GIS AND GAME THEORY FOR WATER RESOURCE MANAGEMENT

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ABSTRACT:

In this study, aspects of Game theory and its application on water resources management combined with GIS techniques are detailed. First, each term is explained and the advantages and limitations of its aspect is discussed. Then, the nature of combinations between each pair and literature on the previous studies are given. Several cases were investigated and results were magnified in order to conclude with the applicability and combination of GIS- Game Theory- Water Resources Management. It is concluded that the game theory is used relatively in limited studies of water management fields such as cost/benefit allocation among users, water allocation among trans-boundary users in water resources, water quality management, groundwater management, analysis of water policies, fair allocation of water resources development cost and some other narrow fields. Also, Decision-making in environmental projects requires consideration of trade-offs between socio-political, environmental, and economic impacts and is often complicated by various stakeholder views. Most of the literature on water allocation and conflict problems uses traditional optimization models to identify the most efficient scheme while the Game Theory,as an optimization method, combined GIS are beneficial platforms for agent based models to be used in solving Water Resources Management problems in the further studies.

1. INTRODUCTION

Resources were always important for human being. More or less, many of them are vital sources of life. As water is the driving force of the nature it can be one of the primary concerns for humanity and governments alike. Water resource planning and management, as one of the principal pillars of societal development both in developed and developing countries, has been a specific focus of nations; and the fields of science related to this topic, especially in developed nations, have often engendered intense and dynamic interest.

Game theory was originated from economics, one of social sciences, but it applies to not just social systems but also the realm of nature (McCain Roger, 2010).

The resolution of scientific problems related to Earth sciences in general and water resources specifically, is a primary driver for the birth of GIS and one of its core objectives.

2. THEORY OF GAMES

Since the work of John Von Neumann, games have been a scientific metaphor for a much wider range of human interactions in which the outcomes depend on the interactive strategies of two or more persons, who have opposed or at best mixed motives. Game theory is a distinct and interdisciplinary approach to the study of human behaviour, an approach that studies rational choices of strategies and treats the interactions among people as if it were a game, with known rules and payoffs. And in which everyone is trying to win. The disciplines most involved in game theory are mathematics, economics and the other social and behavioural sciences. Among the issues discussed in game theory.

Game theory is study of the choice of strategies by interacting rational agents, or in other words interactive decision theory. A key step in game theory strategy is to discover which strategy is a person best response to the strategies chosen by the others. It is to study the mathematical models of conflict and cooperation between intelligent rational decision-makers.
- The Games used in Game Theory should include:

1. Players of the game.
2. Information Available to each Player.
3. Actions available at each decision point.
4. Payoff for the resulting outcome(s).

- Practitioners of Game Theory use Solution Concepts with the above based framework to predict outcome(s) and their associated probability.
- Important topics in Game Theory include Equilibrium concepts, Strategies, Classes of Games and Theorems

A game of perfect information is a game in which every player always knows every move that other players have made that will influence the results of his or her choice of strategies. A game of imperfect information is a game in which some players sometimes do not know the strategy choices other players have made, either because those choices are made simultaneously or because they are concealed (McCain Roger, 2010). All of natural phenomenon in a fundamental level, and the relationship could be described with many sub-theories of game theory like non-cooperative game or cooperative game. Most of events and situations could be projected by the eye of game theory on the aspect that there always exists conflict and cooperation on the interactions in them (McCain Roger, 2010).

Nash equilibrium is a solution concept of a non-cooperative game involving two or more players in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only his or her own strategy (Malczewski, 2006). If each player has chosen a strategy and no player can benefit by changing strategies while the other players keep theirs unchanged, then the current set of strategy choices and the corresponding payoffs constitutes a Nash equilibrium.

Game theorists use the Nash equilibrium concept to analyse the outcome of the strategic interaction of several decision makers. In other words, it provides a way of predicting what will happen if several people or several institutions are making decisions at the same time, and if the outcome depends on the decisions of the others. The simple insight underlying John Nash's idea is that one cannot predict the result of the choices of multiple decision makers if one analyses those decisions in isolation. Instead, one must ask what each player would do, taking into account the decision-making of the others.

3. WATER RESOURCES

Water resources are sources of water that are potentially useful. Uses of water include agricultural, industrial, household, recreational and environmental activities. The majority of human uses require fresh water. An almost 97% of the water on the Earth is salt water and only three percent is fresh water; slightly over two thirds of this is frozen in glaciers and polar ice caps (Figure 1). The remaining unfrozen freshwater is found mainly as groundwater, with only a small fraction present above ground or in the air. Fresh water is a renewable resource, yet the world's supply of groundwater is steadily decreasing, with depletion occurring most prominently in Asia and North America, although it is still unclear how much natural renewal balances this usage, and whether ecosystems are threatened. The framework for allocating water resources to water users (where such a framework exists) is known as water rights.

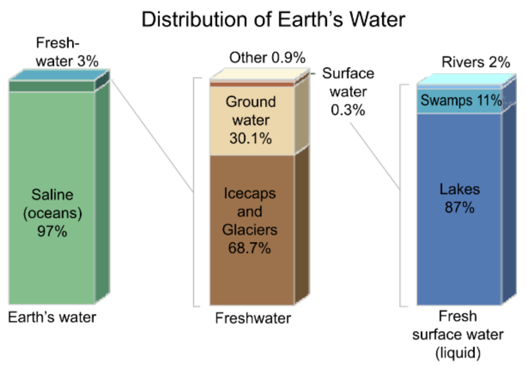

Figure1. A graphical distribution of the locations of water on Earth.

Only 3% of the Earth's water is fresh water. Most of it is in icecaps and glaciers (69%) and groundwater (30%), while all lakes, rivers and swamps combined only account for a small fraction (0.3%) of the Earth's total freshwater reserves.

Water resources nowadays are under different types of treats, from pollution to shortage and almost all the water resources on earth are under great pressure. The problem however, differs in arid or wetland conditions. In arid lands, the problem is usually a well-known water shortage while in wetlands floods are the main concerns of the decision makers. Pollution of water resources can also be associated with both arid and wet lands while the neglecting of pollution in wetlands are more common.

As water moves in time and space consistent with the hydrological cycle, the term 'water management' covers a variety of activities and disciplines. Broadly speaking, these can be divided into three categories: managing the resource, managing water services, and managing the trade-offs needed to balance supply and demand.

Water is a fugitive resource, flowing through space and time across landscapes and through economies. All benefit from it, but few understand how it is actually managed. The management of water is not merely a technical issue; it requires a mix of measures including changes in policies, prices and other incentives, as well as infrastructure and physical installations.

Water resource management is about managing water found in rivers, lakes and groundwater. This includes water allocation, assessment and pollution control; the protection of water-related ecosystems and water quality; natural and man-made infrastructure for the redistribution and storage of these resources; and groundwater recharge.

Water management is underpinned by levels of uncertainty. These are changing as a consequence of global trends in demography, consumption patterns and migration, and climate change, resulting in increased levels of risk Adapting to these uncertainties and developing strategies that mitigate against emerging risks makes water management policies, institutions and regulations more resilient, thereby increasing their chances of generating benefits to society. Adaptive water management extends to integrated water resources management (IWRM) focuses on the necessary integration of water management across sectors, policies and institutions. By focusing on a more flexible management process to address uncertainty and include actors whose decisions affect water, but who do not currently participate as an active part of the water management process.

Furthermore, the complexity of water management, combined with increased uncertainty, both through socio-economic developments and climate change, makes the traditional command-and-control approach less effective.

Sustainability is a concept that must be applied in an environment undergoing multiple changes, changes that are occurring over different temporal and spatial scales. We depend on our water resource systems for our survival and welfare (Loucks, 2009).

Hajkowicz and Collins (Stefan Hajkowicz , Kerry Collins, 2007), have been reviewed 113 published water management

MCA studies from 34 countries. It finds that MCA is being heavily used for water policy evaluation, strategic planning and infrastructure selection. A wide range of MCA methods were being used with the fuzzy set analysis, paired comparison and outranking methods being most common.

Multiple criteria analysis (MCA) is a framework for ranking or scoring the overall performance of decision options against multiple objectives. The approach has widespread and growing application in the field of water resource management (Stefan Hajkowicz , Kerry Collins, 2007).

The basic rationale behind the efforts to integrate MCDA into GIS is that the two distinctive areas of research can complement each other. While GIS offers unique capabilities for storing, managing, analyzing, and visualizing spatial data for decision making, MCDA provides a rich collection of techniques and procedures for structuring decision problems, designing, evaluating, and prioritizing alternative decisions. Although the GIS-MCDA approaches have traditionally focused on the MCDA techniques for individual decision making, considerable efforts have recently been made to integrate GIS with MCDA for group decision making (Bennett, D. A., Wade, G. A., Armstrong, M. P., 1999) (Feick, R. D., Hall, G. B., 1999) (Feick, R. D., Hall, G. B., 2002) (Jankowski, P., Nyerges, T, 2001) (Kyem, 2001)

4. GEOGRAPHIC INFORMATION SYSTEM AND DATA MANIPULATION

GIS is a sub category of the Geo-informatics discipline.

- GIS requires strategies for the following:

1. Linking geographic information to events, points / regions or items of interest (i.e. storage strategy in a database)
2. Data representation (how is the above data represented? i.e. rain over an area vs a house on a hill)
3. Data capture (technologies used and available include cameras, scanners, satellites, etc...)
4. Data restructuring to allow for data compatibility across collection mediums.
5. Projections (display of the data on a representative model.)

- GIS can be used to:

1. Extrapolate into the future for specific events types based on historical geographical and events data.
2. Data Analysis (how much rain over a specific area or how many homes in a one mile radius of a chemical spill.)
3. Topological and Hydrological Modeling can be used to defer the relational links between objects or analyze the objects for situational features (i.e. flow direction, accumulation matrix, etc...)
4. Leverage statistical analysis to interpolate maps based on sample source data. 6
5. Support Multi-Criteria Decision Analysis when making decisions about resource development or impact (Greene, R.; Devillers, R.; Luther, J.E.; Eddy, B.G., 2011).

4.1 Integration of GIS, Water Resources and Game Theory

GIS and game theory integration can be thought of as a process that transforms & combines geographical data & value judgments (the decision-maker's preferences) to obtain information for decision making.

Game theory, has been used in water resources management to allocate the cost of water-resources planning and development; to model water resources systems for conflict resolution in reservoir operation problems; to allocate water rights; and to manage regional water-quality issues. Some challenges, however, remain to be addressed. For example, additional quantitative conflict analysis in the area of water resources could be performed to identify promising strategies and solutions for stakeholders and various game theoretical models could be better integrated into systems analysis for water resources (Madani. K, 2010).

Madani (Madani. K, 2010) in his paper that has been published in Journal of Hydrology, has been reviewed 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 problem.

Homayounfar et al (Homayounfar.M , Ganji. A, Khalili .A, Mousavi. A.A,, 2010) Proposed continuous dynamic deterministic game model to manage water supply and consumption under challenging conditions. Continuous value functions (long term), utility functions (short terms), and equation of motion are defined in the proposed model. The mathematical equations were formed in a way to decrease the computational time. For this purpose the Ricatti equations are used to solve the proposed continuous stochastic game model. The proposed model is applied to the Zayandeh-rud river basin in central Iran. The results were quite favorable compared to the Dynamic Programming (DP) model outcomes.

Danesh-Yazdi et al (Danesh-Yazdi. M, Abrishamch, Tajrishy, 2013) in a study in order to Conflict Resolution of Water Resources Allocations Using the Game theoretic approach in Orumieh basin in IRAN, developed a comprehensive linear programming model to achieve the optimal allocation pattern based on the initial water rights of stakeholders. Then, by using the results of the water planning model combined with the game theoretical concepts such as the Core, the Shapely Value, and, the Gately propensity to disrupt index, evaluated possible cases of cooperation among riparian parties and finally effectiveness and potential advantages of this approach shown, through the case study of the Orumieh River Basin in Iran with scarce water resources and multiple users. They results that cooperative game theory can be applied successfully to assess the cases of cooperation in the Orumieh River Basin in conjunction with a comprehensive water planning model.

Ghaffari Moghadam, et al (Ghaffari Moghadam , A. Keikhah ,M. Sabouhi, 2012)in a study about Optimum Water Resources Allocation Using Cooperative Water Allocation Model (CWAM in order to optimize the allocation of water resources of Chahnimeh natural reservoirs in a 12 month term (April 2005 to March 2006) using Game Theory. CWAM, has been designed as a comprehensive model for efficient and equitable allocation of water in a river basin. This model comprised of two steps: first the initial allocation of water using Lexicographic Minimax Ratio of Water Shortage (LMWSR), and second, water reallocation and net benefit for an efficient and optimal allocation of water transfer model. The second step can use the followings: Irrigation Water Planning Model (IWPM); Hydrologic-Economic River Basin Model (HERBM) and Cooperative Reallocation Game (CRG). The results of LMWSR model showed a satisfaction ratio of 1 to 0.89 for domestic water and 1 to 0.49 for agricultural sector. For allocating water to the reservoirs this ratio is less than 1 for all months. The HERBM model results showed that although the total allocation and profit of domestic water is increased in the optimal allocation, in agricultural section, the model has been indicated decrease in compared to the initial allocation, The reallocation of benefits based on the concept of Shaply value showed that the maximum benefit obtained for the domestic water of Zahedan City which drew the maximum side payment and added value from other stakeholders in the whole period. The least benefit belongs to the agricultural sector.

Lee (C.S., 2012) has been worked on development of a multi-objective game-theory model (MOGM) for balancing economic and environmental concerns in reservoir watershed management and for assistance in decision. Game theory is used as an alternative tool for analyzing strategic interaction between economic development (land use and development) and environmental protection (water-quality protection and eutrophication control). Geographic information system is used to concisely illustrate and calculate the areas of various land use types. The MOGM methodology is illustrated in a case study of multi-objective watershed management in the Tseng-Wen reservoir, Taiwan. The innovation and advantages of MOGM can be seen in the results, which balance economic and environmental concerns in watershed management and which can be interpreted easily by decision makers. For comparison, the decision-making process using conventional multi-objective method to produce many alternatives was found to be more difficult.

Amarsaikhan et al (AMARSAIKHAN. E , ERDENE. T, DAMDINSUREN. A, 2012) worked on Application of game theory and GIS for urban planning analysis in Mongolia to investigating the city management in Ulaanbaatar ,which at the present, the companies are in a non-cooperative equilibrium, and as such, are causing the present state of overcrowded buildings. It is explained by the Tragedy of the Commons, for the over-usage of common land leads to overcrowding, using game theory and a GIS. they did landuse analysis process in ArcGIS area and used its results by Game theory application they considered both cooperative and non-cooperative situations among construction companies in searching for optimal construction strategies and eventually they have found that when companies cooperatively construct buildings, it would greatly increase the land used for green space and for open space but it would also increase the building cost.

Basaran (BAŞARAN Uysal. A, 2005) has used game theory to analyse strategic decision making process for river basin planning. She modeled the strategic decision making process, between the Metropolitan Municipality and a small industrial enterprise in a watershed. Two situations have been represented by two payoff matrices; the present situation (Game I) and the ideal situation (Game II). In Game I, players have made decisions without considering environmental costs whereas players act with consideration of environmental legislation and costs in Game II. These games were two-person, non-cooperative, non-zero-sum and finite games. Nash equilibrium, which demonstrates the best strategy pairs for players, is explored for both games. The Metropolitan Municipality would like to develop industries in organized industrial districts in down-stream areas. However, in the first game, industrial enterprise prefers to locate outside industrial areas in up-stream. In the second game, according to Nash equilibriums, industrial enterprise prefers to locate in the organized industrial districts of the Metropolitan Municipality where the infrastructures are completed. In conclusion, players increase their payoffs and protection of environment is possible in the second game.

5. CASE OF STUDY

As an overview from Malczewski (Malczewski, 2006), based on investigation of 65 GIS-MCDA based articles, only about 10 percent of studies were using Multi-objective decision making models. Here are two fundamental categories of Multi-criteria Decision Analysis (MCDA): multi-attribute and multi-objective decision methods. Multi-attribute techniques are also referred to as the discrete methods because they assume that the number of alternatives (plans) is given explicitly, while in the multi-objective (or continuous) methods the alternatives must be generated (they are identified by solving a multi-objective mathematical programming problem).

At this classification, as for game-theory characteristics it is so similar to multi-objective decision methods. Furthermore there is not any clear boundary between optimization and decision making so perhaps it can be better to say game theory is an optimization tool that have usability in multi-objective decision methods algorithms. According to above classification and explanation about game theory position, we can largely develop characteristics of game theory and Geographical Information Systems combination to collaboration of Multi-objective decision making models and GIS.

5.1 Multi-criteria Decision Analysis for Collaborative GIS

Malczewski (Malczewski, 2006)provides a critical review of GIS-based multi-criteria decision analysis (GIS-MCDA) for supporting group (collaborative and participatory) decision making. The review is based on a survey of referred papers that have been published over the last 15 years or so. The chapter offers a classification of the GIS-MCDA approaches for group decision making. First, the articles are classified according to the generic elements of the MCDA methods. Second, the GIS-MCDA methods are classified according to the various perspectives on collaborative decision support. These taxonomies of the GIS-MCDA approaches provide a background for an evaluation of the contribution of MCDA to GIS-based collaborative decision making.

Types of multi-criteria analysis	Types of uncertainty						Total	
	Deterministic		Probabilistic		Fuzzy		Total	
	#	%	#	%	#	%	#	%
Multi-attribute	47	72.3	4	6.2	7	10.8	58	89.2
Multi-objective	2	3.1	0	0.0	0	0.0	2	31.0
Multi-attribute / Multi-objective	3	4.6	1	1.5	1	1.5	5	77.0
Total	52	80.0	5	7.7	8	12.3	65	100.0

Table 1. Classification of GIS-MCDA papers according to the types of multi-criteria decision methods

Note: # and % indicate number and percentage of papers respectively.

Based on above table, he realized that the complexity of multi-objective modeling is perhaps the major reason for a very limited use of multi-objective optimization techniques in the GIS-based group decision making.

In a general deduction he realized that an integration of MCDA into GIS technology can ultimate to progressive results such as below items:

1. To provide a flexible problem-solving environment where those involved in collaborative tasks can explore, understand, and redefine a decision problem (Kyem, 2001) (Norese, M. F., Toso, F., 2004) (Hossack, I., Robertson, D., Tucker, P., Hursthouse, A., Fyfe, C., 2004)

2. It can support collaborative work by providing a tool for structuring group decision-making problems and organizing communication in a group setting (Zhu, X; Dale, A. P., 2001) (Rosmuller, N., Beroggi, G. E. G., 2004) (Mau-Crimmins, T., de Steiguer, J. E., & Dennis, D., 2005)

3. This integration allows conflict to be reduced by providing mechanisms for revealing participants' preferences, identifying and exploring compromise alternatives, and for building consensus (Feick, R. D., Hall, G. B., 1999) (Jankowski, P., Nyerges, T, 2001) (Kyem, 2001) (Sharifi, M. A.; van den Toorn;W., Rico, A.; Emmanuel, M. , 2002)

4. MCDA manages conflicts in an individual's judging process with no mechanism to interact with the judgment structuring process of a co-member of the decision-making group (Bose, Utpal, and David B. Paradice., 1999)

He also have been mentioned some challenges for integrating MCDA into collaborative GIS such as:

1. An approach to bridge across the individual judging processes can be to provide continuous feedback to each individual separately, as well as to the whole group.

2. Complexity of multi-criteria modeling

3. Despite their potential for improving decision making, MCDA are not readily applied and used in a collaborative GIS setting.

And finally he suggests that the key barrier to the use of MCDA as a component of collaborative GIS is their complexity.

6. CONCLUSION

Considering the importance of GIS in water related studies that are always comprehensive and complex and furthermore the successful application of game theory in solving conflicts and complex problems in other fields and also relatively the limited studies by game theory application in some water management fields such as: cost/benefit allocation among users , water allocation among trans-boundary users in water resources, water quality management, groundwater management, analysis of water policies, fair allocation of water resources development cost and some other narrow fields, combination of game theory-water resources management and GIS can be a powerful applied combination in water studies. However, probably due to its complexity it is still neglected in studies of water resources. GIS-game theory combination can be a great positive development in order to Improving quality and speed of widespread and complex studies and ultimately leading to a more comprehensive and accurate decisions.

Decision-making in environmental projects requires consideration of trade-offs between socio-political, environmental, and economic impacts and is often complicated by various stakeholder views. Multi-criteria decision analysis (MCDA) emerged as a formal methodology to face available technical information and stakeholder values to support decisions in many fields and can be especially valuable in environmental decision making (Huang.I , Keisler.J and Igor Linkov. I., 2011).

Most of the literature on water allocation problems uses traditional optimization models to identify the most efficient scheme, In contrast, game theory, an area of research that has garnered Nobel Prizes in economics, is a powerful conflict resolution methodology used extensively in a variety of fields, ranging from law to evolutionary biology, has been applied rather infrequently to water resources management and allocation problems.

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