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# Non-Cooperative Stability Definitions for Strategic Analysis of Generic Water Resources Conflicts

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**Abstract** In game theory, potential resolutions to a conflict are found through stability analysis, based on stability definitions having precise mathematical structures. A stability definition reflects a decision maker's behavior in a conflict or game, predicts how the game is played, and suggests the resolutions or equilibria of the dispute. Various stability definitions, reflecting different types of people with different levels of foresight, risk attitude, and knowledge of opponents' preferences, have been proposed for resolving games. This paper reviews and illustrates six stability definitions, applicable to finite strategy strategic non-cooperative water resources games, including Nash Stability, General Metarationality (GMR), Symmetric Metarationality (SMR), Sequential Stability (SEQ), Limited-Move Stability, and Non-Myopic Stability. The introduced stability definitions are applied to an interesting and highly informative range of generic water resources games to show how analytical results vary based on the applied stability definitions. The paper suggests that game theoretic models can better simulate real conflicts if the applied stability definitions better reflect characteristics of the players. When there is a lack of information about the types of decision makers, the employment of a range of stability definitions might improve the strategic results and provide useful insights into the basic framework of the conflict and its resolution.

**Keywords** Game theory · Conflict resolution · Stability definitions · Solution concepts · Non-cooperative behavior · Strategic game · Policy · Water resources management

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## 1 Introduction

Because of the great import of water for the very survival of human beings and their civilizations, water inevitably involves conflict. For example, nations sharing a common river, such as the Danube River in Europe and the Mekong River in Southeast Asia, are often in dispute over how much water each country is entitled to use and what types of hydraulic structures can be constructed on the river and its tributaries for controlling flows, producing hydro-electricity, creating lakes for recreational purposes and providing locks for ships. Moreover, pollution discharged into the river at upstream point sources can cause conflict with downstream users who utilize the water for drinking and other purposes. The foregoing and many other examples can be cited to explain how conflict can take place over both water quantity and quality issues. Moreover, these disputes can be exacerbated by the effects of climate change which may cause more severe droughts and more devastating floods, in a world in which population growth is taking place at a great pace, especially in the poorer regions of the planet.

Game theory methods can provide a better understanding of water resources conflicts and how to more effectively manage them in positive and strategic ways (Madani 2010). As an analytical instrument, game theory can enhance our understandings of the interrelationships between stakeholders in water resources governance, and provide practical suggestions for policy development processes (Howard 2006). The basic elements of a water conflict are the decision makers (DMs) or players, each DM's options or courses of action that he or she controls, and each DM's preferences over the possible states or outcomes that could take place as the DMs change their option and strategy selections while the conflict under consideration evolves over time. After developing a model of the conflict, a stability analysis can be carried out in which stability definitions describing how DMs may behave under conflict can be used to determine which states are stable for each of the DMs (stability definition is also often called solution concept, stability concept, player's rationality principle, player's behavior, or solution behavior). Because DMs may behave differently under conflict, a range of different stability definitions have been proposed. Different stability definitions reflect diverse styles of behavior by accounting for a DM's level of foresight, willingness to make strategic concessions, risk attitude, and knowledge of others' preferences. Stability definitions explain how DMs' moves and counter-moves in the course of a conflict can result in specific resolutions. A stability definition suggests whether a possible outcome of the game is stable for a given player. If all players find a specific outcome stable, they are unlikely to move from that set of decisions and that state is an equilibrium or a possible resolution of the conflict. If a state is not stable for a player, stability definitions help predicting how that player changes his decision (strategy) from that state during the course of a conflict.

Occasionally, game model predictions differ from practice as modeling always involves simplifications, resulting in inaccuracies. Thus, simplifying assumptions should be kept in mind when interpreting results. One reason for inaccuracy of results might be the application of imperfect or inappropriate stability definitions for solving the game. To find the possible resolutions of the conflict, an analyst solves the game based on stability definitions and their associated assumptions. If enough attention is not paid to employ appropriate stability definitions, reasonable results should not be expected from the investigation. Selecting appropriate stability concepts for application to a particular game is challenging. An analyst should search for the best stability definition based on the available information about the DMs' characteristics and game's conditions. There is always some uncertainty about the DMs' behavior in the game, making selection of an appropriate stability definition harder. People are different, so their behaviors likewise differ. To strengthen the game analysis in the absence of sufficient information about the DMs' characteristics and behavior, various stability definitions can be employed to analyze the game. Considering more than one stability definition assists the analyst in anticipating the evolution and resolution of the conflict (Hipel et al. 2008a, b). A given equilibrium (solution) is stronger and has a higher chance of being the final resolution of the game if it is stable under a variety of stability definitions.

The current paper focuses on the employment of ideas from non-cooperative game theory for tackling difficult issues in water resources management. In the next two sections, overviews of game theory and important non-cooperative stability definitions are provided followed in Section 4 by an illustration on how these concepts can be used in practice by applying them to a famous game called Prisoner's Dilemma. Within Section 5, conflict studies are carried out for a highly informative range of generic water resources conflicts reflecting general types of water resources controversies that arise in the real world. As is demonstrated, insightful strategic findings can be garnered by formally investigating these disputes using stability definitions. Within Section 6, prior to conclusions, a conflict arising over the sharing of an aquifer between two countries is modeled and analyzed to indicate the value of the reviewed stability definitions in providing strategic insights into real-world water resources conflicts.

## 2 Game Theory in Perspective

Due to the ubiquity of conflict, approaches for dealing with conflict have been developed in many different disciplines such as sociology, systems engineering, psychology, operations research, law and management sciences (see, for example, Hipel 2009a, b; Hipel and Bernath Walker 2010). The set of mathematical tools for formally studying conflict fall within a field called game theory. Not surprisingly, a large variety of game theory methods have been developed for addressing a wide range of conflict problems. Figure 1 displays how these formal models can generally be categorized into two main groups according to the type of preference information that is required when calibrating them (Hipel and Fang 2005).

As can be seen in the genealogy of game theory-based methods listed in Fig. 1, the techniques falling within the left branch rely upon relative preferences while those in the right branch depend upon quantitative preference information. Relative preference is often used in social situations where, for instance, a host may ask a guest whether she would like to have a cup of tea or coffee. In response, the guest may say that she would prefer to have tea, thank you. She would never respond that tea has a utility value of 7.291 and coffee 3.689 and, therefore she will drink tea. The game theory techniques given in the left branch of Fig. 1 only rely upon relative preference information, such as tea being more preferred than coffee, equally preferred or less preferred—the exact amount by which tea is preferred over coffee does not have to

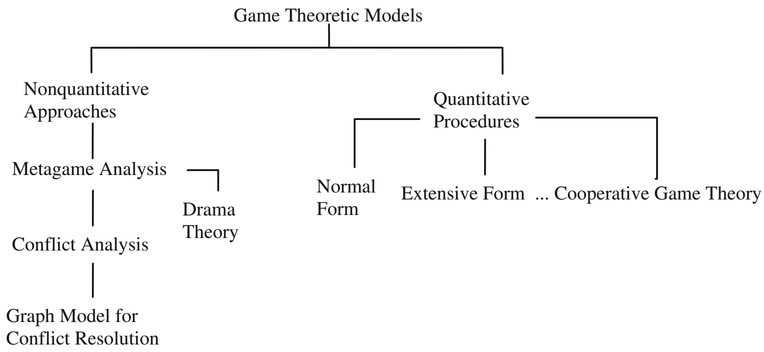


**Fig. 1** Genealogy of game theory techniques

be given. On the other hand, the methods in the right branch of Fig. 1 require cardinal preference information such as dollars or utility values to represent the worth of states or objects. However, it should be emphasized that all methods listed in both the left and right branches of Fig. 1 possess formal mathematical structures. The ones on the left are non-quantitative in nature, since they only require relative (ordinal) preference information, while those on the right are quantitative, because they need quantitative (cardinal) preferences.

The field of game theory was largely established in 1944 with the launching of the landmark book by Von Neumann and Morgenstern entitled "Theory of Games and Economic Behavior". This 1944 classic book dealt with the game theory methods listed in the right branch of Fig. 1, which are often referred to as classical game theory techniques. After the end of the Second World War, most research in game theory concentrated on the development of classical game theory methods, which has continued up until the present time. Nonetheless, in 1971 Howard set off in a radically new direction with the publication of his pioneering book on metagame analysis which created the start of the left branch in Fig. 1. Fraser and Hipel (1979, 1984) expanded the scope of metagame analysis in an approach called conflict analysis while Fang et al. (1993) significantly improved and expanded conflict analysis via the development of the Graph Model for Conflict Resolution. As shown in the left branch, Howard (1994a, b, 1999) also developed drama theory as a means for capturing the dynamic aspects of conflict based upon the metaphor of a drama or play, which has been expanded by other authors such as Bryant (2003) and Levy et al. (2009a, b).

A unique feature of the metagame-founded methods given in the left branch of Fig. 1 is they are based upon the idea of moves and counter moves among DMs participating in a given conflict in order to ascertain the stability of a given state. In other words, a DM participating in a conflict thinks like a chess player who is contemplating the consequences of making a range of possible moves. For example, if all of the unilateral improvements that one DM can take from the state under consideration can be somehow blocked by counter moves of his competitors, the state is defined to be stable. If this state is stable according to some stability definition for all of the DMs, it is deemed to be an equilibrium or resolution to the conflict since the conflict will certainly stay at that equilibrium if it is reached during the evolution of the conflict from the status quo or starting state. The foregoing type of paradigm for ascertaining stability stands in stark contrast to the rather unnatural concept of determining equilibria by maximizing expected utility via a minimax concept as is often done in classical game theory. This type of thought is more like a calculation in economics. Moreover, within the metagame approaches, from any given state DMs can choose to move or stay and move in any order that they desire. Within classical game theory methods expressed in normal form, often called one-shot games, the DMs must decide in advance exactly how they will move.

To better reflect human behavior in a strategic decision making environment, different non-cooperative stability definitions have been proposed which are applicable to non-cooperative games in which the individuals, who may not be willing to cooperate, make individual decisions and compete with one another. Except for the Nash non-cooperative solution concept (Nash 1951), additional non-cooperative stability definitions have been applied to water resources games only by a limited number of people who use the Graph Model for Conflict Resolution (GMCR) (Kilgour et al. 1987; Fang et al. 1993) and its associated decision support system (Fang et al. 2003a, b; Hipel et al. 2007, 2008b) in their strategic studies (Okada et al. 1999; Hipel et al. 2003; Noakes et al. 2003; Li et al. 2004; Gopalakrishnan et al. 2005; Ma et al. 2005; Vieira et al. 2005; Madani and Hipel 2007; Nandalal and Hipel 2007; Elimam et al. 2008; Getirana et al. 2008; Hipel et al. 2008a; Getirana and Malta 2010). Non-cooperative stability definitions can facilitate predicating the likely outcomes of the game and the expected behavior of the players who give priority to their own objectives, rather than the system objective (as considered by cooperative methods). There is a need for better understanding of the available non-cooperative stability definitions in game theory and their applicability in water resources conflict resolution, as they can provide valuable insights, not obtainable through using cooperative stability definitions.

One popular category of quantitative game theory methods mentioned on the right side of Fig. 1 is cooperative game theory techniques, which are sometimes referred to as the characteristic function form of the game. Cooperative models are used to examine the interaction of individuals who must cooperatively decide how to fairly divide a "pie" or some resource in an equitable manner. Therefore, the community has a fixed-sized "pie" and the problem is how to cut the pie in order for each competitor to get a "fair" slice of the pie or resource. These models are often used to analyze coalition formation, voting problems or optimal resource allocation problems. Cooperative stability definitions including Core (Gillies 1953), Nash bargaining solution (Nash 1950, 1953), Shapley value (Shapley 1953), Nash–Harsanyi solution (Harsanyi 1959), Nucleolus (Schmeidler 1969), Kalai–Smorodinski solution (Kalai and Smorodinsky 1975), and $\tau$-value (Tijs 1981) have been commonly used in modeling water resources games (Straffin and Heaney 1981; Young et al. 1981; Szidarovszky et al. 1984; Kilgour et al. 1988; Dinar et al. 1992; Dinar and Wolf 1994; Lejano and Davos 1995; Dinar and Howitt 1997; Lippai and Heaney 2000; Wang et al. 2003; Kucukmehmetoglu and Guldmen 2004; Wu and Whittington 2006; Ganji et al. 2007; Salazar et al. 2007; Wang et al. 2008a, b; Kucukmehmetoglu 2009; Madani 2011). As an example of the utilization of concepts from cooperative game theory, consider the recently formulated Cooperative Water Allocation Model (CWAM) of Wang et al. (2003, 2008a, b). CWAM constitutes a large-scale optimization model based on ideas from cooperative game theory, economics and hydrology to fairly allocate water among competing users in a river basin. Under the umbrella of a systems approach, CWAM takes into account not only the physical systems consisting of hydrological and environmental factors but also the societal system.

Under the characteristic function form for stability, cooperation can be used in games where groups of players make decisions together, allocation of benefits involves cooperative behavior, competition is between coalitions of players rather than individual players, and consensus may be achieved via a grand coalition of all of the players. Madani (2010) argues that most game theory applications in the literature have dealt with water resources games as cooperative games, as cooperative game theory concepts are closer to conventional multi-criteria optimization methods and more convenient to understand for water resources systems engineers. However, these definitions may not reasonably consider the players' behavior in a game which may be rooted in their different factors including, but not limited to, foresight, risk attitude, and knowledge level. Thus, their predictions may not be reliable in some cases, as the final results of the conflicts are highly dependent on such factors. Furthermore, these definitions assume perfect cooperation among those players who can increase their returns by cooperation. In reality, perfect cooperation among the parties may not always exist, as opposing interests of the players, their self-optimizing tendencies, and lack of trust, communication, and clear information may result in non-cooperative behavior (Madani 2010). Since all water resources conflicts are not necessarily cooperative games, the results gained by cooperative game theory may sometimes be misleading when one is attempting to employ it to investigate societal conflicts of the type that can be more readily handled by the methods given on the left in Fig. 1.

Another categorization of quantitative game theory methods listed on the right hand side of Fig. 1 is the extensive form of the game. In this kind of game, also referred to as a sequential or dynamic game, each player makes a move in a specified order. This sequence is followed until some sort of resolution, or equilibrium state, is reached. Extensive form games with well-defined payoffs are depicted using a tree diagram in which a starting state and all the possible moves available to the first player are drawn as arcs denoting the movements and nodes representing the states. From the states representing the results of the first DM's moves, the second DM's movements can be drawn and likewise for additional players. An important capability of an extensive form game is the modeling of how a DM's strategies and preferences can change over time in a dynamic manner. Extensive form games can be employed to ascertain the effectiveness of environmental laws and regulations for inducing compliance using both "carrot and sticks" incentives (see, for example, Kilgour et al. 1992; Hipel and Fang 1994; Hipel et al. 1995; Fukuyama et al. 2000; Fang et al. 2002). Amit and Ramachandran (2009) design a fair contract for managing water scarcity as a two-period principal-agent contract for demand management based on an extensive form mechanism using subgame perfect Nash equilibrium as the solution concept. Another example of the employment of a game theory technique to address a challenging water resources problem is the employment of the nonsymmetric Nash bargaining method within an optimization framework to examine water distributions scenarios in the Mexican Valley (Salazar et al. 2010).

As can be appreciated from the foregoing discussion, game theory methods have a key role to play in water resources and environmental governance. In fact, the import of game theory goes well beyond these domains of applicability. As argued by Hipel and Fang (2005) and Hipel et al. (2007, 2008a, 2009a, b), many conflict problems are highly interconnected with other types of disputes. For instance, disagreements over how to combat global warming and climate change are intertwined with debates over how to handle decreasing supplies of fresh water, confront widespread water pollution, respond to increasingly extreme weather conditions, tackle the food crisis, attend to energy scarcity, reverse the growing gap between the rich and poor, turn around sagging industrial output in many regions, address exploding population growth, and enhance security. This great complexity and close interconnectedness of different kinds of systems, or system of systems (Maier 1998; Sage and Cuppan 2001; Sage and Biemer 2007; Jamshidi 2009), in combination with high risk and deep uncertainty, can lead to unexpected consequences and intense conflict as evidenced by the ongoing food crisis (Hipel et al. 2010). Hence, Hipel and Fang (2005) argue that multiple participant-multiple objective decision making is a key characteristic of most types of systems, or system of systems, whether they be societal, environmental, intelligent or integrated systems. Moreover, a participatory, integrative and adaptive approach to governance is needed within an overall system of systems engineering perspective to tackle tough complex problems facing society now and in the future. Accordingly, the authors of this paper encourage both practitioners and researchers to keep in mind the "big picture" when they employ game theory methods to address tough, complex water resources and other kinds of disputes.

## 3 Non-Cooperative Stability Definitions

The Nash solution concept (Nash 1951) is the most commonly used stability definition in non-cooperative game theory. However, Nash stability only reflects a behavior of a risk-averse myopic player or DM by, implicitly, assuming that a player can only make one decision (strategy choice) while playing the game. This kind of response from players might be far from the reality of DMs' behavior in real world conflicts. Thus, the Nash stability definition often fails to predict accurately the outcomes of conflicts, when applied to real conflict situations, due to restricted assumptions underlying models of players' rationality (Selbirak 1994). For instance, based on extensive laboratory studies and real world common pool resources studies, Ostrom (1990), the economic sciences Nobel Prize winner in 2009, finds that players do not always follow Nash strategies (Ostrom et al. 1994), which are merely based on individual rationality (Ostrom 1998). A DM who plays the game following Nash stability ignores the possibility of a countermove by his opponents when judging potential benefits or losses from departure from the current state (changing his decision). However, in real conflicts, before making a choice, DMs often do consider expected reactions (countermoves) of other players. Howard (1971) shows how Nash stability fails to predict obvious equilibria in two commonly-occurring types of generic games called Chicken and Prisoner's Dilemma, which Howard refers to as the breakdown of rationality.

To improve the myopic Nash solution concept, other stability definitions have been suggested for use with the methods given on the right in Fig. 1, in which a DM tries to envision the counter-moves his opponent may choose in response to his unilateral moves (Selbirak 1994). These stability definitions, which reflect different types of human behavior under conflict and allow for a certain number of moves and counter-moves during the course of a game, include (but are not limited to) General Metarationality (GMR) (Howard 1971), Symmetric Metarationality (SMR) (Howard 1971), Sequential Stability (SEQ) (Fraser and Hipel 1979, 1984), Limited-Move Stability (Zagare 1984; Kilgour et al. 1987; Fang et al. 1993) and Non-Myopic Stability (Brams and Wittman 1981). These stability definitions have been shown to be reliable in predicting the final resolution of different historical water and environmental resources conflicts (Fang et al. 1993; Hipel et al. 1997; Noakes et al. 2003; Ma et al. 2005; Hamouda et al. 2006) and can provide a new perspective on how water conflicts, especially those with socio-political implications, can be better understood and resolved.

Kilgour et al. (1984) and Fang et al. (1989, 1993) compared a wide range of non-cooperative solution concepts. These stability definitions can be categorized based on the following characteristics:

1. Foresight (number of moves or degree of reflection): This is the total number of moves and countermoves considered by the DM before unilaterally changing his decision (Selbirak 1994). The first move is always assumed to be the DM's departure from a given state (outcome). The second move is the reaction by an opponent. In case of two DMs, the third move is his planned counter-reaction, and so on. In games with $n$ players ($n > 2$), the $k$th ($k > 2$) move can be by an opponent different from the one who made the $k-1$th move) or by the DM who made the first move. Generally, DMs have different levels of foresight in the game and might consider a different number of moves and counter-moves before making any decision.
2. Willingness to disimprove: Disimprovement is a unilateral movement to a state which is less preferred than the current state. Based on different stability definitions, different DMs might be willing to make disimprovements during the game.
3. Knowledge of preferences: A DM in the game may only be aware of his own preferences or may be aware of the preferences of all DMs in the game.

A qualitative comparison of the aforementioned non-cooperative stability definitions appears in Table 1. This table shows how different stability definitions can represent diverse kinds of behavior by DMs with various characteristics, reflecting a broad range of human behavior in conflict situations, from cautious and conservative to strategic and proactive, and from naive to sophisticated (Hipel et al. 1997). A DM with a high level of foresight thinks further ahead. Nash stability has low foresight, and the level of foresight increases from Nash stability with the lowest foresight to Non-Myopic stability with the highest foresight, as indicated in the third column from the left in Table 1. Limited-Move stability has a variable foresight level given by the number of movements considered by the DM before making a decision. Some stability definitions, such as Limited-Move and Non-Myopic stabilities, allow strategic disimprovements (temporarily move to a worse state in order to reach a more preferred outcome eventually). Other stability definitions, such as Nash

**Table 1** Stability definitions and human behavior

| Solution concept | Stability description | Characteristics | | |
|---|---|---|---|---|
| | | Foresight | Disimprovement | Knowledge of preferences |
| Nash Stability | Decision maker cannot unilaterally move to a more preferred state | Low (1 move) | Never | Own |
| General Meta-Rationality (GMR) | All unilateral improvements are blocked by subsequent unilateral moves by others | Medium (2 moves) | By opponent | Own |
| Symmetric Meta-Rationality (SMR) | All unilateral improvements are still blocked even after possible responses by the original player | Medium (3 moves) | By opponents | Own |
| Sequential Stability (SEQ) | All unilateral improvements are blocked by subsequent unilateral improvements by others | Medium (2 moves) | Never | All |
| Limited (h)-Move Stability | All players are assumed to act optimally and maximum number of state transitions is specified | Variable (h moves) | Strategic | All |
| Non-Myopic Stability | Limiting case of limited move stability as the maximum number of state transitions increase to infinity | Unlimited | Strategic | All |

stability and SEQ, never allow disimprovements. Others, such as GMR and SMR, permit strategic disimprovements by opponents only. Different stability definitions also imply different levels of preference knowledge. Under Nash stability, GMR and SMR, a DM only needs to know his own preferences, while under SEQ, Limited-Move and Non-Myopic stabilities, the DM must know the preference information for all other DMs of the game (Hipel et al. 2003). Each stability definition is described in more detail in the next section and illustrated by applying it to a famous game called Prisoner's Dilemma.

## 4 Definitions

The non-cooperative stability definitions outlined in Table 1 are explained in this section. In order to fully appreciate what they mean in reality, each of these kinds of stability is applied to the game of Prisoner's Dilemma. For exact mathematical definitions, one can refer to the book by Fang et al. (1993).

### 4.1 Nash Stability

A state $s$ is Nash stable for player $i$, if and only if (iff) there are no unilateral improvements available to player $i$ from state $k$ (the set of DM $i$'s unilateral improvements from state $s$ is an empty set ($R_i^+(s) = \emptyset$)). In other words, if DM $i$

cannot do any better by changing his decision, given the decisions of his opponents, he has no incentive to move from state *s*. If state *s* is Nash Stable for all DMs (there is no DM who can do any better by changing his decision, given the decisions of his opponents), *s* is a Nash Equilibrium (Nash 1951).

Figure 2 shows the Prisoner's Dilemma (PD) game written in normal or matrix form. Each of two captured bank robbers can either confess (C) to the sheriff by telling him where the money is hidden or not confess (DC for don't confess). If a robber confesses he is given a reduced jail sentence. Each cell contains two numbers or values, where a higher number means more preferred. The value on the left is player 1's preference or payoff; the second value is player 2's payoff. The strategies (decisions) which yield the payoffs of each cell are given on the left of the matrix for the first player and on top of the table for the second player. The given payoffs are ordinal and higher payoffs are more preferred, so state (C, C) which occurs when both players confess, is better for player 1 than state (DC, C) in which he does not confess but player 2 confesses, since the preferences for DM 1 for state (C, C) and (DC, C) are 2 and 1, respectively.

To explain how Nash stability is calculated, consider state (C, C). If the conflict is at this state, player 1 can cause the game to move from state (C, C) to (DC, C) by changing his strategy selection from C to DC. As just pointed out, (DC, C) is less preferred to (C, C) by DM 1. Hence, state (C, C) is Nash stable for player 1. Looking at state (C, C) from player 2's viewpoint, notice in Fig. 2 that DM 2 can make the conflict move from state (C, C) to state (C, DC) by changing his strategy selection from C to DC. Because state (C, DC) is less preferred by DM 2 to (C, C), it is not advantageous for DM 2 to alter his strategy choice and, therefore, state (C, C) is Nash stable for him. Since (C, C) is Nash stable for both of the DMs, it constitutes a Nash equilibrium. In fact, it is the only Nash equilibrium in the game of Prisoner's Dilemma. State (DC, DC) is not Nash-stable for any of the DMs. State (DC, C) is Nash-stable for player 2 but not Nash-stable for player 1. The opposite is true for state (C, DC). Therefore, if the players behave according to Nash stability, they end up in state (C, C) which is Pareto-inferior to state (DC, DC), since it is less preferred by both DMs to state (C, C). This is what Howard (1971) refers to as a breakdown of rationality. A Nash player has very low foresight, knows nothing about his opponent's preferences, takes no risk and can make only one move. Not all real DMs in conflicts are Nash players (Ostrom 1998). In practice, depending on the conditions of the game, players might decide to play the game differently to end up in the optimal result consisting of state (DC, DC). To model the behavior of non-Nash-players, other solution concepts must be considered.

**Fig. 2** Prisoner's dilemma

| | | ***Player 2*** | |
|---|---|---|---|
| | | *DC* | *C* |
| ***Player 1*** | *Don't Confess (DC)* | 3,3 | 1,4 |
| | *Confess (C)* | 4,1 | 2,2 |

### 4.2 General Metarationality

State $s$ is GMR stable for DM $i$ iff every unilateral improvement of player $i$ from $s$ can be blocked (sanctioned) by player $j$'s movement to a better or worse state (improvement or disimprovement). In response to player $i$'s improvement from $s$ to $x$, player $j$ may even hurt himself by moving to state $z$ with a lower payoff for both players to punish (block or sanction) player $i$'s improvement. Therefore, the payoff of state $z$ can either be higher or lower than state $x$ for player $j$ but it is definitely lower for player $i$. In such a situation, player $i$ prefers not to move from $s$. Therefore, $s$ is GMR stable for player $i$. If a given state is GMR stable for all players of the game, that state is a GMR equilibrium (Howard 1971).

Consider why state (DC, DC) is GMR stable for DM 1 in Prisoner's Dilemma. Notice that DM 1 can cause the game to move from state (DC, DC) to (C, DC) by changing his strategy selection from DC to C. Because (C, DC) is more preferred to state (DC, DC) by DM 1, this movement is referred to as a unilateral improvement by DM 1. From state (C, DC), DM 2 can unilaterally make the game progress from state (C, DC) to state (C, C) by changing his strategy from DC to C. Since state (C, C) is less preferred to the starting state (DC, DC) by DM 1, state (DC, DC) is GMR stable for DM 1. In a similar fashion, one can explain why state (DC, DC) is GMR stable for DM 2. Because state (DC, DC) is GMR stable for both players, this state forms a GMR equilibrium. State $s$ is also GMR stable for player $i$ if he has no unilateral improvements from state $s$ (the set of player $i$'s unilateral improvements from state $s$ is an empty set ($R_i^+(s) = \emptyset$)). Thus, a Nash equilibrium is also a GMR equilibrium. Hence, state (C, C) is another GMR equilibrium in the PD game.

The GMR stability definition simulates the behavior of a very conservative player who is aware of his opponents' preferences (perfect information). Such a player avoids any risk in making decisions. GMR stability definition is only applicable to evolving games with at least two moves available to each player since in one-move (one-shot) games no counteraction is possible in response. The Nash stability concept is suitable for one-shot games where the game does not pass any state in transition from the status-quo to the final outcome. Application of Nash stability definitions to real world games which are not one-shot games (e.g. common pool resources games), may result in predictions which may not be valid in practice (Ostrom 1998). A GMR player has a horizon of two moves, while a Nash player sees only one move ahead.

### 4.3 Symmetric Metarationality

State $s$ is SMR stable for player $i$ iff not only every unilateral improvement of player $i$ from $s$ to $x$ is sanctioned by player $j$'s movement from $x$ to $z$, but also no unilateral movement is available to player $i$ from $z$ to $y$ where payoff of player $i$ at $y$ is higher than his payoff at $s$. State $s$ is also SMR stable if player $i$ has no unilateral improvements from state $s$ ($R_i^+(s) = \emptyset$). Thus, a Nash equilibrium is also an SMR equilibrium. SMR is a more restrictive stability definition than GMR and hence is a subset of GMR. SMR is similar to GMR except that player $i$ considers not only his own possible moves and possible reactions of player $j$ to his moves, but also his chances to respond to player $j$'s reactions. An SMR player has a horizon of three moves and he anticipates that the conflict ends after his own counter-response. An SMR player is very conservative and has more foresight than a GMR player.

This player assumes that in response to his decisions, opponents might even hurt themselves to block his moves. Similar to GMR, SMR is suitable for games where more than one move is allowed (Howard 1971).

In the PD game, state (DC, DC) is SMR stable for player 1. Specifically, if he changes his strategy from DC to C to form state (C, DC), player 2 responds by changing his strategy from DC to C to create (C, C) which is less preferred to (DC, DC) by player 1. In this situation, player 1 can only react by switching from C to DC to bring about state (DC, C) which is less preferred by him to the starting state (DC, DC). Since player 1 cannot escape from player 2's sanction, state (DC, DC) is SMR stable for player 1. Similarly, (DC, DC) is SMR stable for player 2. Thus, state (DC, DC) is an SMR equilibrium. The other SMR equilibrium of the PD game is (C, C) at which no player has any available unilateral improvement.

### 4.4 Sequential Stability

SEQ is a restricted version of GMR (a subset of GMR) in which player $j$ can only respond to player $i$'s unilateral improvement by a credible action (only a unilateral improvement, not a unilateral movement). This means that a state $s$ is SEQ for player $i$ iff he is deterred from taking any unilateral improvement from $s$ because of a credible action available to $j$ which results in a state less preferred (for player $i$) than $s$ (Fraser and Hipel 1979).

Consider why state (DC, DC) in the PD game is sequentially stable for player 1. Notice that player 1 takes advantage of a unilateral improvement when he causes the game to move from state (DC, DC) to state (C, DC) by changing his strategy from DC to C. However, player 2 can sanction this unilateral improvement by taking advantage of his own unilateral improvement from state (C, DC) to (C, C). Because state (C, C) is less preferred to the initial state (DC, DC), the starting state is SEQ stable for player 1. Likewise, one can explain why state (DC, DC) is SEQ stable for player 2. Thus, state (DC, DC) is an SEQ equilibrium. State $s$ is also SEQ stable for player $i$ if player $i$ has no unilateral improvements from state $s$ ($R_i^+(s) = \emptyset$). Hence, state (C, C) is an SEQ equilibrium.

An *SEQ* player has medium foresight (a horizon of two moves distant) and is not as conservative as SMR and GMR players as he takes some risks by assuming that his opponents are never willing to hurt themselves in order to sanction his unilateral improvements. Accordingly, this type of behavior is often observed in real world disputes.

### 4.5 Limited-Move Stability

Based on the Limited Move Stability concept, a player $i$ can imagine a sequence of moves and counter-moves for a horizon of length $h$. State $s$ is $L_h$ stable for player $i$ when he finds it stable at horizon $h$. To find if a state $s$ is stable for player $i$ under this definition, the sequence of movements is expressed using an extensive form game (similar to a decision tree with more than one DM where the first DM is player $i$) and backward induction is employed to determine stability. It is assumed that all players are rational and act optimally (players only make a unilateral movement if they are sure they can increase their payoff eventually) within $h$ transitions from $s$ (player $i$ makes the first movement from $s$) (Zagare 1984; Kilgour et al. 1987).

Figure 3 shows the $L_3$ stability analysis of state (DC, DC) for Player 1 in the PD game (Fig. 2). Each node represents a state or possible outcome. The left and right entries in parentheses indicate the payoffs for players 1 and 2, respectively, and preferred selections are marked by arrows. The stability analysis works backwards up the tree and asks what the rational strategy choice of each player is at each node (decision point) (Zagare 1984). Starting from the first node (DC, DC) at the top left of Fig. 3, player 1 can unilaterally move the game to state (C, DC) by changing his strategy from DC to C (Don't Stay is written on the branch joining these two states in Fig. 3), or stay at (DC, DC) (Stay). From (C, DC), Player 2 can move unilaterally to (C, C) or stay at (C, DC). Finally, Player 1 can change his strategy and move the game to state (DC, C) or stay at (C, C). The total number of moves and counter-moves in this analysis is three. Since the stability analysis is being carried out from the viewpoint of Player 1, he should be the one who starts the game. This leaves one move to Player 2 and another move to Player 1. To find if (DC, DC) is stable for Player 1, backward induction is employed moving from the last node (C, C) to the first node (DC, DC) of the tree (right to left in Fig. 3). Between states (DC, C) and (C, C), on the top right of the diagram, player 1 prefers (C, C) because of the higher payoff he gains at (C, C). Thus, player 1 will stay at (C, C) and will not change his strategy. To indicate that player 1 prefers to stay, an arrow is drawn from the top (C, C) node to the bottom (C, C) node. Moving one node to the left, at (C, DC) player 2 prefers (C, C) to (C, DC) and is not willing to stay at (C, DC), so an arrow is drawn from (C, DC) to (C, C). At (DC, DC) player 1 should decide between (DC, DC) and (C, C). Since his payoff of 3 at (DC, DC) is higher than his payoff of 2 at (C, C), he prefers to stay at (DC, DC). Therefore, state (DC, DC) is $L_3$ stable for player 1. Similarly, state (DC, DC) is $L_3$ stable for player 2. Thus, state (DC, DC) is an $L_3$ equilibrium for the game. The game has another $L_3$ equilibrium which occurs at state (C, C). Similarly, states (DC, DC) and (C, C) are $L_2$ equilibria in the game. State (DC, DC) is the only $L_1$ equilibrium in the PD game.

The $L_1$ and $L_2$ Stability concepts simulate the behavior of a short-sighted or myopic player who may anticipate only one or two moves into the future (an $L_1$ stable state is also Nash stable and the two solution concepts are mathematically equivalent). However, a player with a long planning horizon can think about many moves and counter-moves into the future. Generally, an $L_h$ player is willing to make

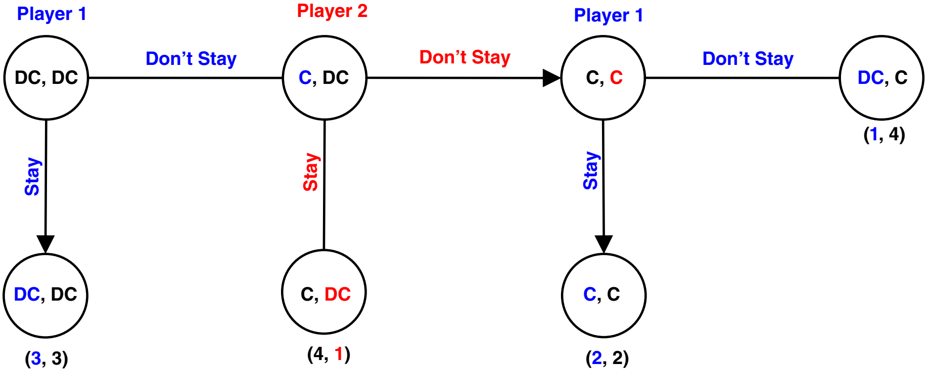


**Fig. 3** L3 stability analysis of state (DC, DC) for Player 1 in the PD game

strategic disimprovements when $h > 1$, meaning that he is willing to temporarily move to a less-preferred state while he knows the sequence of moves and counter-moves will lead to a more preferred state eventually.

## 4.6 Non-Myopic Stability

Non-Myopic Stability is a special case of Limited-Move Stability in which the horizon $h$ increases without bound. A Non-Myopic player has immense foresight and can think about all possible moves and counter-moves into the future. Figure 4 shows the Non-Myopic stability analysis for state (C, C) for Player 2 in the PD game. For a state to be a Non-Myopic equilibrium, the process must not cycle back to the original state. Thus, the sequence of moves and counter-moves must terminate as soon as the game cycles back to the original state and the players should not be allowed to make any further movement. In a 2 × 2 game, there must be no cycle over the four states and the number of moves should be limited to 4. Thus, in a 2 × 2 game, a Non-Myopic stable state is also $L_4$ stable and vice-versa. Since a 2 × 2 game is the simplest game, the number of moves considered by a Non-Myopic player, in general, is always more than or equal to 4. As shown in Fig. 4, state (C, C) is Non-Myopic ($L_4$) stable for player 2. Since the game is symmetric, (C, C) is also Non-Myopic ($L_4$) stable for player 1, and therefore, is a Non-Myopic ($L_4$) equilibrium in the PD game. State (DC, DC) is the other Non-Myopic ($L_4$) equilibrium of this game (Brams and Wittman 1981).

Non-Myopic and Limited-Move stability definitions may not provide as many practical insights as the other solution concepts (Hipel et al. 2008b), as the notion of unlimited strategizing has been challenged (Costa-Gomes et al. 2001; Johnson et al. 2002; Camerer 2003) by arguing that DMs are often incapable of thinking more than a few moves ahead in interactive decision situations. Such an argument is consistent with the findings of Ostrom (1998) who discovered backward induction to be unreliable for predicting the outcomes of real-world common pool resources games.

Figure 5 indicates the interrelationships of the solution concepts, introduced so far, in $n$ player ordinal games. Nash Stability ($L_1$) with its limited foresight and number of moves is a subset of SMR, SEQ and GMR. SMR and SEQ are both subsets of GMR. Therefore, state (C, C) in the PD game shown in Fig. 2 which is a Nash equilibrium is also an equilibrium under SMR, SEQ and GMR. $L_2$ is a subset

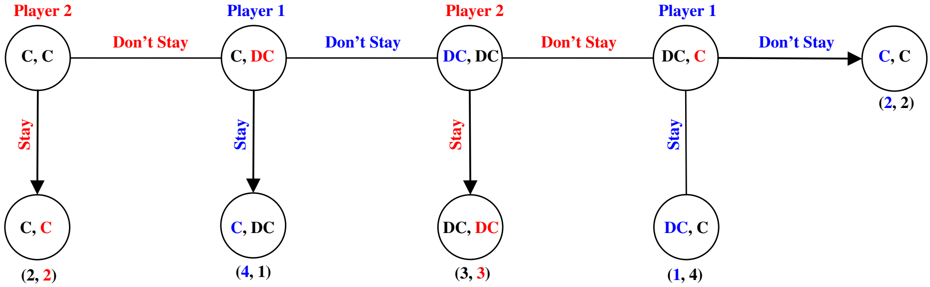


**Fig. 4** Non-myopic (L4) stability analysis of state (C, C) for Player 2 in the PD game

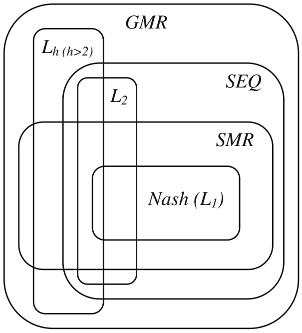


**Fig. 5** Interrelationships of solution concepts (adopted from Fang et al. 1993)

of SEQ and GMR. For instance, states (C, C) and (DC, DC) which are $L_2$ equilibria, are also equilibria based on SEQ and GMR stability definitions. $L_h$ ($h > 2$) and Non-Myopic stability concepts are subsets of GMR. For example, states (C, C) and (DC, DC), which are $L_3$ and $L_4$ (Non-Myopic) equilibria, are also GMR equilibria.

## 5 Applying Non-Cooperative Stability Definitions to Generic Water Resources Games

Water and environmental disputes occurring in the real world are often very complex. Thus, fairly complicated game theory models may be required to describe them. However, studying a given dispute using a very rudimentary conflict model can lead to enhanced understanding of the real-world conflict in terms of its basic structure and strategic potentialities (Hipel 2009a, b). Figure 6 shows four two-by-two generic

| | | ***Farmer 2*** | |
|---|---|---|---|
| | | *LPR* | *HPR* |
| ***Farmer 1*** | *Low Pumping Rate (LPR)* | 3,3 | 1,4 |
| | *High Pumping Rate (HPR)* | 4,1 | 2,2 |

a) Groundwater exploitation game

| | | ***Country 2*** | |
|---|---|---|---|
| | | *I* | *DI* |
| ***Country 1*** | *Increase (I)* | 3,3 | 1,2 |
| | *Don't Increase (DI)* | 2,1 | 2,2 |

b) Neighboring countries with a common environmental problem game

| | | ***Afghanistan*** | |
|---|---|---|---|
| | | *P* | *DP* |
| ***Iran*** | *Pay (P)* | 3,3 | 2,4 |
| | *Don't Pay (DP)* | 4,2 | 1,1 |

c) Iran-Afghanistan conflict on Hirmand River

| | | ***Environmentalists*** | |
|---|---|---|---|
| | | *Proactive (P)* | *Reactive (R)* |
| ***Developers*** | *Sustainable Development (SD)* | 1,4 | 2,3 |
| | *Unsustainable Development (UD)* | 3,2 | 4,1 |

d) Sustainable development game

**Fig. 6** Generic water resources games (adopted from Madani 2010 and Hipel 2009a) water resources games, the first three of which were introduced into the water resources literature by Madani (2010), while the fourth conflict was originally proposed by Hipel (2009a). Here, each game is briefly explained. Then the non-cooperative stability definitions from Sections 3 and 4 are utilized to show how the possible resolutions of these games can change based on the stability definitions being used and to provide strategic insights into these generic games.

### 5.1 Groundwater Exploitation Game

In this game (Fig. 6a), which has the PD structure of the game in Fig. 2, two farmers tap a shared aquifer in a given period of time. A payoff of each player is interpreted as his profit calculated as revenues from crop sales minus the pumping costs. Here, ordinal payoffs are shown. In this game, if both farmers pump at the lower pumping rate (LPR), they can continue pumping at a low cost for the whole pumping period. Pumping at the higher pumping rate (HPR) results in a shut-down of the pumps and revenue losses during the later years of the pumping period due to groundwater overdraft. In this game, cooperative pumping (LPR, LPR) results in higher profits for both farmers overall. Getting a "free ride" (letting others contribute and benefit from their contributions without paying oneself) would be the best outcome for each farmer ((HPR, LPR) for Farmer 1 and (LPR, HPR) for Farmer 2) and giving a free ride would be the worst outcome for each player. State (LPR, LPR) is the socially optimal and Pareto-optimal outcome of the game. However, HPR is a strictly dominant strategy for each player, and the Pareto-inferior resolution (HPR, HPR) is a dominant strategy equilibrium and the only Nash equilibrium of the game, as explained earlier for the PD game in Section 4.1 and Fig. 2. Madani (2010) provides more details about this game in Fig. 6a as well as the ones in Fig. 6b and c.

Table 2 shows the stability analysis results for the groundwater exploitation game for the six stability definitions introduced earlier. Results show that (HPR, HPR) is stable for both players based on all of the stability definitions. Thus, it is an equilibrium based on all solution methods. States (HPR, LPR) and (LPR, HPR) are only stable for one of the players (the one getting a free ride) under all stability definitions and never an equilibrium. The Pareto-optimal outcome (LPR, LPR) is stable under all stability definitions except for the Nash solution. Thus, only a myopic

**Table 2** Stability analysis results for the groundwater exploitation game (Fig. 6a)

| Stability definition | (LPR,LPR) | | (HPR,LPR) | | (LPR,HPR) | | (HPR,HPR) | |
|---|---|---|---|---|---|---|---|---|
| | Stable for Farmer | | | | | | | |
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Nash ($L_1$) | | | √ | | | √ | √ | √ |
| GMR | √ | √ | √ | | | √ | √ | √ |
| SMR | √ | √ | √ | | | √ | √ | √ |
| SEQ | √ | √ | √ | | | √ | √ | √ |
| $L_2$ | √ | √ | √ | | | √ | √ | √ |
| $L_3$ | √ | √ | √ | | | √ | √ | √ |
| Non-Myopic ($L_4$) | √ | √ | √ | | | √ | √ | √ |

player does not find this state to be stable and any player who can view at least two moves (including the opponent's move), finds this state to be stable. A state which is stable under more stability definitions should have a higher chance of being the empirical resolution of the conflict. Therefore, in the groundwater game, (LPR, LPR) and (HPR, HPR) are the more likely outcomes of the game, with (HPR, HPR) having a higher probability of being the final outcome.

Although the groundwater game presented here has a structure similar to PD, the rules of the game might differ from a pure PD game. In the PD game, players are allowed to make only one move (PD is a one-shot game). If prisoners are allowed to learn of and react to other players' decisions, the results of the PD game can become cooperative (similar to the groundwater game). In the groundwater game, the players are allowed to change their strategies many times during the course of the game. Thus, they always have a chance to react to the movement of their opponent. Stability definitions should be selected based on field conditions and according to the rules of the game. Accordingly, some stability definitions are unsuitable for some situations and insights provided by them may be misleading. The Nash stability definition might not be appropriate for the groundwater game if the players are aware of the game's structure and their opponent's selected strategy, and are allowed to change their decisions during continuous play of the game. Such an argument is consistent with the findings of Ostrom et al. (1994) and Fehr and Fischbacher (2002) who discovered that users of a common pool resource (e.g. groundwater) do not always follow Nash strategies. If both farmers start with the non-cooperative pumping rate (HPR, HPR), no individual farmer can bring a better result to the game. To move from (HPR, HPR) to (LPR, LPR), the farmers need to form a coalition and both change their strategies at the same time. Once the cooperation (LPR, LPR) has begun, they will not defer from cooperation, considering the credible threat of the opponent, which takes both players to a worse state.

Choosing non-cooperation in the groundwater game is brought about by a lack of trust or unreliable pump monitoring. If one farmer is assured that he will be alerted immediately after the other farmer changes her pumping rate, he will choose the cooperative strategy and will only defer as a reaction when she defects. However, if the farmers knows that it is not possible to monitor or find out the other's pumping rate, the game is a one-move game with a non-cooperative solution. Another reason for choosing a non-cooperative strategy might be the lack of information about the structure of the game and payoffs. The farmers might be unaware of the changing groundwater level and pumping costs in the long run. In that case, the structure of the game is not as suggested here and this analysis is not valid.

### 5.2 Neighboring Countries with a Common Environmental Problem Game

In this game (Fig. 6b) which has a structure similar to a Stag-Hunt game, two littoral states share a lake; each country has one river flowing into the lake. For the lake and its ecosystem to survive, both countries must increase their water releases to the lake. Due to high evaporation, an increase in flow by only one country cannot solve the problem. The payoff of each country (ordinal payoffs in Fig. 6b) reflects the amount of environmental benefit it gains from the lake, which is the function of the total inflow to the lake, plus the revenue from consumptive uses upstream. In this game, if both states increase their releases to the lake, the environmental benefits will exceed revenue losses due to reduced upstream consumption. Nevertheless, if only one state increases its release to the lake, the environmental benefits will be minimal and that state's payoff will be the lowest due to revenue losses from decreased upstream consumption. The game has one Pareto-optimal resolution (I, I), and two Nash equilibria: cooperative (I, I) and non-cooperative (DI, DI).

Table 3 shows the stability analysis results for this game. The Pareto-optimal resolution (I, I) is stable for both players under all stability concepts, and therefore, seems the most likely outcome of the game, when the players are allowed to change their strategies many times in the course of the game. If the amount of water flowing to the lake is monitored and both countries have real-time access to the flow data, they will realize a change in the inflow immediately and can respond accordingly. In that case, once the countries start cooperation (I, I), they are not willing to decrease their releases to the lake. State (DI, DI) is the other possible outcome of the game which is stable for both players under four solution concepts. Similar to the groundwater sharing (PD) game, to move from (DI, DI) to (I, I) the countries must form a coalition and both should decide to do this at the same time. In an international context, a coalition may be formed by signing a treaty or agreement on the issue.

One insight gained from Table 3 is that the non-cooperative resolution (DI, DI) is not stable under the limited-move ($L_h$) stability definition when $h > 1$ (when parties have a chance to react). This means that while the two countries are experiencing the status-quo state (DI, DI), one nation might strategically put itself in a worse situation for a short period by increasing the inflow to the lake (that country changes its strategy from DI to I). The cooperating country does so to show its "willingness to cooperate" explicitly, in order to earn the trust of the opponent, and to create an incentive for the other player to cooperate, assuming that the other party is rational and willing to select an optimal strategy in any situation. The other country should know that the new situation is temporary and if there is no change in its strategy, the cooperating country will change its strategy back to DI. Therefore, in the Stag-Hunt game, when one of the parties is not willing to cooperate and form a coalition to change its strategy with the other party simultaneously, the other player may try to motivate him to cooperate by sending strong cooperative signals and showing explicit cooperative behavior.

**Table 3** Stability analysis results for the neighboring countries with a common environmental problem game (Fig. 6b)

| Stability definition | (I,I) | | (DI,I) | | (I,DI) | | (DI,DI) | |
|---|---|---|---|---|---|---|---|---|
| | Stable for Country | | | | | | | |
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Nash ($L_1$) | √ | √ | | | | | √ | √ |
| GMR | √ | √ | √ | | | √ | √ | √ |
| SMR | √ | √ | | | | | √ | √ |
| SEQ | √ | √ | | | | | √ | √ |
| $L_2$ | √ | √ | | | | | | |
| $L_3$ | √ | √ | | | | | | |
| Non-Myopic ($L_4$) | √ | √ | | | | | | |

## 5.3 Iran–Afghanistan Conflict on Hirmand River

The Hirmand (Helmand) River is a transboundary river which flows from Afghanistan to Iran and is important for agriculture in both countries and the survival of Hamun Lake in Iran's Sistan-va-Balouchestan Province. Although there is an agreement between the countries about their water shares, the Taliban regime was unwilling (or unable) to pay for the operation and maintenance of the Kajaki Reservoir system located in Afghanistan, which affects the agriculture and urban water supply on both sides of the border and Hamoun Lake and its ecosystem in Iran. Since the Afghan regime was not contributing to the system's maintenance, the Iranians thought of fixing the part of the system located in Afghanistan. This conflict has a structure similar to a famous Chicken game (Fig. 6c). Both countries could benefit from performing the required maintenance. A payoff of each party (ordinal payoff in Fig. 6c) represents the utility of urban and agricultural water plus environmental benefits minus the maintenance costs paid by that party. In the game of Chicken, each side is willing to take a free ride (in this case, do not pay for maintenance) to maximize its payoff. The game's status quo, (DP, DP), in which no party would pay for the required maintenance is the worst outcome, due to high urban, agricultural, and environmental losses. The two Nash equilibria of this game, which also are Pareto-optimal, are (DP, P) and (P, DP) in which one party pays all the costs. As in the Chicken game, the cooperative outcome (P, P), which is the other Pareto-optimal resolution of the game, is not a Nash Equilibrium. Historically, in this conflict, the Iranians chose to chicken out and bear the costs to repair the system.

Table 4 shows the stability analysis results of the Iran-Afghanistan conflict for the six non-cooperative stability definitions. The Pareto-optimal resolutions (P, DP) and (DP, P), in which one party chickens out and loses while the other one wins, are stable for both players under Nash, GMR, SMR, and SEQ definitions (historically, this conflict ended in (P, DP)) when parties are allowed to change their strategies during the course of the game. These resolutions, however, are not equilibria when strategic disimprovements are allowed ($L_2$, $L_3$, and $L_4$). For instance, in this game, a country which has chickened out (has selected P) might decide to put itself in a worse position (DP, DP) when it is sure that the other player will chicken out if the (DP, DP) situation continues. Similarly, in the chicken game, if drivers are allowed to swerve and come back to the road as many times as they wish before the two cars reach a specific point, a driver who has swerved might come back to the road when

**Table 4** Stability analysis results for the Iran-Afghanistan conflict on Hirmand River (Fig. 6c)

| Stability definition | (P,P) | | (DP,P) | | (P,DP) | | (DP,DP) | |
|---|---|---|---|---|---|---|---|---|
| | Stable for Player | | | | | | | |
| | I | A | I | A | I | A | I | A |
| Nash ($L_1$) | | | √ | √ | √ | √ | | |
| GMR | √ | √ | √ | √ | √ | √ | | |
| SMR | √ | √ | √ | √ | √ | √ | | |
| SEQ | | | √ | √ | √ | √ | | |
| $L_2$ | | | √ | | | √ | | |
| $L_3$ | √ | √ | √ | | | √ | | |
| Non-Myopic ($L_4$) | √ | √ | √ | | | √ | | |

*I* Iran, *A* Afghanistan

he discovers that the other player will swerve if the non-cooperative situation (here (DP, DP)) continues. The other Pareto-optimal resolution (P, P) is an equilibrium based on GMR, SMR, $L_3$ and Non-Myopic ($L_4$) stability definitions. Therefore, state (P, P) is another likely outcome of the chicken game, often ignored in the literature. A player who considers more than one move and counter-move (SMR, $L_3$, and $L_4$) or considers the possible blocking (sanctioning) moves, finds state (P, P) stable. The cooperative resolution (P, P) is most likely when both parties are identical in their behavior. If, for example, two identical robots, which have been built by one manufacturer, play the Chicken game (as drivers), the cooperative outcome will be the resolution to the conflict. The two robots have been programmed to stay on the road and swerve only if the opponent's car is still on the road at time $t$. These robots will keep the cars on the road and at time $t + \varepsilon$ ($\varepsilon$ is very small) both cars are out and the game ends in a cooperative state. States (P, DP) and (DP, P) only occur when the players are not identical, which is usual in practice. In that case, a player who has a lower risk tolerance will swerve first.

### 5.4 Sustainable Development Game

This game (Fig. 6d) represents the classical conflict between environmental parties and developers such as dam builders, water exporters, and bottled water producers. The payoff of each player for each outcome reflects its overall utility for that outcome. The developers prefer more economic benefits while the environmentalists prefer more environmental benefits. In this game, the developers can practice sustainable development in their activities or adhere to the conventional unsustainable practices which have widely occurred in practice, mostly due to the lack of knowledge about the negative impacts of human activities on the environment and having benefit maximization as the sole development objective. The environmentalists, on the other hand, either can be pro-active in promoting sustainable development and responsible environmental stewardship by developers, or may choose to be reactive and respond to environmental infractions whenever they occur. In this game, the best outcome to one player is the worst outcome to the other. Generally, the developers prefer adopting unsustainable development policies and less pressure from the environmentalists. Thus, their most preferred outcome is (UD, R) for which they do not practice sustainable policies and they gain the most economic benefits in absence of pressure from the environmentalists. This outcome is the least preferred outcome for the environmentalists due to the high environmental costs of development. The best outcome for the environmentalists is (SD, P) when they are pro-active and promote responsible environmental stewardship, forcing the developers to practice sustainable policies which in turn will minimize the economic benefits of the developers, making (SD, P) the least preferred outcome by the developers. No matter if the developers adopt sustainable or unsustainable development practices, the received environmental benefits are always higher when the society can benefit from the presence of responsible proactive environmentalists. Thus, P is the strictly dominant strategy for the environmentalists. Similarly, UD is the strictly dominant strategy for the developers as they are always better off practicing unsustainable development policies. While all outcomes of the game are Pareto-optimal, the only Nash equilibrium of the game is (UD, P) which is also a dominant strategy equilibrium of the game.

**Table 5** Stability analysis results for the sustainable development game (Fig. 6d)

| Stability definition | (SD,P) | | (UD,P) | | (SD,R) | | (UD,R) | |
|---|---|---|---|---|---|---|---|---|
| | Stable for Player | | | | | | | |
| | D | E | D | E | D | E | D | E |
| Nash ($L_1$) | | √ | √ | √ | | | √ | |
| GMR | | √ | √ | √ | | √ | √ | |
| SMR | | √ | √ | √ | | √ | √ | |
| SEQ | | √ | √ | √ | | √ | √ | |
| $L_2$ | | √ | √ | √ | | √ | √ | |
| $L_3$ | | √ | √ | √ | | √ | √ | |
| Non-Myopic ($L_4$) | | √ | √ | √ | | √ | √ | |

*D* developers, *E* environmentalists

Table 5 shows the stability analysis results for the sustainable development game. The results suggest that outcome (UD, P) is the only stable outcome for both players under all stability concepts. Thus, (UD, P) is the only equilibrium and the most likely outcome of this game. In this game, the developers adopt the unsustainable development strategy even under the pressure by the environmentalists. No matter what type of player plays the game or how many moves are allowed during the game, the final outcome is not desirable for the proactive environmentalists. In such a situation, the likely outcome will not change unless the game's structure evolves through changing the payoffs. To enforce an environmentally friendly outcome in society where unfriendly developers exist, "carrot" mechanisms (e.g. tax incentives that encourage sustainable development practices, educating the developers about the high environmental costs of their unsustainable actions in long-run, etc.) and/or "stick" approaches (e.g. imposing stiff penalties for violations of environmental laws, strict monitoring and enforcement of environmental laws and regulations, etc.) should be adopted (Hipel 2009a).

## 6 Game of Aquifer Sharing under Unequal Access

To show the utility of the reviewed stability definitions in resolving real-world water conflicts, these stability concepts can be used for providing insights and predicting the outcomes of water resources games of greater complexity existing in the literature. In particular, Just and Netanyahu (2004) presented a water resources conflict over sharing a common aquifer between two neighboring countries. In this game, access to the aquifer is unequal because of differences in elevations of the two countries, which result in a deep water table and high pumping costs for Country B. Much water percolates rapidly downwards to two major springs in Country A, making extraction cost negligible for this country. Having no other water sources, Country B depends on sharing water with Country A, while the political relationships between the two countries are not good. A solution for the problem might be that Country B somehow bribes Country A (victim-pays) to be able to have more water.

Figure 7 shows the water sharing problem in normal or matrix form. The strategies of Country A are Water Sharing (WS) and No Water Sharing (NWR) while the other country's options are Payment (P) and No Payment (NP). The status quo is (NWS, NP). This game has a PD structure, similar to the groundwater exploitation game discussed earlier (Fig. 6a), with two possible outcomes: (NWS, NP) and (WS, P). State (NWS, NP) is the only equilibrium of a one-move game. However, this game

**Fig. 7** The water sharing game (adopted from Just and Netanyahu 2004)

| | | Country B: Payment (P) | Country B: No Payment (NP) |
|---|---|---|---|
| Country A | Water Sharing (WS) | 1,3 | -2,7 |
| Country A | No Water Sharing (NWS) | 4,-4 | 0,0 |

is not a one-shot game. It is a continuous game in which parties can make as many moves and counter-moves as they like. A continuous (multi-shot as opposed to one-shot) game is different from a repeated game, in which it is assumed that players play the same game many times, so they might use a mixture of strategies rather than a single strategy. Here, it is assumed that the players play one game only. However, they are allowed to change their finite pure strategies in the course of the game as many times as they want. Normally, the players will pick one pure strategy eventually and stick to that if the conditions of the game do not change.

State (WS, P) is a possible outcome (pure strategy equilibrium) of this game. Just and Netanyahu (2004) argue that victim-pays (bribing) might be infeasible in an international context. Thus, (NWS, NP) might be the only possible outcome of this game. To come up with a solution to the conflict, they suggested linking this game to another game in which Country B has an advantage over Country A. In this way, side payments can be avoided and take the form of concessions on other issues, both parties enjoy the benefits of broader cooperation, and they are less willing to defer from cooperation. Madani (2011) argues how linkage of games, when parties have relative advantages over each other, can expand the feasible solution range and provide the possibility of "strategic loss", where players are willing to strategically lose in sub-games to increase their overall gains in the interconnected game.

The control-of-smuggling game in Fig. 8 was suggested by Just and Netanyahu (2004) to be linked to the water sharing game in Fig. 7. Country B has an advantage relative to Country A in enforcing laws against illegal agricultural trade and has the power of controlling the illegal trade of Country B's products into Country A. This control increases the national welfare of Country A. This game also has the structure of the PD game and non-cooperation is a dominant strategy for each party. Without side payments, state (NP, NC) remains as the only possible outcome of this conflict.

Linking the two games results in the larger game shown in Fig. 9. Payoffs can be calculated by summing the cardinal payoffs from all strategies in the two isolated

**Fig. 8** The control-of-smuggling game (adopted from Just and Netanyahu 2004)

| | | Country B: Control (C) | Country B: No Control (NC) |
|---|---|---|---|
| Country A | Payment (P) | 2,1 | -3,3 |
| Country A | No Payment (NP) | 5,-1 | 0,0 |

**Fig. 9** The interconnected aquifer sharing-smuggling game

a) ordinal form

| Country A | Country B | *P* *C* | *P* *NC* | *NP* *C* | *NP* *NC* |
|---|---|---|---|---|---|
| | *WS* *P* | 7,9 | 3,10 | 4,12 | 1,13 |
| | *WS* *NP* | 10,7 | 5,8 | 7,10 | 3,11 |
| | *NWS* *P* | 10,3 | 5,4 | 6,6 | 2,8 |
| | *NWS* *NP* | 11,1 | 8,2 | 9,4 | 4,5 |

b) state numbers

| Country A | Country B | *P* *C* | *P* *NC* | *NP* *C* | *NP* *NC* |
|---|---|---|---|---|---|
| | *WS* *P* | 1 | 5 | 9 | 13 |
| | *WS* *NP* | 2 | 6 | 10 | 14 |
| | *NWS* *P* | 3 | 7 | 11 | 15 |
| | *NWS* *NP* | 4 | 8 | 12 | 16 |

games. In Fig. 9a, only ordinal payoffs are presented (cardinal payoffs can be found in Just and Netanyahu 2004), as the values of payoffs do not matter in the final resolution of the game as long as the structure of the game does not change. Each country has four strategies in the interconnected game. In Fig. 9b, a number has been assigned to each possible outcome of the game. Overall, the game has 16 possible outcomes.

The introduced stability concepts presented in Section 4 were used to solve the interconnected game and to see if the results differ from the findings of Just and Netanyahu (2004) who used a different approach for determining the resolution of this conflict. Table 6 shows the stability analysis results for the linked aquifer

**Table 6** Stability analysis results for the interconnected aquifer sharing-smuggling game (Fig. 8)

| Stability definition | Equilibrium states | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 6 | 9 | 10 | 11 | 16 |
| Nash ($L_1$) | | | | | | | √ |
| GMR | √ | √ | √ | √ | √ | √ | √ |
| SMR | √ | √ | √ | | √ | √ | √ |
| SEQ | √ | √ | √ | √ | √ | √ | √ |
| $L_2$ | √ | √ | √ | √ | √ | √ | √ |
| $L_3$ | | | | | √ | | √ |
| $L_4$ | | | | | √ | | √ |
| $L_n$ ($n > 4$) | | | | | √ | | |
| Non-Myopic | | | | | √ | | |

sharing-smuggling game that were found using different non-cooperative stability definitions. The results suggest that the cooperative state 10 (WS/NP, NP/C) and the non-cooperative state 16 (NWS/NP, NP/NC) are the most likely outcomes. Although the parties might bribe the other party to cooperate, the victim-pays solutions are not stable based on Nash, Limited Move and Non-Myopic stability definitions and, therefore, are not likely outcomes of the game. State 16 is the only Nash equilibrium. However, the Nash stability concept might not be appropriate here because the players are allowed to make more than one move during the game.

In this game, if the players start cooperating (state 10), they tend to continue cooperating because of the credible threat of the other player to put them in a worse position. In other words, all unilateral improvements from state 10 by one player can be blocked by possible counter-moves of the opponent. The results reveal the unsuitability of victim-pays in this game. Although some equilibria were found which employ side payments (states 1, 2, 6, 9, and 11), they are not considered to be very likely outcomes, being unstable under some stability concepts. Since only states 10 and 16 are stable under a diverse set of stability definitions, it is argued that for finding the possible resolutions of the game, there is no need for excluding the states associated with victim-pays from the feasible outcomes set, as is done by Just and Netanyahu (2004).

If side-payments are infeasible, all the strategies associated with side-payments should be omitted. The revised game will be a smaller game, shown in Fig. 10 in matrix form with ordinal preferences. The game now has a PD structure. Therefore, outcomes (NWS, NC) and (WS, C) are two resolutions of the game based on the stability definitions considered in this analysis. The socially optimal and Pareto-optimal outcome of the game is (WS, C), which is state 16 in the original game. Using a different approach, Just and Netanyahu (2004) found (WS, C) to be an optimal outcome and a possible resolution. However, they did not determine this based on a particular introduced stability definition, as is done here. They correctly reasoned that the parties do not like to defer from cooperative strategies (WS for Country A and C for Country B) because of the credible threat from the other party. This means that if country A decides to change the outcome from (WS, C) to (NWS, C) to increase its payoff, Country B responds by changing the outcome to (NWS, NC). Since state (NWS, NC) is worse than (WS, C) for Country A, it will never switch from its cooperative strategy to its non-cooperative strategy. This is exactly the behavior that solution concepts such as GMR, SMR, SEQ, $L_h$ and Non-Myopic simulate.

**Fig. 10** Revised interconnected game in normal form

| | | ***Country B*** | |
|---|---|---|---|
| | | *C* | *NC* |
| ***Country A*** | *WS* | 3,3 | 1,4 |
| | *NWS* | 4,1 | 2,2 |

The interesting application nicely demonstrates that by employing suitable stability definitions for analyzing a given conflict, game models can generate satisfactory results and valuable insights. When there are uncertainties about the behavior of the players, applying different stability concepts can be beneficial.

## 7 Conclusions

Conflict modeling always involves simplifications and inaccuracies, resulting from the limited information about the game. It is almost impossible to develop a perfect model which accurately simulates every aspect of the conflict and is able to predict the exact outcome of the conflict. However, it is possible to improve outcome prediction and insights by employing appropriate stability definitions. Applications of game theory to water resources conflict resolution are not limited to cooperative game theory concepts. Although these concepts are simple to understand, sometimes more convenient to apply (Madani 2010), very helpful in providing useful insights into cooperative decision making environments, and finding fair benefit/cost allocations, they may not reasonably reflect important characteristics of decision makers, making them imperfect for predicting the strategic behavior of players in non-cooperative situations.

Non-cooperative stability concepts reflect the behavior of players in making decisions. Such behavior depends on different factors such as risk attitude and information availability while playing the game. Selection of proper stability definitions is a challenging task. However, it is possible to model and analyze a game using a range of stability concepts when there is uncertainty about the characteristics of the players and game. A state which is stable under different stability definitions has a presumably higher chance of being the final resolution of the game, if reachable from the status quo.

The Nash stability definition reflects a very restrictive case in assuming that players can only make one decision (unilateral improvement) during the game. Thus, the Nash stability concept might fail in finding the final resolutions of water resources games, which are often not one-move games and have dynamic natures. The Non-Myopic stability definition simulates the behavior of a player with a perfect foresight into the possible dynamic interactions among DMs in a game, which might be unsuitable for water resources games, as real players cannot consider more than a few moves and counter-moves into the future. The other stability definitions introduced here can better predict the possible resolutions of water conflicts as they are not as pessimistic as Nash stability nor as optimistic as the Non-Myopic stability definition.

Different non-cooperative stability concepts were introduced to better reflect the reality of the interactive decision-making process in finite strategy non-cooperative water resources games. The introduced stability definitions were applied to analyze generic and simple water resources games in this paper. Nevertheless, these stability definitions can be applied to solve more complex real-world water resources conflicts. Application of these stability concepts can improve applicability and validity of water resources conflict models and provide valuable insights into conflict resolution. Studying a conflict under different stability concepts reveals how the game's results can change based on different behaviors of the players or changes in the game. When a specific outcome is sought for a conflict, a game might be redesigned so that no matter what type of player is participating, the outcome of the conflict will be the same.

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