems have been modelled as Prisoner’s Dilemma (Madani, Game theory and water resources, 2009). An example of an anti-coordination water resources game is the Iran–Afghanistan Conflict on Hirmand (Helmand) River at the 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 exists 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 yet 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 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 a 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 have benefitted from performing the required maintenance. Payoffs for each country were equal to their urban, agricultural, and environmental benefits minus the maintenance cost paid. 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. 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).

		Country 1	
		P	DP
country 2	P	L,L	L,G
	DP	G,L	HL,HL

P - Country pays for maintenance of shared water resource
DP – country doesn't pay for maintenance of shared water resource

A good tactic in a Chicken game is to reduce one's options and feasible outcomes of the game by signalling 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 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 behaviour of the Taliban benefited the Afghans as a clear signal from the Taliban side, and the Iranians preferred to chicken out to pay for maintenance.

6.3 Stag Hunt (assurance) Game

In this game, two players have to choose whether to hunt a stag together or a hare individually, without knowing the other player's decision. A stag can only be hunted if there is cooperation among both the players, but a stag holds the highest payoff value for both as half the value of the stag goes to each hunter. A hare can be hunted by either of the hunted individually, but it has a lower payoff. The worst case scenario in this game occurs when one hunter decides to hunt a stag but the other one chooses to hunt a hare discretely. Erratically, the hunters might sometimes decide not to cooperate maybe due to lack of trust, and hence it is also called "Trust Dilemma", although this will result in a loss-loss situation for both.

The difference between chicken and stag hunt is that in chicken, each player does the exact opposite of the other player whereas, in stag hunt, the players aim to do the same activity as the other player.

Stag hunt can be applied to water resource management for two countries/districts sharing the same water body. For example, two countries, A and B share a lake and each one of them has a river flowing directly into the common lake and the lake is drying up due to high evaporation and reductions in seasonal flows from the rivers. The lake has to be protected by both the countries by increasing the release of water into that lake or else the countries will have to spend funds on upstream consumption. Only one country alone cannot secure the lake. If both the countries come together and increase the river flow then, they will get the environmental benefit and their expenditure on upstream consumption will be reduced. But if only one country, "A" cooperates then the environmental benefits will be reduced for both the countries and the country A's will further decrease due to revenue losses. As such the aspect of "free ride" is not present in stag hunt game because generally if one country observes cooperation, they automatically cooperate for increased payoffs for both the countries.

In this example, let's assume that 10 is the highest payoff, 5 is a lower payoff and 1 is the least payoff. Now, payoffs for both (A, B) will be:

		COUNTRY A Cooperates	COUNTRY A Doesn't Cooperate
COUNTRY B	Cooperates	10,10	5,1
COUNTRY B	Doesn't Cooperate	1,5	5,5

7. CONCLUSION

Game theory can provide insights to understand and resolve water conflicts which often are multi-criteria multi-decision-makers problems (Madani, Game theory and water resources, 2009). It sometimes can show and address different engineer-ing, socio-economic, and political characteristics of water resource problems even without detailed quantitative information and without a need to express performances in conventional economic, financial, and physical terms (Madani, 2009). Game theory can predict if the Opti-mal resolutions are attainable and explain the decision makers' behaviour under specific conditions. The stakeholders' decisions and behaviours might seem to be irrational from the system engineering perspective, but the game theory can explain how decision makers' rational behaviour, who are trying to maximize their own objectives, might result in overall Pareto-inferior outcomes. By simple examples of two by two water resources games, it was explained 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 simple. The water resource conflicts may not be so simple in practice. However, understanding the basic concepts of game theory allows for modelling of complicated water resource problems to gain valuable insights into behaviours of the stakeholders. Non-cooperative game theory can handle real world conflicts in absence of accurate quantitative information, which is a great advantage of game theory over other systems engineering methods. Although most water conflicts have been previously modelled as Prisoner's Dilemma, simple presented examples of games i.e. Chicken and Stag-Hunt with different structures and characteristics support the idea that not all water resources games are Prisoner's Dilemma. The disturbing thing about the prisoner's dilemma and the chicken game is the way that the common good is subverted by individual rationality. Each player desires the other player's cooperation, yet is tempted to defect himself (Poundstone, n.d.). 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 behaviours of the stakeholders (Madani, 2009).

8. LIMITATIONS

The examples presented here are simple. The water resource conflicts may not be so simple in practice. The conflicts are influenced by a lot of other economic, socio-cultural and political factors; however, this paper assumes that such factors remain constant so that insights in the behaviour of stakeholders (players) can be derived and analysed. Also, this paper does not consider the quantitative analysis of different types and structures of games.

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