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Conflict Resolution for Sacramento-San-Joaquin Delta with Stability and Sensitivity Analyses Using the Graph Model

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Abstract

The goal of this paper is to resolve the strategic long-term dispute for the Sacramento-San Joaquin Delta California using the Graph Model approach for conflict resolution. To facilitate the analysis, a Decision Support System (DSS) has been developed, incorporating multiple-criteria decision analysis, stability and equilibrium analysis, and uncertainty analysis using the info-gap technique. The DSS has been used on the Sacramento-San Joaquin Delta conflict. After specifying the stakeholders with their preferences and possible decisions, the DSS identified the most robust solution, considering the possible actions and counteractions of all stakeholders. Solution robustness was then tested under the uncertainty associated with stakeholders' perspectives, and under cooperative and non-cooperative attitudes. The model results suggest the following: (1) with cooperation between the decision makers, building the tunnel is the most likely solution to replace the existing water export; (2) the second reliable solution is to have a dual conveyance "tunnel"; (3) when decision makers do not cooperate, no-export water is the best solution. Furthermore, no-export solution is impossible and unlikely for this problem since the agriculture production in the Sacramento-San Joaquin Delta is a multi-billion industry.

Keywords: Water disputes; conflict resolution; graph model; decision support systems; multiple criteria decision analysis; Sacramento-San Joaquin Delta; computer applications.

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1 Introduction

In a water conflict, different interest groups can be involved as decision makers, where each decision maker can make choices unilaterally and the combined choices of all players together determine the possible outcomes of the conflict. Instead of unilaterally moving, decision makers also may choose to cooperate or form coalitions. In such situations, Game theory techniques, such as the Graph Model for Conflict Resolution, offer n useful and precise language for discussing conflicts. A systematic study of a conflict provides insights about how the dispute can be efficiently modeled and resolved [1].

Game theory is basically a mathematical study of competition and cooperation. It shows how strategic interactions among players result in overall outcomes with respect to the preferences of those players. Such outcomes might not have been planned by any player [2]. Games are defined mathematically by a set of players, a set of strategies (options) available to them, and the players' payoffs for each combination of such strategies (possible outcomes of the game). The payoffs to players decide the decisions made and the type of the game being played. If the payoffs are equal to zero or a constant then the stakeholders have opposing interests and are playing a zero-sum-game or a constant-sum game; whatever one stakeholder wins, the other stakeholder loses. Non-zero-sum games, in which the sum of payoffs does not equal zero or a constant, have more complications, and likely requires cooperation.

In a typical game, decision makers (players), have conflicting goals and try to overcome one another by anticipating each other's decision. The game is determined as a consequence of the players' decisions. Game theory analyses the strategies players use to maximize their payoffs. A solution to a game prescribes the set of decisions that each decision maker takes at the end. An advantage of game theory over classical quantitative optimization methods is its capability to simulate the actions and counteractions that take place during the negotiation, until a final resolution emerges and is accepted by all stakeholders [1].

The graph model [3] is a comprehensive decision technology has been applied to a range of different conflicts, including local and international trade disputes [4]. In a recent research [5,6], the graph model was used to resolve a construction conflict between an owner and a contractor. The graph model mathematically describes how stakeholders (DMs) interact with one another in terms of negotiation moves and countermoves, based on their preferences.

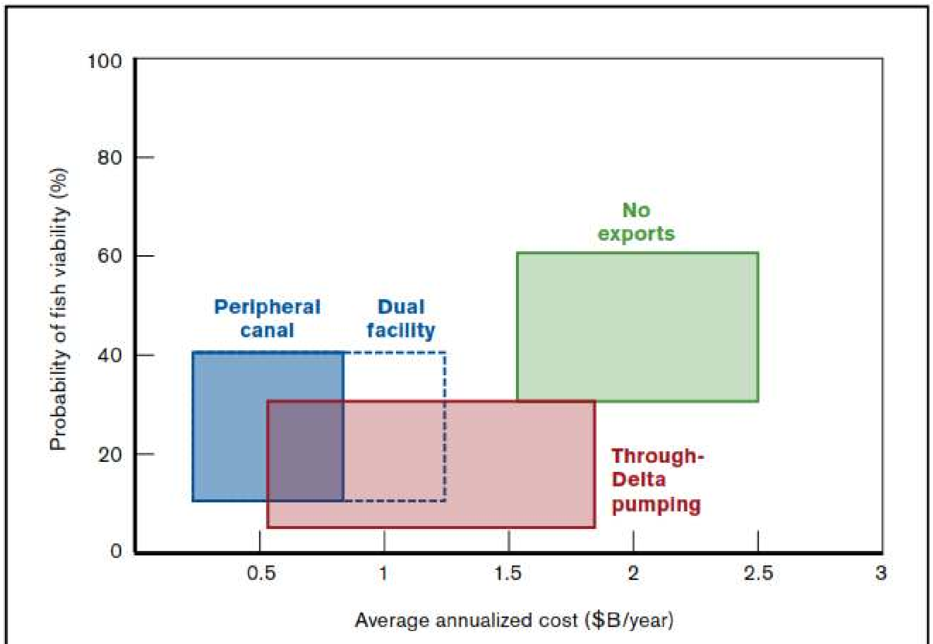
This paper introduces the graph model for conflict resolution [3] as an effective method for modeling and resolving water disputes. To facilitate its application, a decision support system (DSS), called "congress", has been developed based on the early work of [7]. The DSS is then applied to the water dispute in the Sacramento-San Joaquin Delta (California). The DSS helps to select the optimum decision and to examine its robustness under uncertainty in the decision makers' preferences.

2 Case Study

The Sacramento-San Joaquin Delta is part of the largest estuary on the West Coast of the United States, and is a home to a various fish and wildlife. It also a major source of California's water supply, channeling water from Northern California's watersheds to two-thirds of the state's households and millions of acres of farmland in the Central Valley. This area is currently in a serious, long-term crisis. Many of the Delta's native fish populations are experiencing rapid reductions, five are listed as either endangered or threatened species. Many Delta islands are artificially protected by aging levees. The old weak levees defending these islands are subject to increasing water pressure from tides and floods. A major earthquake would cause a catastrophic failure of the levee system. The Delta currently has a system that abstracts water from the Sacramento River in the north, transporting it through the Delta to massive pumps at the Delta's southern edge. The pumps convey this water to users all-over California, from the Bay Area in the north to the Central Valley and Southern California. This water export system has been effective for over 50 years, and has been a large source of income. However, recent federal court rulings reacting to the decline in native fish populations reduced water exported from the Delta substantially. Accordingly, the efficiency of water supply system of California is becoming less reliable [8].

Among various policy initiatives now undertaken to consider the Delta's issues, the Delta Vision initiative has been set out by Governor Arnold Schwarzenegger; this initiative has established co-equal objectives for future Delta management: conservation of the ecosystem and creation of a reliable water supply for California. To achieve these objectives, four key options for Delta water exports are considered: (a) Continue to pump and export water through the Delta; (b) Build a peripheral canal to convey water around the Delta; (c) Operate a "dual conveyance" system, combining the two previous strategies; or (d) end water exports.

Risks come with each of the suggested option. On the one hand, continuing the pumping through the Delta will worsen the situation for the endangered species. On the other hand, ending all water exports may be the best solution for the endangered fish species, but is very costly for California's economy. Fig. 1 summarizes the performance of each alternative in terms of two criteria discussed by [8]: The fish population viability (considered as the environmental sustainability criterion); and the economic cost (as the water supply reliability criterion). As shown in Fig. 1, the performance of each alternative under the two criteria involves considerable uncertainty, reflected by large in the figure. Therefore, there is a need for a technique which can suggest the final outcome of this multi-criteria problem where the performances are uncertain.



NOTE: Range of costs and Delta smelt population viability for Delta export alternatives in 2050.

Fig. 1. Performance of San Joaquin Delta water export alterative under two criteria (adopted from [8]**)**

3 Decision Support System (DSS) Implementation

To facilitate the analysis of the water conflict for the Sacramento-San Joaquin Delta, a decision support system (DSS), called "**con**flict /**G**ame\ **res**olution" or "**conGres**" has been developed at the University of Waterloo based on the work of [5,7,6]. As shown on Fig. 2, the DSS integrates three techniques: (1) the elimination method [9], which is a flexible multiple criteria decision analysis (MCDA) technique used to shortlist the decision alternatives; (2) the graph model for conflict resolution [3] to simulate the conciliation process that takes place; and (3) the information gap (info-gap) theory [10,11] to help choose the best decision in the presence of the uncertainty associated with the stakeholders' preferences. Fig. 3 shows the main interface of "conGres" as applied to the Sacramento-San Joaquin Delta case study, with the following steps showing the details of the implementation, for the goal of identifying the best solution.

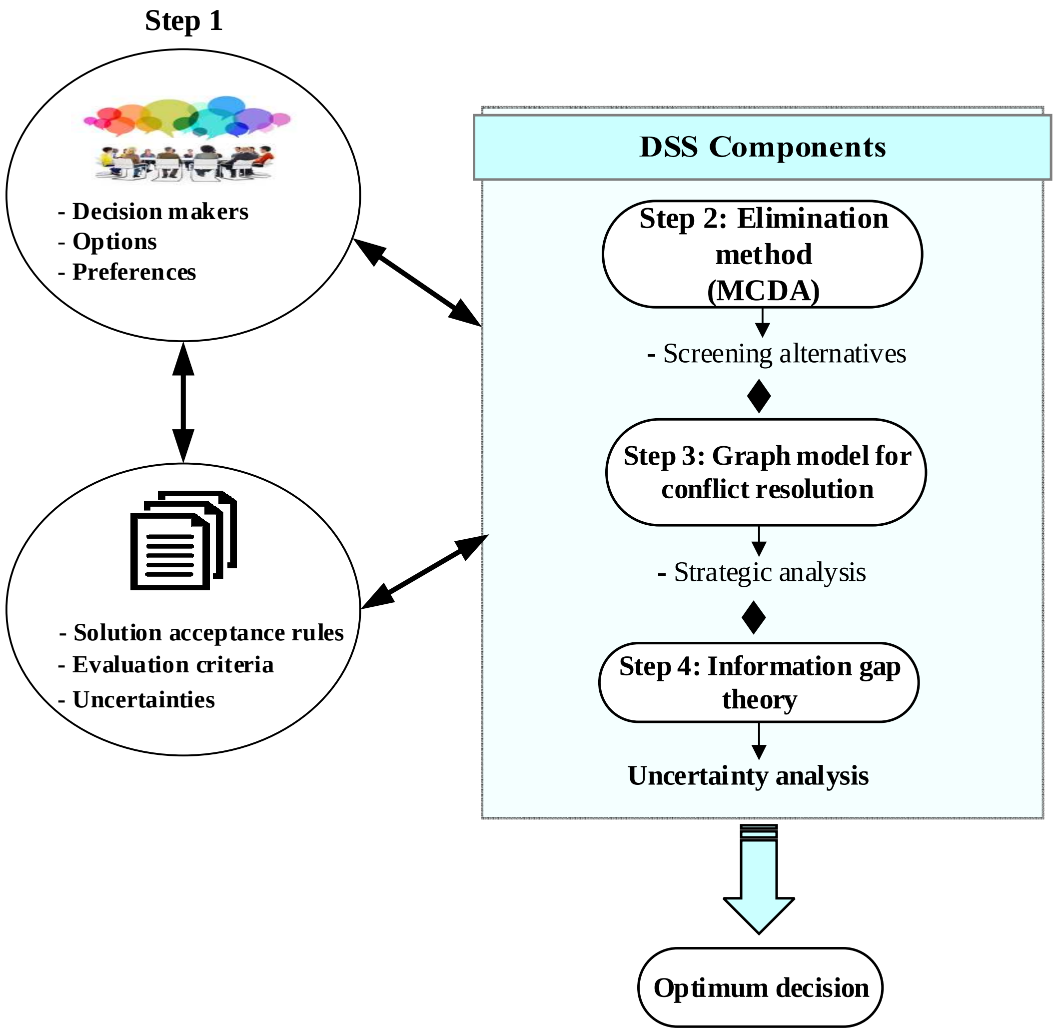
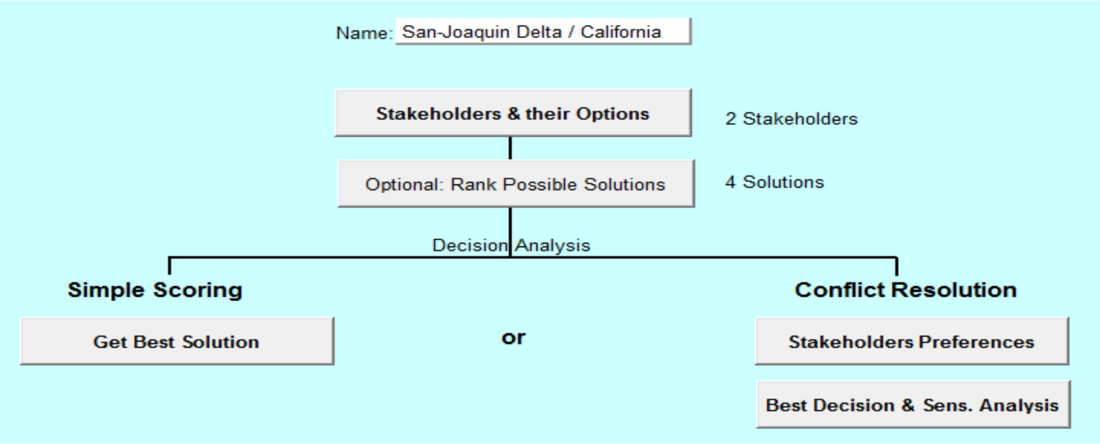


Fig. 2. Components of the decision support system (DSS) for conflict resolution

3.1 Step 1: Define stakeholder and their options

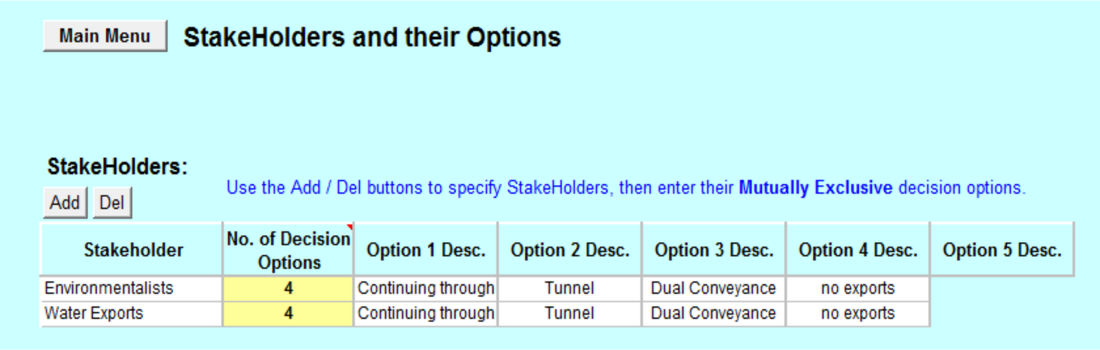
The Delta problem has two decision makers (DMs) with conflicting concerns: the water exporters who are concerned with sustainability of water exports; and the environmentalists who are concerned with native fish population viability. Each of these two DMs can accept any of the four options mentioned earlier (a, b, c, d), as shown in Fig. 4 and listed in Table 1. Therefore, there exists a set of 4 x 4 = 16 "solution states" (or possible resolutions) that combine the decisions of the two DMs.



Name: San-Joaquin Delta / California

Fig. 3. Graph Model Chart for San-Joaquin Delta

For example, decision state 6 (highlighted on top of Fig. 5) represents a decision in which both DMs agree to building a peripheral canal to convey water around the Delta.



Use the Add / Del buttons to specify StakeHolders, then enter their **Mutually Exclusive** decision options.

Stakeholder	No. of Decision Options	Option 1 Desc.	Option 2 Desc.	Option 3 Desc.	Option 4 Desc.	Option 5 Desc.
Environmentalists	4	Continuing through	Tunnel	Dual Conveyance	no exports	
Water Exports	4	Continuing through	Tunnel	Dual Conveyance	no exports	

Fig. 4. Stakeholders and their discrete options

3.2 Step 2: Shortlist feasible solutions

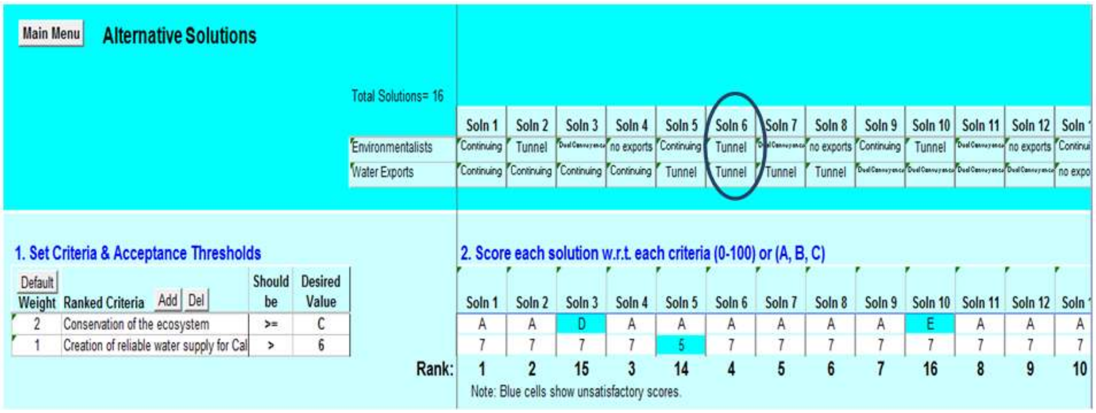
Given 16 decision states, it is important to recognize and eliminate any solution with infeasible combinations of options and to focus only on the most promising ones. The elimination method provides the ability to eliminate some of the alternatives that do not meet stakeholders' threshold values of acceptance. Fig. 6 shows possible cooperative outcome, occurring when both DMs select the same strategy. Based on the game structure suggested by [12] shown in Fig. 6, twelve options were eliminated. The DSS allows the user to set any number of criteria to use for the elimination process. After the user evaluates each decision state in terms of these criteria, the DSS ranks the solution states. Accordingly, the user can eliminate the lower ranked options. Following this process, only the four solutions in which both parties agree to a certain solution are feasible, therefore producing the short list in Fig. 7.

3.3 Step 3: Carry out conflict resolution analysis

In this step, the mechanism of the graph model for conflict resolution is used, and the process examines the stability of the shortlisted solutions with respect to the DMs' preferences. Following the Graph Model approach of [3], the relative preferences of each DM in the shortlisted solutions are first specified. To do that, this study uses the cardinal matrix specified by [13,8] and shown in Eq. 1. The numbers on the left and right columns of the matrix indicate the average utilities of the DMs, from the four alternatives. In this ordinal matrix, higher values represent higher preference of the DM. Based on these values, it is possible to rank the alternatives for each DM.

$$\text{Cardinal Form Matrix} = \begin{array}{c} \begin{array}{cc} \text{Exporters} & \text{Environmentalists} \end{array} \\ \begin{bmatrix} 1.205 & 17.5 \\ 0.550 & 25.0 \\ 0.750 & 2.50 \\ 2.000 & 45.0 \end{bmatrix}_{4\times 2} \end{array} \qquad (1)$$

Once the preferences were determined and entered as shown in Fig. 7, the Graph model uses the stability concepts (Nash (R), General Metarationality (GMR), Symmetric Metarationality (SMR), Sequatial Stability (SEQ)), listed in Table 2, to test each solution in terms of stability and equilibrium (i.e., stability for all DMs). For mathematical definitions, all information can be found in [3,5,6]. Each stability concept has a different perspective. For instance, a decision state is Nash stable for one DM if the DM cannot unilaterally move to more preferred state. When a decision state is found to be stable for all the stakeholders, it represents an equilibrium situation, i.e., a decision state that has high potential of satisfying all parties.



Total Solutions= 16

	Soln 1	Soln 2	Soln 3	Soln 4	Soln 5	Soln 6	Soln 7	Soln 8	Soln 9	Soln 10	Soln 11	Soln 12	Soln
Environmentalists	Continuing	Tunnel	Dual Conveyance	no exports	Continuing	Tunnel	Dual Conveyance	no exports	Continuing	Tunnel	Dual Conveyance	no exports	Continui
Water Exports	Continuing	Continuing	Continuing	Continuing	Tunnel	Tunnel	Tunnel	Tunnel	Dual Conveyance	Dual Conveyance	Dual Conveyance	Dual Conveyance	no expo

1. Set Criteria & Acceptance Thresholds

Weight	Ranked Criteria	Should be	Desired Value
2	Conservation of the ecosystem	>=	C
1	Creation of reliable water supply for Cal	>	6

2. Score each solution w.r.t. each criteria (0-100) or (A, B, C)

	Soln 1	Soln 2	Soln 3	Soln 4	Soln 5	Soln 6	Soln 7	Soln 8	Soln 9	Soln 10	Soln 11	Soln 12	Soln
	A	A	D	A	A	A	A	A	A	E	A	A	A
	7	7	7	7	5	7	7	7	7	7	7	7	7
Rank:	1	2	15	3	14	4	5	6	7	16	8	9	10

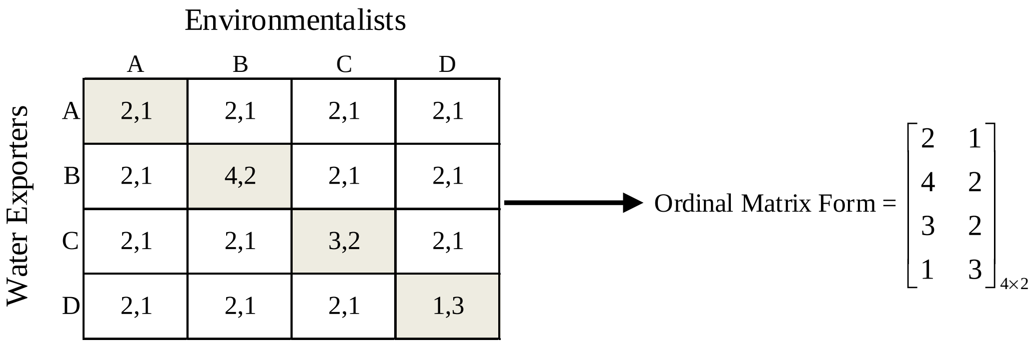
Note: Blue cells show unsatisfactory scores.

Fig. 5. Solution states and the elimination method

Using the DSS for this case study, the shortlisted solution were further examined based on the stakeholders' preferences shown at the bottom of Fig. 7. Based on the stability analyses tests, solution 2 was determined to be the optimum one and is in equilibrium with respect to all the stability concepts, as shown on Fig. 8. Solution 2 "Tunnel" received the highest number of score of 9500, followed by option 3 "dual conveyance" with a score of 9250 as shown in Table 3. Further, the "no export" is the least favourable solution.

Table 1. Performance of Delta alternatives under two criteria [12]

Alternative	**Average annual cost ($ billion/year)**	**Likelihood of fish population (%)**
a- Continue pumping through Delta	0.55 - 1.86	5 - 30
b- Tunnel	0.25 - 0.85	10 - 40
c- Dual Conveyance	0.25 -1.25	10 - 40
d- No exports	1.5 - 2.5	30 - 60



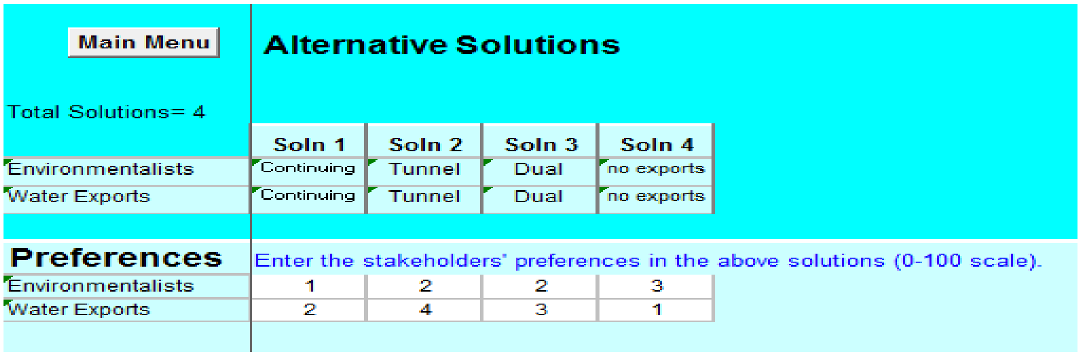
Environmentalists

Water Exporters

	A	B	C	D
A	2,1	2,1	2,1	2,1
B	2,1	4,2	2,1	2,1
C	2,1	2,1	3,2	2,1
D	2,1	2,1	2,1	1,3

$$\longrightarrow \text{Ordinal Matrix Form} = \begin{bmatrix} 2 & 1 \\ 4 & 2 \\ 3 & 2 \\ 1 & 3 \end{bmatrix}_{4\times 2}$$

Fig. 6. Game structure with cooperative outcomes (adopted from [12] **)**



Alternative Solutions

Total Solutions= 4

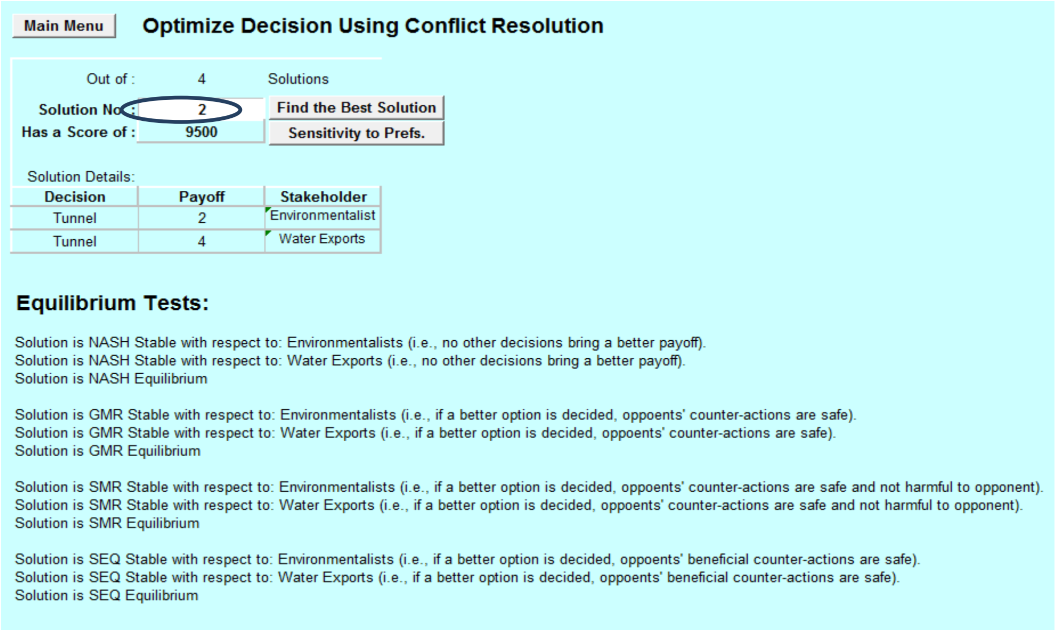
	Soln 1	Soln 2	Soln 3	Soln 4
Environmentalists	Continuing	Tunnel	Dual	no exports
Water Exports	Continuing	Tunnel	Dual	no exports

Preferences

Enter the stakeholders' preferences in the above solutions (0-100 scale).

Environmentalists	1	2	2	3
Water Exports	2	4	3	1

Fig. 7. Shortlisted decision states (after elimination) with stakeholders' preferences



Optimize Decision Using Conflict Resolution

Out of : 4 Solutions
Solution No.: 2
Has a Score of : 9500

Solution Details:

Decision	Payoff	Stakeholder
Tunnel	2	Environmentalist
Tunnel	4	Water Exports

Equilibrium Tests:

Solution is NASH Stable with respect to: Environmentalists (i.e., no other decisions bring a better payoff).
Solution is NASH Stable with respect to: Water Exports (i.e., no other decisions bring a better payoff).
Solution is NASH Equilibrium

Solution is GMR Stable with respect to: Environmentalists (i.e., if a better option is decided, oppoents' counter-actions are safe).
Solution is GMR Stable with respect to: Water Exports (i.e., if a better option is decided, oppoents' counter-actions are safe).
Solution is GMR Equilibrium

Solution is SMR Stable with respect to: Environmentalists (i.e., if a better option is decided, oppoents' counter-actions are safe and not harmful to opponent).
Solution is SMR Stable with respect to: Water Exports (i.e., if a better option is decided, oppoents' counter-actions are safe and not harmful to opponent).
Solution is SMR Equilibrium

Solution is SEQ Stable with respect to: Environmentalists (i.e., if a better option is decided, oppoents' beneficial counter-actions are safe).
Solution is SEQ Stable with respect to: Water Exports (i.e., if a better option is decided, oppoents' beneficial counter-actions are safe).
Solution is SEQ Equilibrium

Fig. 8. Decision optimisation using conflict resolution

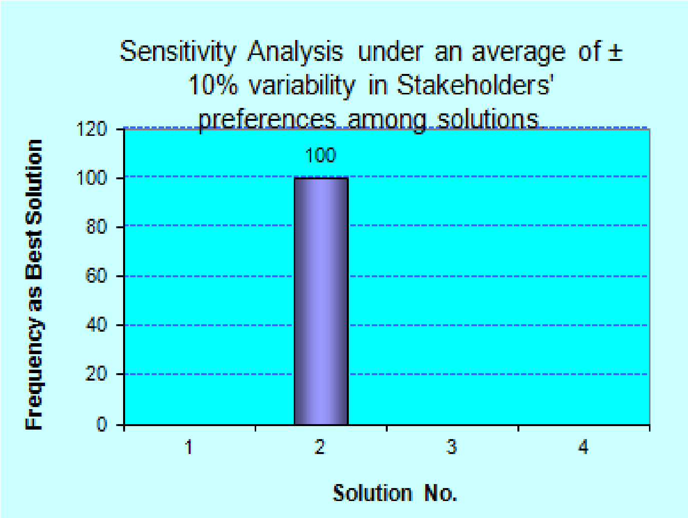


Fig. 9. Sensitivity analysis result

Table 2. Solution concept for conflict resolution

Solution concept	**Description**
Nash stability (R)	No other decisions bring a better payoff.
General metarationality (GMR)	If a better option is decided, opponent's counter-actions are safe.
Symmetric metarationality (SMR)	If a better option is decided, opponent's counter-actions are safe and not harmful to opponent.
Sequential stability (SEQ)	If a better option is decided, opponent's beneficial counter-actions are safe.

3.4 Step 4: Accounting for uncertainty

In this step, the uncertainties associated with ambiguity in stakeholder preferences are considered and its impact measured on the final resolution of the conflict. To specify the degree of uncertainty, Table 1 includes an uncertainty range for the performance of each alternative, which gives a good representation of the variability in the preferences. Based on these ranges, the DSS uses the info-gap theory [11] to furnish the user with the ability to consider uncertainties. The info-gap method runs a systematic procedure for investigating the robustness of a decision under the uncertainty of the stakeholder preferences [10].

Table 3. Best solution with decision makers Payoff and Equilibria

Option	**Environmentalists payoff**	**Water exports payoff**	**Scores**	**Best solution**	**Equilibria**
1	Continuing (1)	Continuing (1)	8750	4th	R, GMR, SMR, SEQ
2	Tunnel (2)	Tunnel (4)	9500	1st (Best)	R, GMR, SMR, SEQ
3	Dual Conv. (2)	Dual Conv. (3)	9250	2nd	R, GMR, SMR, SEQ
4	No export (3)	No export (1)	9000	3rd	R, GMR, SMR, SEQ

In this case study, uncertainty analysis associated with stakeholders' preferences was performed. Table 4 lists the percentages of the assumed uncertainty level for each of the DM's preference values. Both the Water Exporter and the Environmentalists are assigned a value of +10% uncertainty to their preferences. Once the uncertainty level was specified, the DSS then performs a number of experiments (the default is

100), varying the preferences randomly within the uncertainty range. It then presents the results in the form of a histogram. The results indicate the robustness of solution 2 as the best final resolution, as shown in Fig. 9. The results of this paper match the results obtained from [12], where Monte-Carlo game theoretic approach with uncertainty were used.

Table 4. Uncertainty and stakeholder

Stakeholder	Uncertainty (0-100%)
Environmentalists	±10
Water Exports	±10

4 Summary and Concluding Remarks

This study introduced the graph model for the water dispute in Sacramento-San Joaquin Delta problem. This area faces a serious water exports and decline fish which considered as a endangered species. This proposed DSS was used to find the optimum solution based on stakeholders preferences. In the Sacramento-San Joaquin Delta problem, the 16 alternatives were reduced to only 4 feasible solution. In addition, using conflict resolution with info-gap theory led to solution 2 as the best solution. Uncertainty analysis with ±10% variability for environmentalists and water exports and 100 experiments were considered. This solution is to build a peripheral canal "Tunnel", conveying water around the Delta. The solution was successful in achieving equilibrium in four stability concepts of Nash, GMR, SMR, and SEQ. In conclusion, with cooperation between the decision makers, building the tunnel is the most likely solution to replace the existing water export. It was found that the second likely and reliable solution is to have a dual conveyance "tunnel". Having no-export solution is not possible for this problem, as the agriculture industry in the Sacramento-San Joaquin Delta is a profitable business. The developed DSS, “congress”, proved to be practical and can be used for variety of disputes. The elimination process is one of the great advantages, particularly in larger disputes that involve a large number of infeasible solution states. The simplicity of the DSS makes it a viable tool for applying conflict resolution, stability analyses, and robustness analysis. This study ignores other issues, which may indirectly affect this conflict, such as water allocation among other users, agricultural cropping rotation, hydropower, and climate change. This paper is also did not focus on the other source of water such groundwater and desalinated water.

Competing Interests

Authors have declared that no competing interests exist.

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