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Evolution of game theory application in irrigation systems

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Abstract

Agriculture is the largest consumer of water. Since water demand for irrigational purposes is expected to rise and given the fact that freshwater is not an unlimited resource, conflicts about the use of water and allocation issues are becoming more intense. The present paper examines the potential for water conflict when water consumption for irrigation takes place. In order to contribute to the discussion on this issue, game theory is used as a platform that provides predictions about strategies of irrigation followed by stakeholders. Previously published research work on game theory applications analyzing agricultural water rights is reviewed. The paper also discusses the nature and characteristics of selected games. The goal of this article is to highlight the evolution of game theory application in irrigation and contribute to the discussion about resolving resource conflicts generated by irrigated agriculture. The results of this analysis may be appreciated by policy makers for creative problem solving about water use in the field of irrigation management.

Keywords: agriculture; irrigation; water conflict; game theory; strategy; water policy

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1. Introduction

Water plays an essential role, both for humanity's survival and prosperity. Its close involvement to the processes of Life and its strong interaction with bio-societies reflects its vital significance. Welfare is constrained directly by access to safe water supply. Early great civilizations had been developed and evolved along rivers, lakes, deltas and seas. By the very early, they understood the importance of water and adapted their structure and economies to the water flow and supply (water-centric economies). Over the time, humans have learned to control water in order to satisfy their needs (including agricultural, industrial, household, recreational and environmental activities) and developed methods to harvest, transport, store, treat and manage fresh water resources (rainwater, river water, spring water and groundwater). Hence, nowadays modern societies are characterized by the level of integrated water resources management plan approach they follow. However, still they have to face up with several problems concerning water.

In a rapidly changing world, with growing population, fast-rising world food demand, rapid urbanization and industrialization, expansion of business activity and technological progress, increase of pollution and deforestation, climate change and change in precipitation patterns, extreme events, depletion of water resources and water quality deterioration, there are alarming messages about water crisis. Access to reliable and safe water becomes one of the critical challenges of the 21st century. Since there are too many interdependencies (externalities) among water uses and the fact that water in not always available at the ‘right’ time and the ‘right’ location, water users have to share water, this valuable and vital resource, at different levels of access. This variation about the distribution of water, its availability, its qualitative characteristics and the composition of its sectoral use contributes to the arising of conflicts among water users. The risks for abusing the available fresh water are getting higher and water scarcity affects the living standards. In such a case, the number and level of conflicts are quite likely to be elevated in the future. Because water is so essential to agricultural sector, conflicts and disputes over the use of irrigation water tend also to arise. Conflicts take place in several levels: on local, inter-state or international level (i.e. disputes between upstream and downstream irrigators or between two countries sharing a water body), between sectors (i.e. agricultural versus industrial water use), among competing economic and social interests (i.e. to invest on small-scale irrigation schemes or not), etc.

The present paper examines conflicts that take place over irrigation water. The following approach is under game theoretical perspective. Game theory offers insights into any economic, political, or social situation that involves individuals who have different goals or preferences and make decisions that will influence one another's welfare (Myerson, 1991)[1] and, for that reason, it serves in a better understanding of conflict. Discussion on the evolution of game theory applications in irrigation may help in better understanding of past and present dilemmas about water consumption. The goal of this article is to contribute to the discussion about resolving conflicts generated by irrigated agriculture. Previously published research work on game theory applications, analyzing agricultural water rights, is reviewed. Reviewing cases of recent empirical studies could assist in better understanding of research direction over such issues. The results of this analysis may be appreciated by policy makers for creative problem solving about water use in the field of irrigation management.

Section 2 briefly emphasizes the contribution of irrigation to our livelihood, demonstrates some basic irrigation statistics and discusses the arising conflicts. Section 3 briefly describes some basic concepts about game theory. Section 4 gives examples of typical games in agriculture water and focuses on published research work on game theory and irrigation issues. Section 5 presents conclusions.

2. Irrigation: water for agriculture, a cause of conflict

2.1. Irrigation statistics

Agriculture is responsible for approximately 70 % of water withdrawals, but 90 % of the water consumption (FAO, 2014)[2]. This account of water abstraction for satisfying agricultural needs goes up to 95% in developing countries. These statistics, illustrated in Fig.1a, reflect that agriculture is the sector with by far the largest water withdrawal and consumptive water use. Irrigation is used in order to counterbalance the lack of precipitation in cultivated areas and improve food production around world. For that reason, it takes the lion’s share of water use in agriculture sector, depending on the characteristics on each country (Dinar et al., 2013)[3].

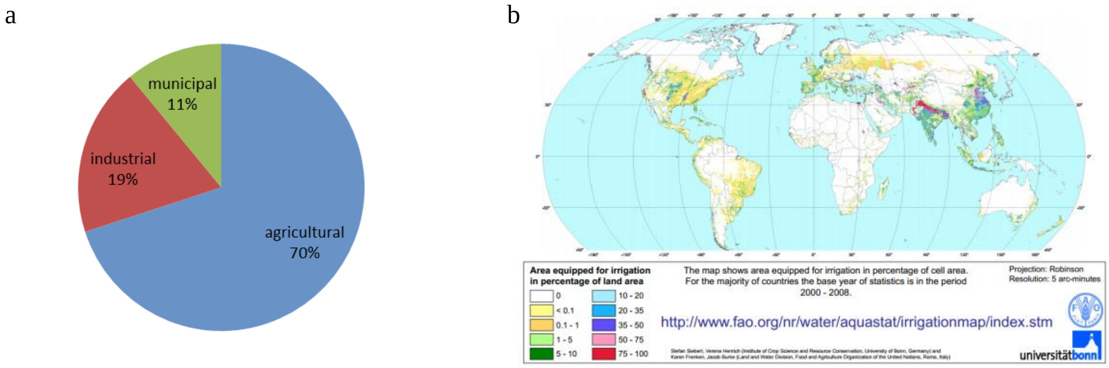

Fig. 1. (a) Global sum of water withdrawals; (b) The digital global map or irrigation areas.

Table 1 lists briefly the benefits and adverse effects of irrigation. In order to exploit the benefits of irrigation, the latter should be managed carefully to avoid or reverse environmental damages and abuse of water resources.

Table 1. Irrigation pros & cons.

Benefits	Adverse effects
Gives higher yields in crops and boosts agricultural productivity	Provokes waterlogging and depletion of water sources
Increases food production and security	Leads to water table lowering
Provides option for diversification in cropping	Contaminates local groundwater basins and stream flows
Reduces vulnerability to drought phenomena	Provokes siltation
Lessens risk of moisture stress of plants in critical growing periods	Provokes salinization and alkalization of land
Gives higher yields in pasture and increases livestock production	Contributes to soil infertility
Increases surface area for profit exploitation	Contributes to erosion of topsoil
Increases value of land	Provokes poor aeration of soil
Increases farmers income and standard of living	Needs investment and maintenance cost
Increases labor employment	Spreads water-borne diseases

According to data collected from 165 countries around the world for year 2012 by AQUASTAT database (FAO, 2014)[2] the total irrigated area is estimated 299 Mha and the annual irrigation water withdrawal is about 2672 km^3. At world continent level, Asia abstracts 76% of total irrigation water (2026 km^3/year), Americas 15% (397 km^3/year), Africa 6.5% (171 km^3/year), Europe 2.5% (69 km^3/year) and Oceania 0.3% (9 km^3/year). The analysis of statistical global survey data about density of irrigation areas is illustrated in the following map (see Fig. 1b) produced by Siebert et al (2013)[4]. This geospatial information on position and extend of irrigated areas shows that irrigation water use per unit of surface area is largest in arid regions with high cropping intensity. i.e. Egypt, Pakistan, India, Mexico, just to name a few, in which the risk of drought is relatively high. High cropping intensity, powered by irrigation ensures food production. According to FAO (2007)[5], food production has increased by more than 100 % in the last 30 years. FAO also estimates that the world's growing population will require about 50 % more food by 2030 compared to 1998. To cover this requirement, 70 % of gains in cereal production are expected to come from irrigated land the next 30 years. It is estimated that irrigated land in developing countries will increase by 34 % by 2030, but the amount of water used by agriculture will increase by only 14 %, thanks to improved irrigation practices.

2.2. Irrigation conflicts

Conflicts in irrigation are as old as the irrigation agriculture itself. Actually, sharing a body of water, for agricultural purposes, dates from the time of first land-holding farmers. It is noticeable that the words ‘rival’ and ‘rivalry’ which mean ‘competitor’ and ‘conflict’, respectively, originate from the latin world ‘*rivalis*’ which meant one who uses a stream in common with another, equivalent to ‘*rīvus*’ i.e. ‘stream’ plus ‘*-alis*’ i.e. a suffix with the general sense ‘of the kind of’. The original meaning was sharing, but it was evolved in competitiveness and conflict (Bolton, 2010)[6].

The first recorded dispute in antiquity took place between the cities of Umma and Lagash in the Middle East over irrigation systems and diversion of water from Tigris and Emphratis rivers. That dispute had lasted for 100 years from 2500 to 2400 B.C. Continuing conflicts over Mesopotamia through passing of years led Hammurabi the king of ancient Babylon in 1790 B.C. to enforce laws prohibiting water theft in irrigation systems, in his famous ‘Hammurabi’s Code’ (Hatami and Gleick, 1994)[7]. An early example of water value for cities versus farms is the famous dispute about irrigation water rights, in eastern California. It dates in the late of 19th century and was continued till 1926 between the city of Los Angeles that was growing continuously and farmers and ranchers in the Owens Valley of Eastern California. The cause of conflict was the fact that agriculture was starting to fall dramatically after the construction of an aqueduct that diverted water from the Owens River to Los Angeles. This led to farmers' rebelling. They tried to destroy the aqueduct in 1924. Los Angeles had suffered the repeated aqueduct bombing, but kept the water flowing. By 1926, Owens Lake was completely dry due to water diversion. Owens

Valley economy collapsed. The City of Los Angeles continued to purchase private land holdings and water rights of farmers in Owens Valley and agriculture interests in the valley were stopped (Reisner, 1993)[8]. The continuous dispute over irrigation water rights between India and Pakistan was also on the brink of war. The conflicts started in 1948 and ended up in 1960, after negotiations of World Bank and the signing of Indus Waters Agreement (Wolf, 1998)[9]. On the contrary, war broke out about the waters of Jordan River shared by Jordan, Syria and Israel, in the 1950's and 1960's (Kliot, 1994)[10]. These military actions contributed to the tension that led to the 1967 Arab-Israeli War (Gleick et al., 1994)[11]. In Ethiopia, during the drought of 2004-2006, there was significant fighting over water wells between local pastoral farmers and herders called "well warlords" and "well warriors". The extensive fighting, known as the "*War of the Well*," left over 250 dead and many injured (Kreamer, 2012)[12]. A interesting timeline of conflict events around world over irrigation water and other water conflict types has been developed by the Pacific Institute, showing detailed information about each conflict (Pacific Institute, 2014)[13].

3. Game theory

3.1. Background

Game theory (GT) is a mathematical method of problem analysis and decision making in strategic interaction. In other words, GT builds mathematical models and draws conclusions by studying situations/problems in which a group of people don't necessarily share the same interests and have to make decisions (interactive decision-making). Under a GT perspective, the outcome of a situation/problem (game) is determined by the moves (strategy) made by participants in the game (players). Each game consists of:

- a set of players, $N = \{1, 2, \ldots i-1, i, i+1, \ldots n\}$),
- a set of strategies for each player individually, i player has $S_i = \{S_1, S_2, \ldots S_k\}$ strategies, and
- a set of payoffs of each player for each set of strategies $u_i = \{u_1, u_2, \ldots u_k\}$.

The process of setting up a game model includes defining players' options and preferences. The aim of each player is to reach its expectations. GT allows simulation of the self-centred attitude of the involved players with a fairly realistic manner. In that context, GT methods compared to other conventional methods of strategic analysis, such as linear programming, provide better understanding of issues describing the competition and cooperation between players and make better estimations of the conflict outcome. However, it should be mentioned that GT is based on rationality. A GT simulation will work only if a) players act rationally, so as to maximize theirs payoffs and b) they believe that all the other players take rational decisions, too. Still, many decisions can be affected not only by rational judgments, but also by other factors, i.e. pressure, fears or aspiration, risk aversion, etc.

As a scientific discipline, GT was introduced in the publication *Theory of Games and Economic Behavior* by John von Neumann and Oskar Morgenstern (1944)[14], finding application in economics. However, before this publication, several GT topics had been discussed, but not in a systematic way (Gura and Maschler, 2008)[15]. Even though GT is a relatively young branch of mathematics, through the passing of seventy years, it has been widely used in many other disciplines, such as political science, computer science, biology, psychology, sociology, and other fields. GT applications has been used as the means to understand many environmental issues, including water quantity and quality management, water allocation, water sharing, water diplomacy and many other fields. The following section discusses applications of GT in water irrigation issues.

The fruitful contribution of GT in many scientific fields is demonstrated by the number of international awards, in Memory of Alfred Nobel, as recognition of scientific advances. From 1968 till today, thirteen game-theorists have received the Nobel Prize in Economic Sciences. A famous winner is John Nash, who shared the Nobel Prize with John Harsanyi and Reinhard Selten in 1994. The first awarded GT researcher was Paul A. Samuelson in 1970 and the last is Jean Tirole in 2014 (http://www.nobelprize.org/).

3.2. Taxonomy

As Selten stated (1991)[16], GT has been created as a theory of conflict and cooperation among rational individuals. This statement becomes more easily understood when studying the two main branches of GT: non-cooperative and cooperative game theory. The former analyses games where players interact with others in order to achieve their own goals without any coalitions or binding agreements and they act competitively. On the contrary, the latter analyses games where players are driven into mutually binding agreements (Gura and Maschler, 2008) [15].

Another classification of games is zero-sum and non-zero-sum games. Games that have winners and losers in the sense that one player “wins” only if the other “loses” are called zero-sum games. Zero-sum games were the first type of game to be studied formally. In contrast, in non-zero-sum games the gain by one player does not necessarily correspond with a loss by another (Webb, 2007)[17].

An additional branch of games is the following: static and dynamic games. Static games are actually one-shot games in which players play once with a single decision. Each player has no knowledge of the decision made by other players. So, decisions are assumed to be made simultaneously. However, there are situations in which players' strategies depend on past moves. These cases are described by dynamic games (or sequential) in which players play over and over (Dinar and Albiac, 2009)[18].

There are many other distinctions between games, such as games with complete (perfect) or incomplete (imperfect) information in which the payoffs for each move is known or not by the players (Osborne and Rubinstein, 1994)[19]. A classification of incomplete information games are Bayesian games in which there is uncertainty about player's preferences and other important parameters of the game situation (Harshanyi, 1967)[20]. Another category is about stochastic games in which there are probabilistic transitions in the players' moves (Shapley, 1953)[21] and fuzzy games that model the fuzziness in behavior of players (Billot, 1998)[22]. Differential games are those in which parameters, affecting players decisions, are governed by differential equations. Metagames study problems in a non-qualitative basis, through options method analysis (Howard, 1971)[23]. In this very coarse representation in the present manuscipt, the described types of games are the most common in literature. Typical games that define the main concepts of GT are Prisoner's Dilemma, Chicken Game, Matching Pennies, the Battle of Sexes, Hawks-Doves etc. The taxonomy list of GT is still long as the number of publications on GT has grown exponentially. As Madani and Hipel (2011)[24] stated, the large variety of GT methods have been developed for addressing a wide variety range of conflict problems.

4. Game theory & Irrigation

4.1. Classic example games

This sub-section illustrates the basic concepts of GT, by presenting simple and figurative games of competition and cooperation in irrigation. These games depict how strategic interactions among players result in non predictable situations with respect to the preferences of the players.

Pumping groundwater game: This game (Fig. 2a) was introduced into water resources literature by Madani (2010)[25] and follows the concept of Prisoner's Dilemma game. In this game, there are two farmers that share an aquifer in order to irrigate their crops. Each farmer has to choose between the cooperative and non-cooperative pumping rate. Pumping costs in cooperative rate are lower than in non-cooperative one. The higher the pumping cost, the lower the grounwater table and simultaneously the lower the net benefits (profits) for each farmer. The best outcome for each farmer is to let the other farmer to commit for pumping at a low rate, while he pumps at the higher rate (acting as a free-rider). In constrast, if the two farmers cooperate and agree at a low pumping rate (and keep their committment), then their payoffs will be lower. While the best strategy for both farmer is to cooperate, GT suggests that the two farmers lack of trust with each other and each individual farmer finds non-cooperation as strictly dominant strategy. Non-cooperation is the predicted outcome of the game and confirms Hardin's theory (1968)[26], known as "Tragedy of the Commons", that describes the resources depletion and the social and environmental damage because of resources overexploitation. Hardin’s model (1968)[26] and non-cooperative games (like those following the reasoning of Prisoner’s dilemma) are closely related concepts to the free-rider problem (Ostrom, 1990)[27].

Water rights game: This game (Fig. 2b) was presented by Galaz (2004)[28] and raises the question of cooperation or defection when the balance of water use is modified. In this game there are two players (a) a group of farmers and (b) an urban water company. At *status quo* the two water users have an agreement about the consumption of existed water resources. The game analyses what happens when one player (for example, the urban company) breaks this agreement. The other player can either accept the violation or not. The answer on this problem depends on the preference order of both players.

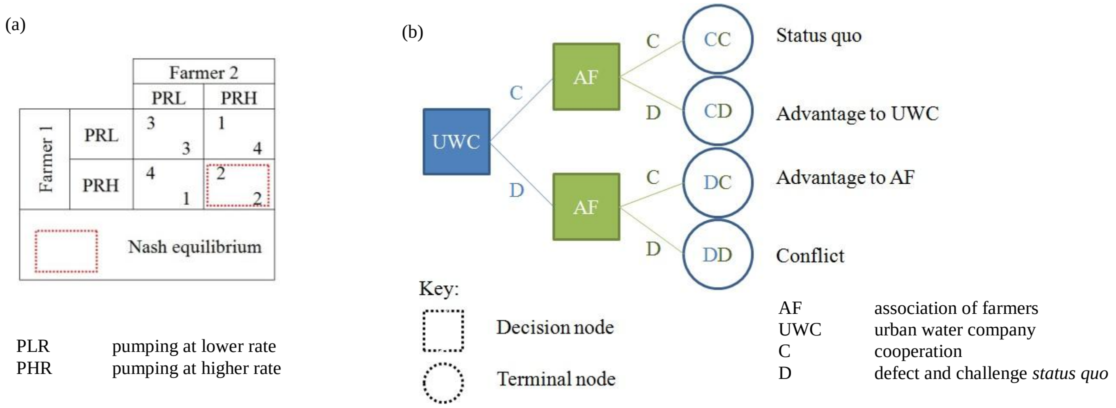

Fig. 2. (a) Pumping groundwater game in strategic form; (b) Water rights game in extensive form

4.2. Literature Evolution

Decrease in exploitable freshwater resources (intended for agricultural use) and continuing increase in agricultural production needs have boosted the competition for irrigation water and raised many conflicts about water shares. In many developing countries, this problem is much more intense. That fact led many researchers to discuss that issue, trying to develop practical and sustainable solutions. Game theory applications are not excluded from this effort. Interesting reviews, concerning approaches and applications of GT to issues of water resources (among them irrigation), has been conducted by Parrachino et al. (2006)[29] and by Herath (2006)[30].

One of the earliest studies in the context is that of Rogers (1969)[31], who analyzed the disputes between India and Pakistan about the water of Ganges and Brahmaputra rivers, that serve in irrigation and other water uses. Rogers demonstrated this international water conflict by using techniques of linear programming and GT. Another early publication is that of Bogardi and Szidarovsky (1976)[32], which sets the definition problem about the equilibrium on water volume for irrigation purposes among farmers in a rather qualitative perspective about the goal function of each farmer's interest. In this article, the oligopol model is suggested as\ applicable towards the solution of problems considering irrigation systems. Gisser and Sanchez (1980)[33] described the problem of farmers pumping water from a common aquifer by presenting raised externalities. They tried to compare following strategies under no control (free marker) and optimal control by using deterministic equations (application in Pecos River Basin, New Mexico). They concluded that if the storage capacity of aquifer is relatively large, the exponents of the two models will be practically identical. On the contrary, Negri (1989)[34] elaborated further the problem of using a common property aquifer. He reviewed the groundwater pumping model and examined the adopted pumping strategies in aquifer (with restricted access) by using differential open loop and feedback games.

During 90's, literature is more focused in cooperative games about the use of irrigation water and incorporates environmental issues, as well. An interesting manuscript is that of Yaron and Ratner (1990)[35]. The two researchers examined the problem of increasing use in irrigation of low quality water (with high salinity). They applied their considerations into a quasi-empirical case in Israel (Negev area). They analyze the economic potential of cooperative associations and they calculated income distribution schemes among three farms with the aid of cooperative game theory algorithms. On the other hand, Dixon (1991)[36] presented GT perspective for analyzing ground-water extraction and drainage water management, by illustrating different typed of behavior in players; myopic (i.e. players not adjust behavior when the water table is lowering), open-loop (ie player ignores the effect of pumping on the extraction costs of the other players), conventional closed-loop (ie player adjusts his behavior in response to the actions of the opponent), and trigger strategy (ie all farmers agree to pump in a collusive rate and trigger punishments if some farmers pump more). He concluded that trigger stategy equilibria may be difficult to implement, but should be applicable in ground-water extraction setting (application in San Joaquin Valley, Kern County, California). Dinar et al. (1992)[37] presented two interesting empirical applications of cooperative GT over irrigation water under water scarcity and salinity. The first case study discusses the problem of reused water for irrigation and the second deals with inter-farm cooperation in water use for irrigation and the determination of the optimal water quantity and quality mix for each water user. Their study implied that cooperation increases the net benefit of farmers and the efficiency of water allocation. A quality-quantity groundwater problem in the context of irrigated agriculture is also analyzed empirically by Xepapadeas (1996)[38] in Greece (Irakleio, Crete) where GT tools (non-cooperative game) were used in order to investigate regional profits over a fixed time horizon. His work tried also to set a regulatory framework (water tax) which could help in achieving efficient water allocation under the specific water consumption conditions in the area.

Moreover, during 90's, articles about regulatory schemes over irrigation systems made use of methodologies from the toolbox of GT. An interesting example is the work of Weissing and Ostrom (1991)[39] which is one of the first attempts that examined how irrigation institutions affect the distribution of equilibrium outcomes of irrigators. They combined game theory with policy analysis about irrigation issues. The two researchers examined irrigation games without guard positions and concluded that there is always some stealing concerning pumped water. They developed non-cooperative GT models to examine how stealing and monitoring rates are affected under different situations i.e. changes in number of irrigators, alterations in monitoring cost, different detection probabilities, different rewards when a stealing event is discovered etc. A similar attempt is that of Ostrom and Gardner (1993)[40] who sketched asymmetries in irrigation systems between farmers located near the source of water (head-enders) and farmer placed in distance from it (tail-enders) and paid attention to the design of irrigation institutions and works. They concluded that bargaining between parties about allocation of water and maintenance of the irrigation system can benefit all sides. Empirical evidence in Tambesi irrigation system (Nepal) showed that design of institution that enforce rules among irrigators can enhance the agricultural yield.

In the first decade of the new millennium, various GT applications to practical irrigation issues appeared in the literature. Concerning cost-sharing arrangements in irrigation systems, Dayton-Johnson approached the problem empirically through evidence from Mexico by publishing two articles. In the first one, he discussed water and cost allocation arrangements under different distributive rules (Dayton-Johnson, 2000a)[41]. In the second essay, the determinants of cooperation in a farmer-managed irrigation system are highlighted (Dayton-Johnson, 200b)[42]. On the other hand, Sakurai and Palanisami (2001)[43] compared collective action in farming (tank irrigation) versus individual irrigation schemes (well irrigation) under the prismatic view of GT and applied their model (chicken game) in India (Tamil Nadu) where rice farming consumes a great amount of water. Posing the question tanks or well for local irrigation systems, they deducted that individualized irrigation systems are more preferable by the farmers to invest. However, their analysis indicated that neither tanks nor well will dominate the supply of water. Faysse (2003)[44] explored the question about the best water allocation rule in farming when (i) farmers are autonomous in decision-making regarding irrigation and (ii) a manager impose some rules about the water distribution to farmers and the fee-payments (application in El Melalasa, Kairouan, Tunisia). Cost-sharing rules over an irrigation ditch between head-enders and tail-enders were also discussed by Aadland and Kolpin (2004)[45] in their econometric analysis based on fundamental GT concept from two surveys in south –central Montana, USA. Formulating water allocation decisions as a cooperative game in irrigated land of Kat River Basin in South Africa is surveyed by Dinar et al (2006)[46]. They compared their results with the results from a Role Playing Game and discussed the differences in these two procedures. Based on results of Dinar et al. (2006), a similar comparison between these two methods regarding common property water allocation among farmers in the Kat River Basin was made by Désolé (2007)[47] in order to provide insights on the issue of game contextualization.

Furthermore, during 2000-2010, we find many articles concerning irrigation water that combine GT applications with other innovative approaches. An interesting application is the work of Zorba et al. (2000 & 2001)[48,49] in which farmers' pumping strategies are following the pattern of Prisoner's Dilemma game and genetic algorithms are used as an optimization tool in order to maximize the number of farmers with increase in their income. A different demonstration of water sharing game for agriculture at international level is given by Just and Netanyahu (2004)[50]. They linked theory about interconnected games with real case conflict situations between Israel and Palestine, in order to examine negotiation feasibilities and infeasibilities. They modeled Israeli-Palestinian aquifer sharing as a Prisoner's dilemma. Another interesting article about irrigation that combines many GT applications is that of Salazar et al. (2007)[51]. They described a conflict resolution method applied to an irrigation district in Alto Rio Lerma Irrigation District, Mexico, regarding over-pumping and potential environmental risk, by using 4 different method solutions under different cropping patterns and chemical loading. Through this analysis they estimated the optimal groundwater withdrawals. A fuzzy GT approach combined with sequential bargaining games was described by Kerachian et al. (2010)[52] who examined arising conflicts among water users and water agencies in Tehran, Iran.

Since 2010, many articles on GT applications regarding irrigation water have been published. The article of Madani (2010)[25] addresses several types of (and reasons for) conflicts over water issues and reviews applicability of game theory to conflict resolution by presenting simple water resource non-cooperative games. It has been ranked as one of the hottest articles of the Journal of Hydrology by Elsevier from its publication year till today. Janssen et al. (2011)[53] studied asymmetries in strategies between head-enders and tail-enders in irrigation systems and discussed the dilemma of farmers regarding how much to invest in construction of shared infrastructure for irrigation purposes. One year later, Janssen et al. (2012a)[54] elaborated further his previous work and discussed how cooperation among farmers evolve when head-enders and tail-enders face asymmetric dilemmas. Fair water allocation in farming under different allocation rules is also examined by Janssen et al. (2012b)[55] who experiment their hypothesis in rural Colombia and Thailand. Results from experiments show the level of cooperation among farmers depend on the rate of trustworthiness among villagers in the community. The development of norms regarding fair water-sharing is a necessary condition of irrigation systems to self-organize. Yamamoto et al. (2012)[56] applied simple GT (Prisoner's dilemma) to a water-shaving project (drip irrigation) in Tarim River Basin, China. They investigate the cost of work and maintenance in this project, water-fee reductions after the introduction of water-shaving irrigation and yield benefits. The analysis shows that the incentives for irrigators to follow a drip-irrigation plan are not high and proposes policies to solve this problem. Zaikin and Espínola-Arredondo (2012)[57] present an experiment (non-cooperative game) under with farmers from Uzbekistan (Dashtobod) in which water applied allocation norms embrace penalty and bonus rules. The experimental observations indicate '*the carrot or the stick*' policy is effective in motivating irrigators to reduce water consumption. A work by Sechi et al. (2013)[58] deals with water cost allocation arrangements in among competitive water requests for irrigation and civil/industrial use and applied the model in Sardinia, Italy under a cooperative GT approach. The applied methodology provides insights in rational and fair distribution of water resources.

Recent publications about GT and irrigation are related one way or another with social learning and adapting behavior. Finger and Borer (2013)[59] applied GT to identify the factors contributing to the continuation of traditional channel based irrigation systems in a rural area of Swiss territory (canton of Valais) even though irrigation is not profitable for the majority of community. Kimmich (2013)[60] associates groundwater irrigation with electricity policies for irrigation in India (Andhra Pradesh) and presents a situation of social learning depicted as a sequential nested coordination game. Msangi (2014)[61] discusses the learning behaviour among farmer agents that pump from the same aquifer, in a non-cooperative manner. The researcher expands this model by incorporating uncertainty (shochastic equations) about the levels of inflow into the aquifer system and examines how players adapt into new situations of competitive extraction (application in Kern County, California, USA). Roseta-Palma et al. (2014)[62] elaborate the problem of illegal groundwater pumping. They created a model of groundwater management that explicitly recognizes the existence of distinct groups of players (namely legal and illegal water users) and analyze adaptive behavior of irrigators under the supervision of a regulator/social planner that poses economic and social penalties to illegal users.

5. Conclusions

Water conflicts have increased over the last decades. Game theory is a rapidly advancing approach for analyzing conflicts over common pool resources, like water. GT applications in water resources literature cover a range of water resource problems in diverse categories and types. (Madani, 2010) [25]. Regarding irrigation, GT applications address issues associated with the concept of a) fair and equitable water allocation, b) balanced cost allocation among irrigators, c) equilibriums on water withdrawals and environmental sustainability. Whether the game is static or dynamic, whether the users are cooperative or competitive, whether the equations are deterministic or fuzzy, GT could provide insights in strategic interaction of farm agents that have to decide upon the operation of their irrigation systems and to develop broadly acceptable solutions.

The purpose of the paper is to review the literature about GT and irrigation and water-related issues. Presenting the evolution of GT articles in literature discussing matters over irrigation water, a transition of argued issues becomes apparent. Premature works use more descriptive methods, but give less emphasis on environmental adverse effects of water overexploitation. Over the passing of years, as environmental problems became more intense, researchers incorporated in their equation-models more environmental parameters. Afterward, the discussion is focused on water allocation issues, given narrow water resources for irrigation purposes. This discussion is moved to cost allocation issues, under more sophisticated econometric analyses, in which the factor of uncertainty is investigated. Simultaneously, issues about the operation and management of self-organized irrigation systems and irrigation institutions become more open to debate. Last years, discussed conflicts over irrigation water are not limited to sharing of costs/benefits or management issues, but are extended to other social and political aspects of decision-making, like social learning and adaptive behavior of players. It is noticeable that the majority of works is focused more on over-pumping from aquifers and less on withdrawals from surface water. It is also noteworthy, that the majority of empirical cases and approaches are referred in developing countries, where access to water resources (in quantity and quality) is lacking or highly variable. Trying to classify the main water management problems, it seems that so far literature addresses issues/conflicts regarding water/cost allocation, groundwater management, balancing water quality-quantity issues, institutional arrangements and social learning.

By documenting articles in the literature on GT dealing with irrigation issues, we understand that there is a pluralism of addressed subjects regarding water for agriculture and conflicts over its use, allocation, cost and policy action. This fact illustrates the utility of GT and indicates the great potentials of GT processes to understand complex problems about irrigation water and to improve agriculture governance.

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