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Decision Process in a Water Use Conflict in Brazil

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Abstract This paper presents a procedure for decision analysis in water use conflicts among irrigators. It seeks feasible compromise term among decision makers by using optimal results for different proposals of solutions. The process is developed by applying the Graph Model for Conflict Resolution. The case study is the existing conflict among Coqueiros canal water users. This 45 km canal belongs to a complex irrigation and drainage canal network and it is located at Campos dos Goytacazes municipality, in the northern region of the State of Rio de Janeiro. Its basin has a potential irrigable area of approximately 14,000 ha. Six hypothetical scenarios have been built, each one corresponding to different alternatives to the conflict solution. In addition, two different tendencies were adopted by the Management Institution (MI) in order to take care of the conflict. The first tendency takes into account that the MI has no explicit preferences for any of its actions. As for the second one, the MI shows explicit preferences for the scenarios which provide more income taxes. Some scenarios that reached the state of equilibrium were analyzed to provide solutions to the conflict.

Key words water resources management · conflict analysis · game theory · graph theory

1 Introduction

The dispute for goods occurs when they become scarce or insufficient to supply all the demands. This concept applies to any natural resource in our planet, including water. It is noteworthy, in the Brazilian territory, the number of great rivers and their enormous discharges. Such discharges totalize an average superficial water production near 250,000 m^3/s (the European continent produces about 100,000 m^3/s). Nevertheless, approximately 70% of Brazil's fresh water is concentrated in the Amazon region, while the other 30% is distributed to 95% of the population living elsewhere in the Brazilian Territory.

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Since the new Water Act (Federal Law no. 9433) was enacted in 1997, establishing the National Water Resources Policy and creating the Water Resources National System, significant developments related to the water resources management have been achieved, not only at the specialized academic level, but also involving the different government levels (federal and state) and basin committees.

Despite Brazil's continental dimension, there are many water scarcity problems in Brazil, most of them caused by the increasing demand for water resources. However, it is in Northeastern and Southeastern regions of Brazil that these problems become more evident. Many conflicts caused by water unavailability are related to agricultural water uses. It is well known that this sector is responsible for the consumption of most of the water. However, each situation must be analyzed individually since, in most cases, very specific water resources uses, politics, economy, and local society interfere in the final decision, ruling out the application of identical solutions.

Scarcity and water quality problems are the major causes of water use conflicts, which are intensified with the growth of world population and water demand. One can notice that it has occurred a considerable increase in the number of reported water conflicts, not only in Brazil, but also on a global scale (United Nations 1988; Furtado and Campos 1997; Unesco 2002; Carneiro 2004; Mbonile 2005; Sneddon and Fox 2006). Additionally, one can also notice an increase of research on mathematical models capable of representing more accurately the components of a conflict (Fang et al. 1993; Hipel et al. 1997).

This paper aims to describe the development of a water use conflict decision process in irrigated agriculture, in the State of Rio de Janeiro, Brazil. This conflict has been described by Carneiro (2004) and Getirana (2005). The Graph Model has been used for Conflict Resolution (GMCR) to model the preferences of distinct stakeholders in this conflict.

2 Water Use Conflicts and Conflict Modeling

There are many different definitions for conflict in the literature. According to Malta et al. (2005), a conflict condition occurs whenever there is a dispute among two or more groups with decision power and different interests. Conflict modeling seeks to represent conceptually a real conflict situation, highlighting its major characteristics and representing them by using a formal mathematical structure. After calibrating a model for a specific dispute, it is possible to study different movements and counter-movements of each decision maker (DM) and then foresee feasible solutions to the conflict. In other words, a conflict model is a general tool normally used to study actual, past and hypothetical disputes (Fang et al. 1993).

2.1 Game Theory

The Game Theory dates back to Fermat's works in the XVII century in living room games, and had its modern base developed by Von Neumann (1928). Ever since, many developments have significantly increased its applications. There are models developed, for instance, to analyze games with two DMs and more specific models capable of analyzing games played by more than two DMs. These models can also be classified according to the number of actions that each DM can take, the kinds of structures of preference adopted by the model (transitive cardinals, related transitive, also called ordinals, or even related non-transitive), the level of DMs information access (complete or incomplete, perfect or imperfect, and symmetric or asymmetric), the colligation possibilities (cooperative and non-cooperative games), and temporal evolution modeling approach of games (static models, supergames, or differential games). Several developments increased significantly the range of topics and subtopics dealt with by the Game Theory, as shown in Table 1. The conflict model, first developed by Howard (1971), is one of the several branches of Game Theory.

2.1.1 Game Theory Applications in Water Resources Management

Game theory applications in conflict analysis for environmental and water resources planning are very common in practice. Many examples of game theory applied to conflict analysis, decision making and other real problems can be mentioned: The first game theory applications in water use conflicts were formally presented in the 1960s by Rogers (1968). This author evaluated solutions to an international conflict between India and Pakistan caused by damages arising from floods in the lower portion of rivers Ganges and Brahmaputra. Barkhi (2005) used the game theory as a negotiation instrument in group decision support systems, comparing the performance and information exchange truthfulness of groups under these different experimental conditions. Fang et al. (1993) presented important applications of the game theory with GMCR. The model was applied in the conflict over the Garrison Diversion Unit (GDU). With a long history, dating back to the nineteenth century, this conflict is about the construction of a Missouri River diversion in the state of North Dakota, and involves two countries: the USA and Canada. A fundamental part of the GDU plan was the transfer of water from the Missouri River Basin to the Hudson Bay Basin for use in irrigation. The runoff from the irrigated fields would flow through the Red and Souris rivers into Canada.

Another game theory approach in a resource dispute was presented by Ribeiro and Dorfman (1996). The authors used cooperative game theory to analyze how cooperation among irrigators affects global agricultural production. To accomplish it, they considered the cooperation relied on the redefinition of water quotas established by the water manager. Other Brazilian experience with game theory application was presented by Malta et al. (2005). The authors analyzed the importance of the water management institutional system

Table 1 Solution concepts and human behavior, adapted from Fang et al. (1988)

Solution concepts	References	Characteristics	
		Foresight	Disimprovements
Nash equilibrium	Nash (1950, 1951); Von Neumann and Morgenstern (1953)	Low	Never
General Metarationality	Howard (1971)	Medium	By opponents
Symmetric Metarationality	Howard (1971)	Medium	By opponents
Sequential stability	Fraser and Hipel (1979, 1984)	Medium	Never
Limited-move stability (L_h)	Kilgour (1985); Kilgour et al. (1987); Zagare (1984)	Variable	Strategic
Nonmyopic stability	Brams and Wittman (1981); Kilgour (1984, 1985), Kilgour et al. (1987)	High	Strategic

in the solution of a conflict over the use of water in the Lima Campos/Orós reservoir system located in Northeastern Brazil. Other applications of game theory in water resources management can also be found in recent works in Brazil (Vieira and Ribeiro 2005; Souza Filho and Porto 2005; Rufino et al. 2005).

3 The GMCR Model

The aim of this section is to present the main features of the GMCR Model developed by Fang et al. (1993). While the first part describes the key components of a conflict model, the second one illustrates some concepts of the Graph Theory. Finally, the third part introduces the GMCR Model.

3.1 Main Components of a Conflict Model

To understand the basic concepts of a conflict model formulation, it is fundamental to recall some definitions. The most important ones are shortly described as follows.

Decision maker (DM) The group of DMs is defined as those who are in disagreement over a certain issue. A DM can consist of a single person or a group of people who can obtain benefits or who can be affected or harmed in some way by the possible solutions of the conflict.

Options and strategies The options of a DM are the actions that he may take in a conflict. The strategy of a given DM is his decision making with respect to which options to take and which not to take. The set of available strategies for a DM is in principle given by the set of all combinations of his decisions for every option.

Stages and states The GMCR model accepts that the DMs may change their strategy along the evolution of the conflict, and whenever a DM changes its strategy, the conflict is said to have changed its stage. The state of a conflict in a certain stage is defined by a set of strategies selected by every DM.

Preferences In a conflict, every DM associates the set of viable states of the conflict to a structure of preferences. In general, during the evolution of the conflict, each DM will act trying to change the conflict towards the state of his highest preference.

Unilateral movement A unilateral change or unilateral move occurs when a DM decides to move the conflict by changing the selection of his strategy. When the change is made towards a state of highest preference, it is called an unilateral improvement.

Stable state A state is stable for a DM when he does not consider advantageous to move the conflict of this state through a unilateral change.

Balance state If the state is stable for all DMs, this state is a possible solution of the conflict and is called a balance state.

Stability Criteria One can calculate the stability of an action through a clear mathematical definition of human or social behaviors in a conflict situation. The characteristic of the

DM's behavior that corresponds to several stability criteria used in literature is presented in Table 1. In this table, columns 3 (foresight) and 4 (disimprovements) supply the qualitative characterization of the stability criterion. In the characterization, foresight refers to the ability of a given DM to think about possible moves that he could take in the future. If the DM has a strategic behavior, he can temporarily move to a worse state in order to reach a preferred state in the future. These actions are called disimprovements. Disimprovements by opponents mean that a DM can move to a worse state in order to block other DM's unilateral improvements.

3.2 Concepts from the Graph Theory

Some relevant graph theory definitions are given here. For further details regarding graph theory, other works available in the literature are suggested, for instance, Bondy and Murty (1976); Berge (1973); Harary (1969) and Harary et al. (1965).

A directed graph D is defined as a 2-tuple (V, A), where V is the set $\{v_1, v_2, v_3,...,v_n\}$ of elements called vertices and A is a set $\{a_{ij}, a_{kl},...\}$ of elements of the Cartesian product $V{\times}V$ called arcs. If $a_{ij}\in A$ is an arc and V_i and V_j are vertices such that $a_{ij}=(v_i,v_j)$, then a_{ij} is said to join v_i to v_j, where v_i and v_j are, respectively, the tail and the head of a_{ij}. An arc with identical head and tail is called a loop.

In a graph D, an alternated set of vertices and arcs $(v_0,a_1,v_1,a_2,...,v_{k-1},a_k,v_k)$ defines a directed way if, for any a_i, v_{i-1} is its tail and v_i is its head.

The adjacency matrix **A** of a directed graph D is the $n{\times}n$ matrix $[a_{ij}]$, with $a_{ij}=1$ if (v_i,v_j) is an arc of D, and $a_{ij}=0$ otherwise.

If there is a directed (v_i,v_j)-path in D, vertex v_j is reachable from the vertex v_i in D. The reachability matrix (Harary et al. 1965; Harary 1969) R of a directed graph is the $n{\times}n$ matrix $[r_{ij}]$ with $r_{ij}=1$ if v_j is reachable from v_i, and $r_{ij}=0$ otherwise.

A directed graph is called transitive if there is an arc (v_1,v_3) whenever arcs (v_1,v_2) and (v_2,v_3) are in D, for any distinct vertices v_1, v_2, v_3. For a transitive directed graph, the reachability matrix **R** and the adjacency matrix **A** satisfy the following equation:

$$\mathrm{R} = \mathrm{A} + \mathrm{I} \tag{1}$$

where **I** is the identity matrix (Harary et al. 1965).

3.3 Definition of the GMCR Model

Let a conflict where $N=\{1, 2,..., n\}$ be the set of indexes of the decision makers and $U=\{1, 2,..., u\}$ the set of indexes of the states of the conflict. For each DM i, one can obtain a vector of preference for the states in U, also called payoff function, P_i: $U \rightarrow R$, where R is the set of real numbers:

$$P_i = (P_i(1), P_i(2), \ldots, P_i(u)) \tag{2}$$

In the GMCR model, the conflict is represented by a set of finite directed graphs, one for each i, denoted by $D_i=(U, A_i)$, with $i\in N$. The set of vertices U contains the possible states of the conflict. Each set of arcs A_i defines the possible unilateral moves of the decision maker i. The arc (k, q) exists in A_i if decision maker i can provoke a unilateral change in one step from state k to state q. The payoff functions represent the DM state ordinal preferences. If $P_i(k)>P_i(q)$, then from i's point of view, state k is more preferable than state q. The set of directed graphs and of payoff functions constitute the Graph Model of Conflict.

3.3.1 Payoff Function

A binary relation Θ_i on the set U is $\Theta_i \subset U$xU. Decision maker i's binary preference relation Θ_i is assumed to be known; Θ_i represents i's preferences in the sense that $u_1\Theta_i u_2$ iff i prefers u_1 to u_2 or is indifferent between u_1 and u_2. Suppose O_i denotes a DM i's (strict) *preference relation* on U, and I_i the associated *indifference relation*, i.e., if $u_1\Theta_i u_2$, then $u_1 I_i u_2$ if $u_2\Theta_i u_1$ is also true, but $u_1 O_i u_2$ if $u_2\Theta_i u_1$ is false. The pair $\Theta_i=\{O_i, I_i\}$ is said to constitute a preference structure on U. Note that:

1. O_i is asymmetric (i.e., it cannot be that both $u_1 O_i u_2$ and $u_2 O_i u_1$).
2. I_i is reflexive and symmetric (i.e., if u_1, $u_2 \in$U, then $u_1 Iiu_1$ and, if $u_1 Iiu_2$, then $u_2 Iiu_1$).

Other additional assumption about the preference structure $\Theta_i=\{O_i, I_i\}$ is that:

3. $\{O_i, I_i\}$ is strongly complete (i.e., if u_1, $u_2 \in U$, then either $u_1 O_i u_2$ or $u_1 I_i u_2$ or $u_2 O_i u_1$).

Supposing that condition 3 holds is equivalent to assuming that all states are "comparable." Let Θ_i^2 denote the relation defined as $u_1\Theta_i^2 u$ iff $\exists\ u_3 \in U$: $u_1\Theta_i u_3$ and $u_3\Theta_i u_2$. If $O_i^2 \subset O_i$ (O_i is transitive) and $I_i^2 \subset I_i$ (i.e., I_i is transitive), the preference structure is a *weak-order* (or total *pre-order*) structure. These concepts are also presented by Roubens and Vincke (1985). According to these authors, Θ_i presents a weak-order structure iff there is a real-valued function P_i on U, such that:

$$u_1 O_i u_2 \ \mathit{iff}\ P_i(u_1) > P_i(u_2) \tag{3}$$

$$P_i(u_1) = P_i(u_2) \text{ implies } u_1 = u_2 \tag{4}$$

Where P_i is called the payoff function for a DM_i. For convenience, small positive integers are used as values of the payoff function, where a higher value means higher preference. P_i measures the degree of preference of a state for DM_i. Thus, if k, $q \in$ U, $P_i(k)>P_i(q)$ indicates that i prefers k to q, but the value of $P_i(k)-P_i(q)$ gives no meaningful information about the strength of this preference. Beyond the ordinal information, nothing will be inferred from the values of P_i.

3.3.2 Reachable Matrix and Lists of the Unilateral Movements of Decision Makers

The reachable matrix of the unilateral movements of a DM can be represented as the matrix $u\times u$, $\mathbf{R}_i$, where: $\mathbf{R}_i(k,q)=1$, if the DM_i can unilaterally move the conflict in one step from state k to state q, otherwise $\mathbf{R}_i\ (k,q)=0$. $R_i(k,k)=0$ by convention.

The reachable matrix $\mathbf{R}_i$ represents analytically the graph of a decision maker i. An equivalent expression of the decision making possibilities of the DM_i is the reachable list of the unilateral movements of the DM_i, $S_j(k)$, for every $k \in U$. Each list $S_j(k)$ is formed by the states in which the DM_i can unilaterally move the conflict in one step when the conflict is in the state k. Therefore:

$$S_i(k) = \{q : R_i(k,q) = 1\} \tag{5}$$

A conflict can be represented by $n\times u$ reachable lists, one for each DM and state, and n payoff functions.

3.3.3 Reachable Matrix and Lists of the Unilateral Improvements of Decision Makers

One can also define unilateral improvement from a particular state and for a specific DM as a better state, which the DM can unilaterally move itself. To represent unilateral improvements, each DM's reachable matrix $\mathbf{R}_i$ can be replaced by $\mathbf{R}_i^+$.

$$\mathbf{R}_i^+(k,q) = 1 \text{ if } R_i(k,q) = 1 \text{ and } P_i(q) > P_i(k) \tag{6}$$

$$\mathbf{R}_i^+(k,q) = 0 \text{ otherwise.} \tag{7}$$

Similarly, the DM's reachable lists $S_i(k)$ can be replaced by:

$$S_i^+(k) = \left\{q : \mathbf{R}_i^+(k,q) = 1\right\} \tag{8}$$

3.3.4 Stability Analysis in Conflicts Involving Two Decision Makers

The precise mathematical definition of how stability can be calculated must include a description of social or human behavior in a conflict situation, since humans may react in different fashions in the dispute.

Consider a problem of a decision maker i in an initial state k, according to Fig. 1. If i has the first move and decides to take the conflict to the state $k_1 \in S_i(k)$, then his opponent may decide not to stay in k_1 and move the conflict to another state. Depending on what decisions k may choose in each $k_1 \in S_i(k)$, i may choose not to move the conflict at the first time, keeping it in stage k. If this happens, k is stable for i. If a state k is stable for both decision makers, k is in equilibrium, i.e. a state of a conflict that can be expected to persist if it arises. The definition of the stability concepts for a conflict of n decision makers is analogous. In Fig. 1, i expects that j will stay in any state that i moves to, and consequently that any state that i moves to will be the final state. The initial state k is therefore stable iff i cannot move from k to any state i prefers.

Nash Stability (R) Let $i \in N$. A state $k \in U$ is Nash stable (or individually rational) for the decision maker i, iff $S_i^+(k) = \emptyset$.

General Metarationality (GMR) For $i \in N$, a state $k \in U$ is general metarational for the decision maker i iff for every $k_1 \in S_i^+(k)$ there exists at least one $k_2 \in S_j(k_1)$ with $P_i(k_2) \leq P_i(k)$.

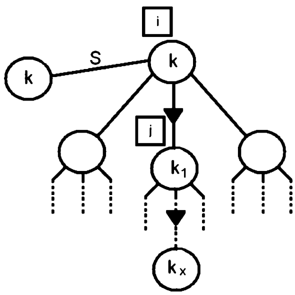

Fig. 1 Decision maker i's decision problem in initial state k in a two-decision maker conflict where j is i's opponent, that is, j=2 if I=1 ; k, k_1 and k_x, are states; and s means stay

Symmetric Metarationality (SMR) Let $i \in N$. A state $k \in U$ is symmetric metarational for the decision maker i, iff for every $k_1 \in S_i^+(k)$ there exists $k_2 \in S_j(k_1)$, such that $P_i(k_2) \leq P_i(k)$ and $P_i(k_3) \leq P_i(k)$ for all $k_3 \in S_i(k_2)$.

Sequential Stability (SEQ) Let $i \in N$. A state $k \in U$ is Sequentially stable for the decision maker i, iff for every $k_1 \in S_i^+(k)$ there exists $k_2 \in S_j^+(k_1)$ with $P_i(k_2) \leq P_i(k)$.

Limited-move Stability (L_h) Let $i \in N$. A state $k \in U$ is Limited-move for the decision maker i iff $G_h(i, k) = k$. The vector $G(I,k)$, $k \in U$ is called anticipation vector [$G(I,k)$ is the final state of game beginning in state k with initial move made by decision maker i].

The analysis of L_h stability requires the calculation of the $G_h(i,k)$ values for every $I \in N$ and for every $k \in U$. For the calculation of $G_h(i, k)$ first one should remember that if $S_i(k) \neq 0$, then state k is L_h stable and therefore one simply has to verify the state k whenever $S_i(k) \neq 0$. In what follows, It is assumed that k is such that $S_i(k) \neq 0$. Let $V_h(i,k) \in U$ be the largest payoff that the decision maker i can obtain moving the conflict from state k, and $A_i(i,k)$ the state for which it should move the conflict to obtain $V_h(i,k)$.

Non-myopic Stability (NM) Let $i \in N$. A state $k \in U$ is non-myopic stable for the decision maker i iff there exists a positive integer t' such that $G_t(i, k) = k$ for every $t \geq t'$.

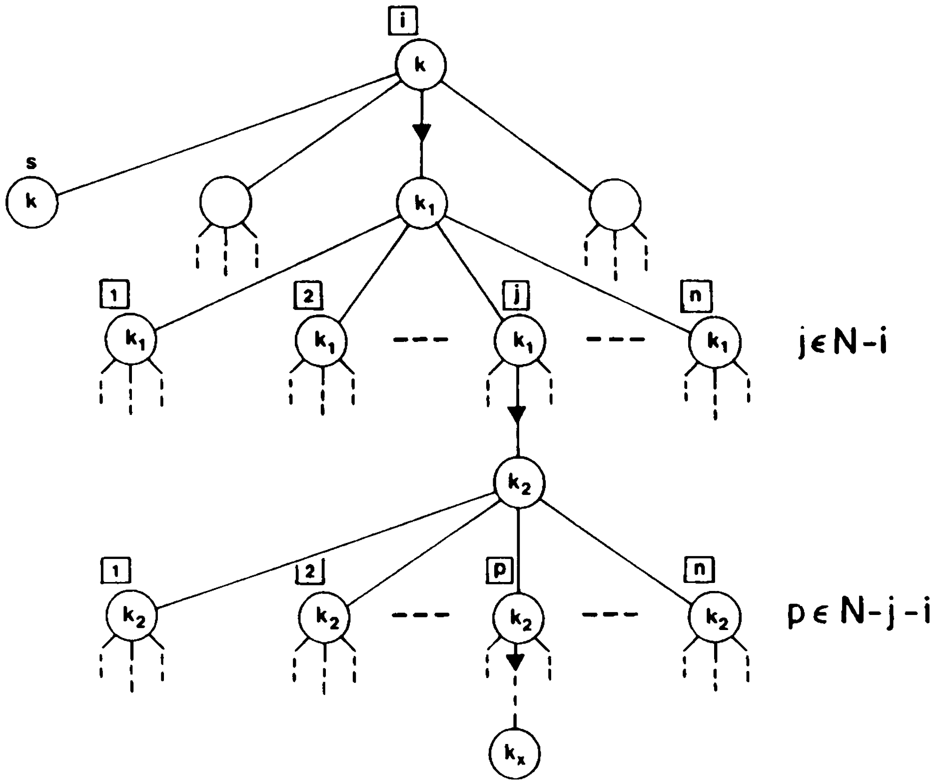

Fig. 2 Decision maker i's decision problem in initial state k in a n-decision maker conflict where k_1, k_2 and k_x, are states and s means stay

In a conflict with $n>2$ decision makers (Fig. 2), the problem of the decision maker i in initial state k can be described as follows: if i takes the initiative and decides to move the conflict for any state, then another decision maker j can move the conflict from k_1 to $k_2 \in S_i(k_1)$. Depending on j's decision, another decision maker p can decide to move the conflict from k_2 to $k_3 \in S_i(k_2)$, for example, and so on. Depending on what the decision maker i expects the other decision makers make for each $k_1 \in S_i(k)$, i can decide to keep the status quo k.

In an n-decision maker conflict, i's decision problem in initial state k is illustrated in Fig. 2. If i takes the initiative and moves, for instance to state $k_1 \in S_i(k)$, then some other decision maker j, $j \in N{-}i$, may move from k_1, say to $k_2 \in S_j(k_1)$. Depending on j's move, yet another DM p, $p \in N{-}j{-}i$, may move from k_2, say to $k_3 \in S_p(k_2)$, and so on. Depending on what player i expects the other decision makers ($N{-}i$) to do from each $k_1 \in S_i(k)$, i may prefer to stay in k.

4 Case Study

The conflict analyzed herein is located in a complex irrigation and drainage canal network which is part of the physiographic configuration of Baixada Campista (Lowlands of Campos dos Goytacazes), in the northern region of the State of Rio de Janeiro, Brazil. This network crosses Baixada Campista's fertile soils from north to south, starting from the right bank of Paraíba do Sul River and ending in the Atlantic Ocean. They were projected and built in the last century between the 1940s and 1970s by DNOS (National Department of Sanitation Structures), nowadays an extinct governmental agency, whose aim was to eliminate frequent focuses of diseases in this region by draining lakes, lagoons and ponds. Today, these canals add up a total length of about 1,300 km. With increasing water demand for irrigation in the past decades, these canals started to be used to convey water to irrigators.

At the point where it crosses Baixada Campista, Paraíba do Sul River has a minimum water discharge of 302 m^3/s over 95% of the time. This amount of water would be sufficient to supply all irrigation demands in the region. Nevertheless, due to the existence of some hydraulic problems – such as the reduction of sections caused by sediment settlement and land depressions in some particular paths – the canals do not have adequate capacity to convey all the water required to supply the demand. The section reductions cause problems to irrigators with water deviations after these discharge constraints because they cannot have enough water to irrigate. Otherwise, if the discharge constraints are not obeyed, farmers who have their properties close to canals may have their potentially irrigated soils flooded due to rising water levels. As a result, in order to deliver water to some irrigators, other farmers will be badly affected by the saturation of their potentially irrigated soils or even by their submersion. Thus, the current conflicts among irrigators may be characterized, mainly by the inefficiency of the flap gate operation associated to the high pluviometric indices in the rainy months and problems of hydraulic nature caused by factors such as extremely low slopes of the canals, existence of land depressions and frequent sedimentation along the canals.

Sugar cane is the main irrigated crop in this region, however a few other focuses of policulture can also be found. Even though there is an expressive number of sugar cane farmers surrounding the canals, most of them practice "sequeiro" production, i.e., dryland farming. Consequently, water demand is not high, except in dry months when its demand increases.

Among all the existing canals in Baixada Campista, we chose to study and apply the model to only one canal: Coqueiros canal. According to some results presented in Getirana et al. (2005), based on cartographic information, the canal's basin has about 14,000 ha of potentially irrigable soils and it is, approximately, 40 km long (Fig. 3). Besides the good quality of soil, the conflicts described occur in moderate proportions among water users along this canal and are likely to increase over the years, due to climate changes in Northern Rio de Janeiro.

Some results from Getirana (2005) have been used to begin the study. The author applied a Linear Programming model to optimize scenarios reaching feasible solutions for the conflict. The objective function was crop production maximization. Considering sugar cane as the prevailing cultivated crop in the region, all the proposed scenarios assume the intensification of sugar cane monoculture irrigation.

Other hypotheses such as water allocation criteria (quotas and crop production optimization) were adopted in order to create these scenarios. These hypotheses are described in what follows. The results of these scenarios were then adopted as input data to the GMCR model to analyze the Coqueiros canal conflict.

4.1 Criteria for the Arrangement of Solution Proposals

Getirana (2005) proposes three hypotheses to solve the conflict among the irrigators. One of them is based on structural interventions, while the other two rely on non-structural

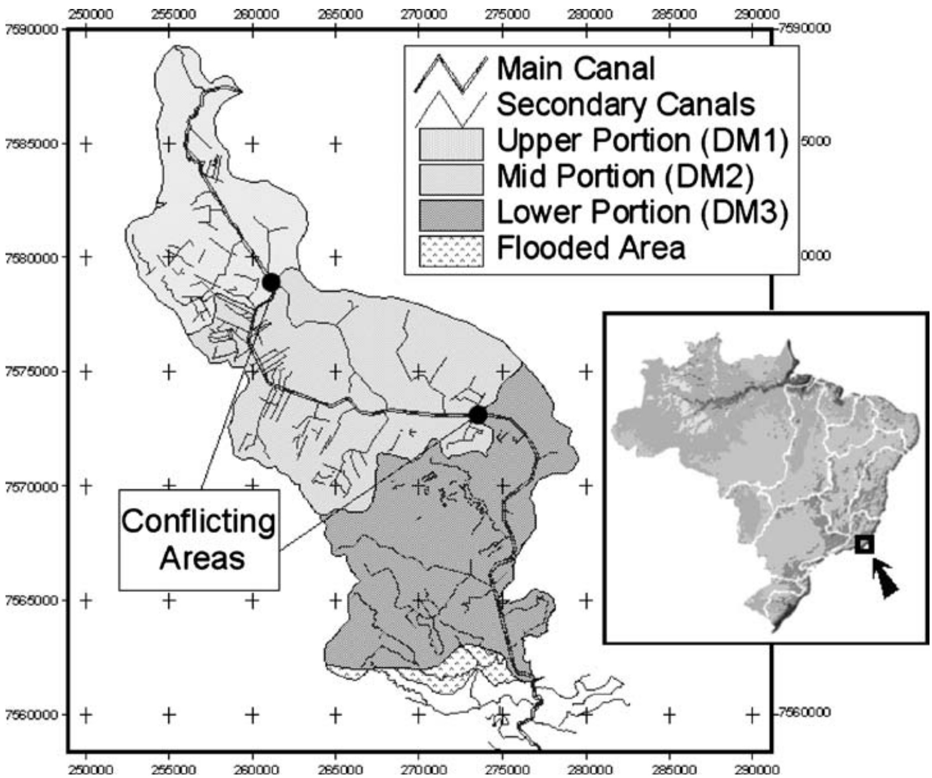

Fig. 3 Coqueiros canal hydrological limit and its location in Brazil

interventions. The hypotheses are: (1) discharge constraints, seeking to avoid high water levels in some potentially irrigable lands causing, as a consequence, water unavailability for all irrigators downstream; (2) ignore discharge constraints, to make water available to irrigators downstream, saturating fertile soils upstream; or (3) execution of structural interventions, for instance building embankments, canal rectification etc. as a feasible solution to end (or, at least, reduce) the discharge constraints and flooded lands in these canal segments. In this work, it is proposed essentially sugar cane monoculture. It was also assumed that the expenses related to structural interferences in the canal will be paid by the State Government, which intends to provide better conditions to irrigators, increasing their production.

Two ways of allocating water for irrigators have also been considered (Getirana 2005): (1) by quotas; or (2) by net profit optimization of irrigation development. The first one is based on the potentially irrigable area of each farmer (the bigger the potentially irrigable area is, more water the irrigator receives) and the second one is based on water application efficiency of each irrigator (the higher the efficiency is, more available water the irrigator has). In the latter, the efficiency is defined by crop production generated for a cubic meter of water used in the system (R $/m^3, where R $1.00=US $0.40). These last two criteria represent different water allocation proposals that the Management Institution (MI) might adopt. The first one defines an unbiased MI's point of view and the second one characterizes MI's preference for those who have a better production, i.e., better water application efficiency. Table 2 presents the results achieved by applying the optimization technique for each scenario. It can be noticed that regardless of all groups of irrigators and

Table 2 Proposed scenarios with feasible agreements among groups of irrigators (Decision makers) and fractions of the total available water allocated, for each basin portion, in the month with the largest water deficit for the six scenarios

Parameter	Water use groups	Scenarios					
		Quota allocation			Optimal allocation		
		1	2	3	4	5	6
Hydraulic conditions[a]	–	w/ restr.	w.o/ restr.	w/ interf.	w/ restr.	w.o/ restr.	w/ interf.
Potentially irrigable area by basin portion (ha)	Upper	4,019	4,019	4,019	4,019	4,019	4,019
	Mid	3,140	2,840	3,140	3,140	2,840	3,140
	Lower	6,962	6,263	6,962	6,962	6,263	6,962
	Total	14,121	13,122	14,121	14,121	13,122	14,121
Allocated water of the total available(%)	Upper	41.3	30.6	28.5	34.8	32.4	31.0
	Mid	33.8	21.6	22.2	27.3	20.8	21.2
	Lower	25.0	47.7	49.3	25.0	46.8	47.7
	Total	100.0	100.0	100.0	87.1	100.0	100.0
Estimated net profit in 6 years (10^6 R$)	Upper	35.68	31.42	29.20	35.68	33.23	31.88
	Mid	27.86	22.10	22.72	27.86	21.28	21.78
	Lower	25.55	48.77	50.38	25.69	47.97	48.87
	Total	89.09	102.28	102.29	89.23	102.47	102.53

[a] Consider hydraulic conditions "w/ restr." (with restrictions), "w.o./ restr." (without restrictions) and "w/ interf." (with interferences), respectively, as the preservation of maximum discharge constraints in the segments with restrictions, the non-consideration of maximum discharge constraints in the canal segments with restrictions decreasing potentially irrigable lands in these areas and increasing the water availability for irrigators supplied downstream and, finally, water discharge after the necessary structural interventions in the canal developed by the State government

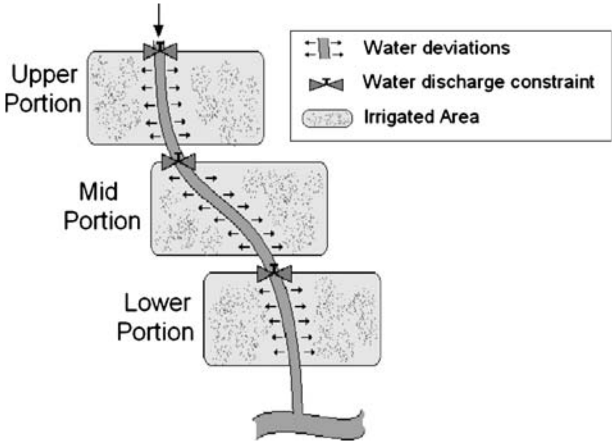

Fig. 4 Water use conflict scheme. Three groups of decision makers were identified in the Coqueiros Canal Basin: upper portion irrigators, mid portion irrigators and lower portion irrigators

scenarios (except scenarios 2 and 5 – without discharge restrictions) the same potentially irrigated area has been obtained, associated to different water demands and net profits. This is explained by the fact that, according to each soil type, distinct crop yields and water demands were considered.

Figure 4 shows a simple representation of the conflict. It is important to notice the three different groups of irrigators and the discharge constraints between each pair of group. According to results of hydraulic simulation run at the Hydrology and Environmental Studies Laboratory at the Federal University of Rio de Janeiro (Getirana 2005), two discharge constraints were identified, starting from upstream: 4.7 and 2.0 m^3/s.

The GMCR model was applied to this conflict to verify the best alternatives to the DMs considered in the water use dispute. Table 3 presents the DMs, their options and strategies. According to the latter table, it can be noticed that DM1, DM2 and DM3 have only one option of movement, while DM4 (MI) can move to a larger number of states. Table 4 shows the possible states of the conflict, the reachable list and the payoff functions of each DM. To obtain the list of states presented in the table, it was considered that “Y” and “N” represent the opposite interests of a DM for a specific option, i.e., the first one means that the DM says “yes” to the option and the second one means that he says “no” to the option. A

Table 3 Coqueiros Canal conflict: decision makers, options and strategies

Number	Decision maker	Options	Strategies
1	Upper portion irrigators	Accept the MI decision	(Y),(N)
2	Mid portion irrigators	Accept the MI decision	(Y),(N)
3	Lower portion irrigators	Accept the MI decision	(Y),(N)
4	Manager Institute (MI)[a]	1	(Y,N,N,N,N,N)
		2	(N,Y,N,N,N,N)
		3	(N,N,Y,N,N,N)
		4	(N,N,N,Y,N,N)
		5	(N,N,N,N,Y,N)
		6	(N,N,N,N,N,Y)
		No decision	(N,N,N,N,N,N)

[a] MI options are numbered according to the scenarios in Table 2.

Table 4 Coqueiros canal conflict: viable states, reachable list, and payoff functions for every decision maker, for both cases analyzed

No	States	S1	S2	S3	S4	P1	P2	P3	$P4_1$	$P4_2$
1	(Y)x(Y)x(Y)x(YNNNNN)	–	–	8	2,3,4,5,6,7	46	46	1	46	3
2	(Y)x(Y)x(Y)x(NYNNNN)	20	14	9	1,3,4,5,6,7	26	33	41	46	8
3	(Y)x(Y)x(Y)x(NNYNNN)	21	15	–	1,2,4,5,6,7	1	37	46	46	11
4	(Y)x(Y)x(Y)x(NNNYNN)	22	16	10	1,2,3,5,6,7	44	44	2	46	5
5	(Y)x(Y)x(Y)x(NNNNYN)	23	17	11	1,2,3,4,6,7	37	1	34	46	16
6	(Y)x(Y)x(Y)x(NNNNNY)	24	18	12	1,2,3,4,5,7	30	26	42	46	19
7	(Y)x(Y)x(Y)x(NNNNNN)	25	19	13	1,2,3,4,5,6	21	21	21	46	1
8	(Y)x(Y)x(N)x(YNNNNN)	–	–	1	9,10,11,12,13	45	45	3	46	4
9	(Y)x(Y)x(N)x(NYNNNN)	31	26	2	8,10,11,12,13	25	32	32	46	9
10	(Y)x(Y)x(N)x(NNNYNN)	32	27	4	8,9,11,12,13	42	43	4	46	6
11	(Y)x(Y)x(N)x(NNNNYN)	33	28	5	8,9,10,12,13	36	3	24	46	15
12	(Y)x(Y)x(N)x(NNNNNY)	34	29	6	8,9,10,11,13	28	25	33	46	18
13	(Y)x(Y)x(N)x(NNNNNN)	35	30	7	8,9,10,11,12	10	22	12	46	1
14	(Y)x(N)x(Y)x(NYNNNN)	36	2	26	15,16,17,18,19	24	29	38	46	9
15	(Y)x(N)x(Y)x(NNYNNN)	37	3	–	14,16,17,18,19	2	35	45	46	12
16	(Y)x(N)x(Y)x(NNNYNN)	38	4	27	14,15,17,18,19	43	40	6	46	6
17	(Y)x(N)x(Y)x(NNNNYN)	39	5	28	14,15,16,18,19	35	5	27	46	15
18	(Y)x(N)x(Y)x(NNNNNY)	40	6	29	14,15,16,17,19	29	16	40	46	18
19	(Y)x(N)x(Y)x(NNNNNN)	41	7	30	14,15,16,17,18	9	11	19	46	1
20	(N)x (Y)x(Y)x(NYNNNN)	2	36	31	21,22,23,24,25	19	31	37	46	9
21	(N)x (Y)x(Y)x(NNYNNN)	3	37	–	20,22,23,24,25	3	36	44	46	12
22	(N)x (Y)x(Y)x(NNNYNN)	4	38	32	20,21,23,24,25	40	42	7	46	6
23	(N)x (Y)x(Y)x(NNNNYN)	5	39	33	20,21,22,24,25	33	2	26	46	15
24	(N)x (Y)x(Y)x(NNNNNY)	6	40	34	20,21,22,23,25	22	24	39	46	18
25	(N)x (Y)x(Y)x(NNNNNN)	7	41	35	20,21,22,23,24	6	20	18	46	1
26	(Y)x(N)x(N)x(NYNNNN)	42	9	14	27,28,29,30	23	28	30	46	10
27	(Y)x(N)x(N)x(NNNYNN)	43	10	16	26,28,29,30	41	39	8	46	7
28	(Y)x(N)x(N)x(NNNNYN)	44	11	17	26,27,29,30	34	6	23	46	14
29	(Y)x(N)x(N)x(NNNNNY)	45	12	18	26,27,28,30	27	17	31	46	17
30	(Y)x(N)x(N)x(NNNNNN)	46	13	19	26,27,28,29	7	10	11	46	1
31	(N)x (Y)x(N)x(NYNNNN)	9	42	20	32,33,34,35	12	30	28	46	10
32	(N)x (Y)x(N)x(NNNYNN)	10	43	22	31,33,34,35	38	41	9	46	7
33	(N)x (Y)x(N)x(NNNNYN)	11	44	23	31,32,34,35	32	4	22	46	14
34	(N)x (Y)x(N)x(NNNNNY)	12	45	24	31,32,33,35	18	23	29	46	17
35	(N)x (Y)x(N)x(NNNNNN)	13	46	25	31,32,33,34	5	18	10	46	1
36	(N)x (N)x(Y)x(NYNNNN)	14	20	42	37,38,39,40,41	11	27	35	46	10
37	(N)x (N)x(Y)x(NNYNNN)	15	21	–	36,38,39,40,41	4	34	43	46	13
38	(N)x (N)x(Y)x(NNNYNN)	16	22	43	36,37,39,40,41	39	38	5	46	7
39	(N)x (N)x(Y)x(NNNNYN)	17	23	44	36,37,38,40,41	31	7	25	46	14
40	(N)x (N)x(Y)x(NNNNNY)	18	24	45	36,37,38,39,41	17	9	36	46	17
41	(N)x (N)x(Y)x(NNNNNN)	19	25	46	36,37,38,39,40	8	8	17	46	1
42	(N)x (N)x(N)x(NYNNNN)	26	31	36	43,44,45,46	20	13	14	46	2
43	(N)x (N)x(N)x(NNNYNN)	27	32	38	42,44,45,46	13	12	20	46	2
44	(N)x (N)x(N)x(NNNNYN)	28	33	39	42,43,45,46	14	19	13	46	2
45	(N)x (N)x(N)x(NNNNNY)	29	34	40	42,43,44,46	15	14	15	46	2
46	(N)x (N)x(N)x(NNNNNN)	30	35	41	42,43,44,45	16	15	16	46	1

S1, S2, S3 and S4 are the reachable lists and P1, P2, P3 and $P4_{1,2}$ are the payoff functions of DM1, DM2, DM3 and DM4, respectively.

Table 5 Coqueiros canal conflict: stable states

Case	Criteria				GMR	SMR
	R	SEQ	L_h	NM		
1		2, 6, 7, 8, 10, 17, 21			*	**
2		6			6	6

* All, except 1, 3, 4 , 5, 11, 15, 23 and 33.

** All, except 1, 3, 4 , 5, 11, 15, 23, 30, 33, 35, 38, 42,43,44, 45 and 46.

strategy is created for a DM when he decides which option to invoke. When each DM decides upon his strategies, the overall result is a state.

The payoff functions were numbered according to predictions of the authors related to the reactions of the decision makers. It can be noticed that some states were not included in this table. For example, the states (N)x(Y)x(Y)x(YNNNNN) and (Y)x(N)x(Y)x(YNNNNN) are not listed above. This is explained by the fact that no decision maker will say "no" to move the conflict to the state that gives him the best payoff function. This manual reduction of the number of states improves the computer processing and makes the analysis of results faster and easier.

5 Results and Discussions

The results shown in Table 5 represent the stable states of Coqueiros Canal conflict according to the stability criteria adopted in Case 1 and Case 2.

First, it has been analyzed the stability found in state 6 in both cases (Case 2, in particular, achieved only this stable state).

In Case 1, where the MI shows no preference for any state, the results are an intermediate answer to DM1 and DM2, with P1=30 and P2=26, while decision maker 3 obtained P3=42. It can be noticed that for the first three decision makers, for any unilateral movement they make, all payoff functions will be lower than the current ones. Consequently, they stop in this state and thus state 6 becomes the stable and balance state to the conflict.

In Case 2, the situation (payoff function) does not change to any decision maker. Nevertheless, decision maker 4, who has different levels of preference for the various states, does not move because the other states he can move, i.e., states 9, 10, 11, 12 and 13, have payoff functions with lower values than state 6, where $P4_2=19$. Thus, he stops in state 6. It is noteworthy that this result represents scenario 6, according to Tables 2 and 3, which is the one that yields the highest net profit.

In Case 1, there are other states (2, 6, 7, 10, 17 and 21), which have reached the stability in all criteria, except L_4 (Table 6). Other states reached stability only by applying GMR and SMR, or only GMR. It can be noticed that the payoff functions show high values for, at least, three DMs in all analyzed cases for all criteria. Besides, when there is a DM with a low payoff function value, he does not move because his possibility of movement would take him to a worse state. As an example, state 17 presents P2=5. DM2 considers his situation stable because his only option of movement is to state 5 where P2=1, i.e. his worst state. Hence, state 17 becomes his stable state.

State 7 has P1=P2=P3=21, i.e. an intermediate payoff function value, while DM4 has $P4_1=46$. Since any movement of all DMs means unilateral fall, all of them prefer to stay in state 7. Nevertheless, according to Table 5, this is an unacceptable state to the MI. Consequently, state 7 does not represent a feasible solution, thus maintaining the conflict.

Another important detail in the analysis of results is that the two best results (states 2 and 6) are those for which DM1, DM2 and DM3 accept the MI's decision. In other words, the end of the conflict could really happen. Thus, for Case 1, it can be said that the best states (stable states) are 2 and 6, where the *P* values are relatively high to all DMs involved in the dispute.

6 Conclusions

The acceptance of the incorporation of models based on Conflict Theory by professionals specialized in water resources management practices (and, consequently, its analysis) is already well-known. But the number of works applying this class of models is still limited. The present study discusses the application of conflict theories, more specifically the Graph Model for Conflict Resolution (GMCR) presented by Fang et al. (1993), to the analysis of a dispute for water resources based on the conflicts described in this paper and discussed in more details in Carneiro (2004) and Getirana (2005).

In spite of the existence of the real situation, the analysis was developed from an academic point of view, without consulting the real decision makers of the conflict, i.e. the irrigators and the MI. This consult would enable us to validate the conflict modeling. Nevertheless, the results have revealed the importance of an institutional system of water resources management and how fundamental can be the decision power of a Water Resources Management Institution to conflict solution.

The present investigation shows that it is possible to identify and, sometimes generalize, important characteristics of water resources management problems by applying the GMCR model.

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