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Systems Thinking in Fair Water Resources Allocation

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ABSTRACT: Systems thinking approaches are employed to construct a formal decision making methodology for equitably allocating water among competing users in a river basin when taking into account both the societal and physical systems aspects of the allocation problem. In particular, within the societal component of the decision problem, multiple participants, their multiple objectives, equity principles, and economic factors are considered, while the physical systems part reflects relevant hydrologic and environmental factors. The Cooperative Water Allocation Model (CWAM) incorporates these societal and physical systems concerns within the framework of a large-scale optimization program which is divided into two main steps. Firstly, water is allocated among users based on existing legal water rights regimes or agreements. Secondly, water and associated benefits are reallocated among stakeholders to maximize basin-wide welfare. CWAM is applied to the South Saskatchewan River Basin located in the Canadian province of Alberta to demonstrate how it can be conveniently applied to a water allocation system of systems problem.

MOTIVATION

Under the pressure of climatic change, burgeoning population, drastically expanding industrialization of developing countries such as China and India, and widespread water pollution, fresh water is destined to become a scarcer and scarcer natural resource. Therefore, the importance of equitably allocating water among competing demands in a highly interconnected world is one of the greatest challenges facing humankind. Clearly, a systems thinking approach is required to provide sound decision methodologies and insightful policies for managing water at the local, basin, regional, national and international levels in order to reflect the value systems and concerns of all stakeholders.

As a well known illustration of the devastating consequences that can be wreaked upon society by inappropriate water allocation within a relatively dry area of the world, consider the Aral Sea tragedy. Starting more than 80 years ago during the Soviet era, huge quantities of water were diverted from rivers flowing into the Aral Sea for inefficient irrigation purposes such as growing cotton for export. This sequence of misplaced political decisions caused the Aral Sea to shrink drastically in size, ruined the fishing industry, created a toxic mix of highly concentrated pollutants in the sea, and, overall, gave the Aral Sea the infamous distinction of being one of the worst ecological disasters in history (see Wang *et al.*, 2007a) and Nandalal and Hipel (2007) along with references cited therein). In Australia, as well as other nations of the world, a protracted drought, and the threat of even worse water shortages brought about by ongoing climatic change, put the future of this nation in jeopardy. The rapid shrinking of glaciers in the Rocky Mountains of Western Canada as a direct result of climate change is causing the summer flows of the Saskatchewan River and its tributaries to decrease during the summer season. Since the rivers flowing from west to east across the provinces of Alberta and Saskatchewan eventually reach Lake Winnipeg in the province of Manitoba, this will cause Lake Winnipeg and other nearby lakes to greatly decrease in size. In fact, Lake Winnipeg has the potential to become the "Aral Sea" of North America.

As explained in the next section, systems thinking has a key role to play in virtually all areas of water resources and environmental management. Figure 1 emphasizes the fact that in order to execute a proper and realistic systems study one must consider all

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interconnected aspects of a given systems problem using a rich range of societal and physical systems models. Accordingly, in this paper the Cooperative Water Allocation Model (CWAM) for use at the basin level, combines multiple stakeholders, their multi-dimensional objectives, and economic factors from the realm of societal systems, along with hydrologic and environmental factors from the physical systems domain, under the overall umbrella of a large-scale optimization formulation. The efficacy of this systems thinking methodology for fair water allocation in a river basin is illustrated by applying CWAM to a complex water allocation problem in the South Saskatchewan River Basin located east of the Rocky Mountains in Alberta, Canada.

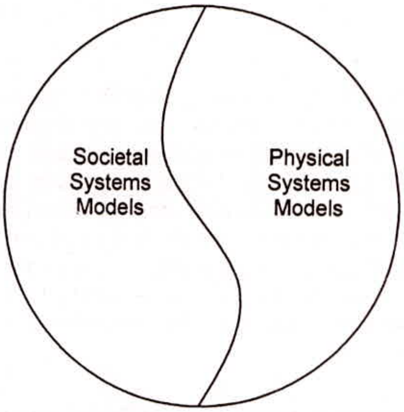

Fig. 1: The duality of systems modeling of a realworld problem

SYSTEMS METHODOLOGIES IN WATER RESOURCES

Systems methodologies and associated techniques for formally modeling and analyzing decision making processes have been developed within a range of systems-related disciplines including operations research, systems engineering, decision analysis (Edwards *et al.,* 2007), industrial engineering, and project management. Although there are many differences among these and other related systems-based disciplines, they do possess many common features and any differences that do exist are usually complementary (see, for instance, Johnson (1997), Emes *et al.* (2005), and Hipel *et al.* (2008a)). All of these fields, for example, were founded just before, during or soon after the end of World War II. Operational or Operations Research (OR) was initiated in July 1938 when the British High Command ordered that research be carried out with respect to the operational aspects of radar systems and during the Second World War. OR was successfully utilized by both the British and American armed forces in the systematic execution of large-scale military operations (Blackett, 1962; Waddington, 1973). After WW II, OR societies were founded in many industrialized countries around the globe. The field of Systems Engineering (Sage, 1992; Sage and Rouse, 2008) also traces its roots back to WW II and became strongly established as a discipline at NASA (National Aeronautics and Space Administration) in the USA in the 1960s and 1970s. Historically, OR mainly optimized the performance of existing systems, while Systems Engineering focused on the development of new or modified systems. Moreover, OR tended to be reductionist in its outlook while Systems Engineering was holistic (Hipel *et al.,* 2008b). Nevertheless, these various disciplines are converging in their focus and objectives by readily developing and adopting new systems thinking approaches for addressing complex systems, or system of systems problems, and expanding their application domains to encompass important challenges now confronting society, such as security, global warming, sustainable development, infrastructure renewal and logistics. In addition, the systems-based disciplines recognize the need to be able to handle unforeseen problems, which may suddenly emerge in the future; decision-making in real time, such as internet-based commerce (Hipel *et al.,* 2007); and the need to entertain the concept of a system of systems structure (see Hipel *et al.* (2008d) for references regarding a system of systems and its employment in sustainable development).

Systems methodologies can be utilized in the optimal management of complex water resources "systems of systems". As argued by Hipel *et al.* (2008a), these systems methodologies and techniques can be employed within an adaptive (Holling, 1978; Walters, 1986; Gunderson, 1999) and integrative (Mitchell, 1990; ICWE, 1992) management approach to sustainable development, often in real time. Recently, Jain and Singh (2003), Loucks (2004), and Nandalal and Simonovic (2003) have written books that present systems approaches to addressing complex problems in water resources planning and management. From a Systems Engineering viewpoint which explicitly considers hierarchical multiple objectives, Haimes (2004) provides a comprehensive methodology for realistically addressing complex risk assessment and management decision problems in water resources and many other fields. Of particular concern is how to handle the multiple participant-multiple objective decision making aspects occurring in water resources and environmental management (Hipel and McLeod, 1994; Hipel and Fang, 2005).

Conflict, or differences of opinion, inevitably arises whenever people interact with one another. For example, because Canada possesses the world's largest quantity of fresh water, private companies would like to consider water to be the same as any other commodity and export it in bulk quantities to other countries. Accordingly, environmentalists are in direct conflict with these companies at various locations in Canada, as exemplified by conflict studies carried out by Hipel and Fang (2005), Hipel *et al.* (2008a), and Hipel and Obeidi (2005). In other conflict situations, there may be a relatively large degree of agreement and cooperation among disputants. For instance, agricultural, industrial, commercial, residential and other competing users in a river basin may adopt a "fair system" for equitably sharing water to mutually benefit all competing parties, as is explained later in this paper. Clearly, this interactive phenomenon called conflict arises in virtually every domain of human activity. Moreover, the types of conflict that can occur can range from being completely competitive, wherein decision makers behave in noncooperative ways, to highly cooperative, in which decision makers can form coalitions in order to reach win/win resolutions.

As a result of the ubiquitous nature of conflict, research on conflict resolution has taken place in a wide range of disciplines. As explained in an overview paper by Hipel (2002) and in articles contained within the theme on Conflict Resolution in the Encyclopedia of Life Support Systems (EOLSS, 2002), a wide range of psychological, sociological, operational research, game theory, systems engineering and other kinds of models have been developed for systematically studying conflict and its resolution from both noncooperative and cooperative viewpoints, as well as interesting combinations thereof. However, a significant amount of research remains to be done in the development of formal decision making methods for systematically investigating conflict and its many nuances for situations in which two or more decision makers interactively behave according to their multi-dimensional value systems when attempting to reach their goals in conflict situations.

Members of the Conflict Analysis Group in the Department of Systems Design Engineering at the University of Waterloo, have made significant progress during the past three decades in the development of Systems Engineering approaches to conflict resolution. Figure 2 displays a road map of research in conflict resolution for which substantial progress has been made and for which challenging work remains to be done under the two main categories of competition and cooperation. Consider the Graph Model for Conflict Resolution shown in the left branch of Figure 2. This Systems Engineering approach to systematically investigating conflict (Kilgour *et al.*, 1987; Fang *et al.*, 1993) constitutes a significant advancement of conflict analysis (Fraser and Hipel, 1979, 1984) which in turn

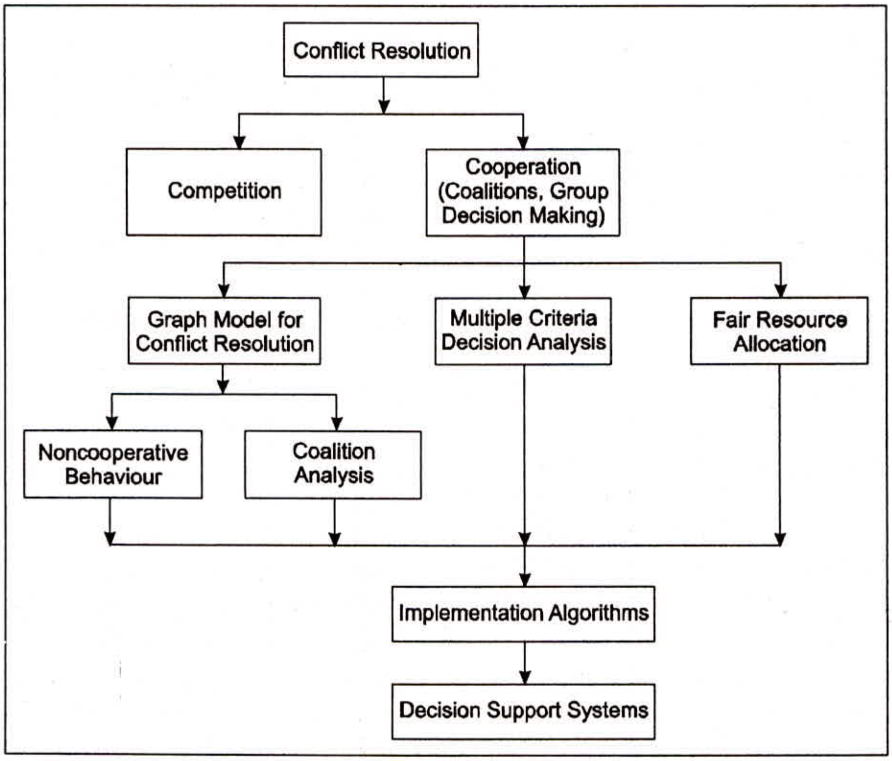

Fig. 2: Competition and cooperation in conflict resolution

is an improvement of metagame analysis (Howard, 1971), which has some links with classical game theory (Von Newman and Morgenstern, 1953). Inherent advantages of the Graph Model are that it only requires relative preference information (i.e., one only has to know if a given scenario is more preferred or equally preferred to another), can take care of a rich variety of ways in which people may behave under conflict, can handle any finite number of decision makers and options, can take care of irreversible and common moves by decision makers, can reflect any order of moves and counter-moves made by decision makers during the evolution of dispute to its final resolution, and can be applied to a rich range of realworld disputes. Under noncooperative behavior shown on the left in Figure 2, methodological advances permit the Graph Model to handle a range of complications that arise in practice such as tracing the evolution of a conflict from a status quo situation to a final equilibrium (Li *et al.*, 2004b, 2005b), taking uncertain preference information (Hipel and Ben-Haim, 1999; Ben-Haim and Hipel, 2002; Li *et al.*, 2004a, 2005a) and strength of preference (Hamouda *et al.*, 2004, 2006) into account, describing how emotions can affect decision making under conflict (Obeidi *et al.*, 2005, 2006), and policy analysis (Zeng *et al.*, 2007). The utility of these new decision technologies was demonstrated via strategic analyses of realworld disputes arising over the pollution of an underground aquifer, degradation of surface water quality, sustainable development, proposed exports of water in bulk quantities, trade in services, and trade versus the environment.

Notice in Figure 2, that besides competitive or noncooperative behaviour, the Graph Model has been expanded to take into account coalitions (Kilgour *et al.*, 2001; Inohara and Hipel, 2008a,b). In a coalition, two or more disputants cooperate with one another in order to benefit the members of the coalition. In fact, when carrying out a strategic study using the Graph Model, it is first recommended that one ascertain the best result that a given decision maker can achieve on his or her own through noncooperative behaviour and then determine if the decision maker can fare even better by cooperating with others via joining a coalition. Finally, to apply the Graph Model to practical problems, one can employ the Decision Support System GMCR II (Fang *et al.*, 2003a, b; Hipel *et al.*, 1997, 2001).

Under the cooperation branch shown on the right in Figure 2, notice that Multiple Criteria Decision Analysis (MCDA) is another set of techniques that can be employed in group decision making. When employing MCDA, parties having common interests, such as section heads in a company may attempt to find an optimal or satisfying solution to a particular problem by evaluating and comparing potential solutions according to a range of criteria which reflect the value systems of the stakeholders (see for instance, contributions to MCDA by Rajabi *et al.* (1999, 2001) and Chen *et al.* (2006, 2007, 2008)).

The remaining systems thinking approach to investigating cooperation among stakeholders is the Fair Resource Allocation approach given on the right in Figure 2. Within this procedure, concepts from cooperative game theory, economics and hydrology are embedded within an overall large-scale optimization model to determine how water can be fairly allocated among competing users in a river basin. This approach should have particular significance in an era of water shortages, drought and climate change, and is the focus of the rest of this paper. Finally, as pointed out at the bottom of Figure 2, implementation algorithms, such as the new matrix approaches of Xu *et al.* (2007, 2008) for employment with the Graph Model, allow the decision methodologies to be implemented as decision support systems (Hipel *et al.*, 2008c).

COOPERATIVE WATER ALLOCATION MODEL

Integrated water resources management is a multiple dimensional process centered around the demands for water, the policy to meet these needs and a management strategy to implement the policy, which requires the integration of various components including physical, biological, chemical, ecological, environmental, health, social, and economic aspects (Singh, 1995). After discussing water allocation issues at the basin level, fairness principles are embedded into the design of the Cooperative Water Allocation Model in this section.

Water Allocation at the Basin Level

Water allocation issues can be addressed at national, provincial, basin and local levels. At the provincial or national level, a water allocation policy deals with the interacting obligations of water users and the regulatory authorities. In many countries, the state is the owner of all or nearly all water and allocates water permits or user rights (water rights) according to specific water rights systems (Savenije and Van der Zaag, 2000). For international river basins between countries, generally there are no formal inter-country water rights systems but international water agreements defining ownership of the water resources (Wolf, 1999). At the basin or operational level, a water allocation plan is concerned with shorter-term, usually annual, management of reservoir storage, river flows, and diversions. At the local level, the distribution rules and priorities are specified for water uses to share the diversions determined at the operational level (UNESCAP, 2000).

As water scarcity is becoming a common occurrence in many countries (UNWWAP, 2003), discussions arise addressing institutions and polices for water allocation, and associated equity, efficiency and sustainability principles (UNESCAP, 2000). Although many simulation and optimization models for water quantity, quality and economic management have been developed for operational use under various water rights systems (McKinney *et al.,* 1999), there are only a few studies that jointly consider both efficiency and equity (Cai *et al.,* 2002).

Due to differences of capability in generating economic benefits, water allocations merely based on a water rights approach usually do not make efficient use of water for the whole river basin. Meanwhile, an economic efficient water allocation plan generally is not an equitable one for all water users or stakeholders. To overcome this dilemma, a modeling framework named the Cooperative Water Allocation Model (CWAM) has been developed by Wang *et al.* (2003, 2007a, 2007b, 2008a, 2008b) which can be used to promote cooperation of stakeholders in a river basin to obtain equitable, efficient and sustainable water allocations. This methodology carries out water allocation in two steps: (1) initial allocation of water rights to water uses founded on legal water rights systems or agreements; and (2) reallocation of water to achieve efficient use of water and equitable redistribution of net benefits to promote cooperation of all stakeholders in a river basin. CWAM is applied to a complex water allocation problem in the South Saskatchewan River Basin in western Canada in the next main section, based on earlier work by Wang *et al.* (2008a) and Wang (2005). Within the Aral Sea Basin, Wang *et al.* (2007a) and Wang (2005) investigate allocation of water rights.

Applying Fairness Principles to Water Allocation Systems

Fairness and Existing Water Rights Systems

Resource allocation problems are concerned with how limited resources should be distributed fairly among competing activities in the achievement of optimal performance of a complex system or system of systems. Essentially, fairness is an abstract socio-political idea that implies impartiality, justice and equity (Young, 1994). The efficient and fair allocation of water has become a controversial issue within and among many countries (UNWWAP, 2003; Wang, 2005). Conflicts often arise among irrigation, urban, industrial, recreational, environmental and other uses since water is often argued to be a public good and should be equitably used. Many negotiations among stakeholders or users base their initial positions in terms of rights (Giordano and Wolf, 2001), which provokes the most fundamental of problems—how to allocate water rights in a fair way.

For water rights allocation inside a country, water rights systems form the legal basis for water management, each of which may be founded upon one of three basic doctrines: riparian rights, prior rights and public allocation (Savenije and Van der Zaag, 2000). Many recent studies promote water transfers and market mechanisms to improve economic efficiency and effectiveness of water resources utilization (McKinney *et al.,* 1999; Mahan *et al.,* 2002). This necessitates the fair allocation of water as property rights which is the foundation for a water market.

For international river basins among nations, water sharing is generally dictated according to international water agreements defining ownership of the water resources. An agreement may be based upon one of the following principles: absolute sovereignty, absolute riverine integrity, limited territorial sovereignty, and economic criteria (Wolf, 1999; Giordano and Wolf, 2001). Although international water laws assert that the water should be equitably allocated, they provide no well-defined, transferable and measurable criteria for water rights allocation, and few models concerning fair water rights for transboundary basins exist in the literature (UN, 1997; Seyam *et al.,* 2000).

Principles and Methodologies for Fair Resource Allocation

Fairness ideas include Pareto optimality, monotonicity, consistency, impartiality, priority, and envy-free (Young, 1994). By adopting some of these principles, various mathematical models can be formulated for application to different equitable allocation problems, including integer allocation, divisible good allocation, cooperative games and bargaining. It should be pointed out that depending on the nature of the resources, not all of the above principles may be achievable. The choice depends on one's value system. Consider a complex large-scale system, such as a water allocation system, consisting of competing uses which require the resources to fulfill their various activities. Let $x = (x_1, x_2, \cdots, x_h)$ be the vector of decision variables representing the allocations to be determined and Ω denote the feasible set of x defined by the constraints. Without loss of generality, resource allocation can be viewed as a generic multiple objective optimization problem,

$$\max[f(x) : x \in \Omega] \qquad \ldots (1)$$

where $f(x) = f_1(x), f_2(x), \ldots f_m(x), f_i(x)$ is the jth objective function, $j = 1, 2, \cdots, m$. To trade off the multiple objectives, the concept of fairness must be accounted for by defining some type of aggregation function, $u(f(x))$, to optimize based upon the individual objective functions. Since fairness is essentially an abstract social-political concept implying equity and justice (Young, 1994), a social aggregation objective function $u(f(x))$ may be defined and the generic multiple objective resource allocation problem is restated as,

$$\max[u(f(x)) : x \in \Omega] \qquad \ldots (2)$$

Ogryczak *et al.* (2003) extend monotonicity, impartiality and equitability principles, summarized in Table 1, to generic multiple objective resources allocation problems, and propose the lexicographic optimization approach for fair resource allocation.

Table 1: Fairness Principles for Multiple Objective Fair Resource Allocation

Principle	*Interpretative Description*
Monotonicity	Each user's allotment becomes no worse when the amount of resources increases.
Impartiality	Allocations are made based on the availability of resources and the nature of demands, rather than the identities of the users.
Equitability	Resource is allocated to satisfy rational transfers such that a transfer of any small amount from an outcome to any other relatively worse-off outcome results in a more preferred overall outcome.
Priority	Resource is allocated according to the priority ranks of the individual demands, such as the realization of water rights allocation under a prior allocation regime.

The priority principle is utilized by Wang (2005) in terms of a utility function aggregating the multiple objectives. When a utility function satisfies the monotonicity, impartiality and equitability principles, it is called a *perfectly equitable* utility function for the generic resource allocation problem. The solution of the maximization of a *perfectly equitable* utility function will produce a *perfectly equitable* resource allocation scheme. If a utility function satisfies the monotonicity and priority principles, it is called a *priority equitable* utility function for the generic resource allocation problem. The solution of the maximization of a *priority equitable* utility function will produce a *priorty equitable* resource allocation scheme. It has been shown (Yager, 1988, 1997; Ogryczak *et al.,* 2003) that the lexicographic maximin (or equivalent lexicographic minimax) problem is a specific formulation of the generic resource allocation problem, whose solution is a *perfectly equitable* allocation scheme. For *priorty equitable* resource allocation problems, the priority-based sequential solution method can be utilized to find the allocation schemes.

Applying Equity Principles to the Generalized Water Allocation Problem

The described fairness principles and solution concepts may be applied to water allocation at both the operational and local levels although the following discussion focuses on the former. The water allocation problem is formulated based on a generalized node-link river basin network system model (Wang, 2005). For a typical water allocation problem, there are several thousands of physical, policy and systems control constraints. Typical physical constraints include mass balances and capacity limits. The system control constraints are used to compensate for the simplified abstraction of the river network, hydrological or social-economic processes. For example, the total inflow to any nonstorage node subtracting the return flows to it should exceed the total diversions from it because in reality those return flows are not available for diversion at that node.

A river basin network is a multiperiod configuration connected by the reservoir carry-over storage links. Thus, water allocation at the basin level is mathematically expressed as a generalized multiple objective multiperiod network flow programming problem: *max* or *min* $f(Q, S, C, X_s)$, where, $f(Q, S, C, X_s)$ is a vector of multiple objectives, $f = (f_1, f_2, \ldots, f_m)$; Q, S and C are, respectively, the vectors of network variables representing water flows, aquifer and reservoir storages, and pollution concentrations in link flows, aquifers or reservoirs; and X_s is the vector of non-network type decision variables (side variables), which may be water prices, water transport costs, pollution control costs, crop types, irrigation areas, and/or product prices. Some common types of objectives include: satisfying existing or projected water demands, minimizing the difference in water deficits among all demand sites, maximizing the flow to downstream nodes, maximizing economic production, minimizing the concentration of salts in the system, and minimizing water diverted from other basins. Accordingly, various fair water allocation problems are possible when the fairness principles are applied.

COOPERATIVE WATER ALLOCATION MODEL (CWAM)

As shown in Figure 3, CWAM distributes water resources in two steps: initial water rights are firstly allocated to water uses, or users, based on rights systems or agreements, and then water is reallocated to achieve efficient use of water through water transfers. Correspondingly, sub-models are constructed to incorporate considerations for allocating resources in a fair and efficient manner in two aspects: (1) fair rights allocation from a social-political viewpoint; (2) fair reallocation of benefits through side payments.

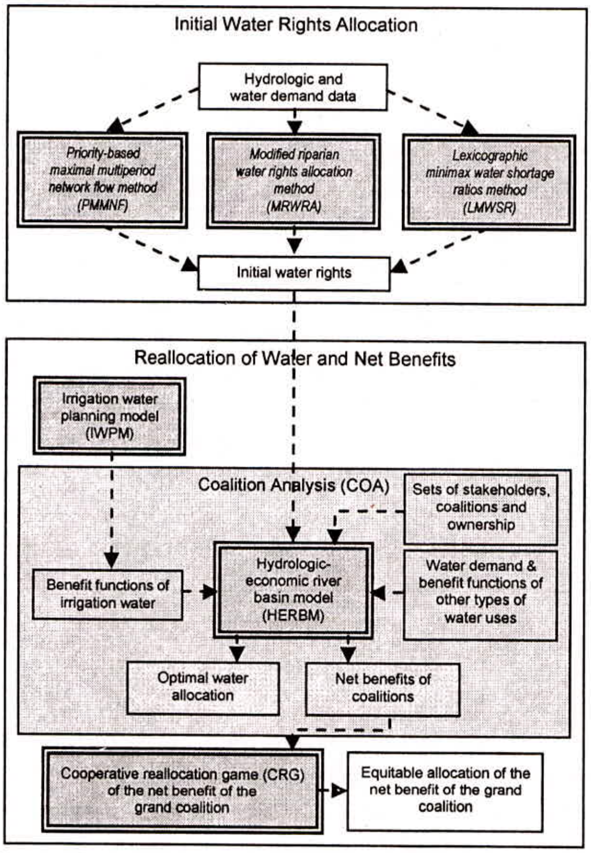

Fig. 3: Components and data flows of the Cooperative Water Allocation Model (CWAM)

Priority and Lexicographic Approaches for Water Rights Allocation

Three methods are developed for deriving equitable initial water rights allocation among competing water uses: the Priority-based Multiperiod Maximal Network flow (PMMNF) programming, Modified Riparian Water Rights Allocation (MRWRA) and Lexicographic Minimax Water Shortage Ratios (LMWSR) methods. PMMNF is a very flexible approach and is applicable under prior, riparian and public water rights systems. MRWRA is essentially a special form of PMMNF adapted for fair allocation under the riparian regime. LMWSR is designed for application under a public water rights system, which adopts the lexicographic minimax fairness concept. Note that, for a non-storage demand site, the water rights are defined as a set of volume and pollutant concentration limits for all inflows and outflows. For a storage reservoir, the water rights are defined as a set of reservoir storage and pollutant concentration limits.

(A) *Priority Formulation*

The PMMNF method is designed for water allocation under various water rights allocation regimes, which allocates water to meet inflow and storage demands strictly according to priorities. Junior uses are allocated after senior uses have been satisfied, as fully as possible, subject to hydrologic constraints. Priority is normally assigned to uses according to "first in time, first in right" under a prior water rights system, or following the relative locations of water uses under a riparian system, or according to the functional importance of water uses in a public water rights regime (Savenije and Van der Zaag, 2000).

In the PMMNF formulation, each inflow link to a demand node is viewed as consisting of one or more dummy sublinks and each sublink has a withdrawal demand and corresponding priority. The storage of every reservoir is divided into several subzones according to reservoir operating rules. Each sub-zone has a storage and corresponding priority. If a vector x is used to represent all of the control or decision variables (Q, S, C and X_s) and Ω is utilized to denote the feasible set defined by the constraints in the PMMNF formulation, the problem can be expressed in a more compact form as,

$$\text{Max}[f^{(m)}(x): x \in \Omega] \quad \ldots (3)$$

where, $f^{(m)}(x) = (f_{r1}(x), f_{r2}(x), \ldots, f_{rm}(x))$, r_i is the priority assigned to a reservoir subzone or inflow sublink, from highest to lowest priority, and f_{r_i} is the sum of the storage and inflows to demands owning the same priority r_i during all of the time periods.

(B) *Lexicographic Formulation*

Under a public water rights system, one approach for allocating equitable water rights is to have water shared among all demands such that shortage ratios of water uses and differences among them are reduced as much as possible while taking account of their relative importance (weights). This equitable water sharing can be formulated as a lexicographic minimax water shortage ratios program (Wang, 2005),

$$\text{lex}\min[f^{(\mu\tau)}(x) : x \in \Omega] \qquad \ldots (4)$$

where, μ is the number of uses; τ is the number of planning periods, usually the number of months; $f^{(\mu\tau)}(x)$ is the vector of $\mu\tau$ elements $f_{jt}(x)$, where these elements are sorted in a nonincreasing order; and $f_{jt}(x) = \omega(j, t)$. $R(j, t)$ is the water shortage ratio of demand node j during period t, in which $\omega(j, t)$ is the weight for the corresponding water shortage ratio $R(j, t)$. For a nonstorage demand node, the water shortage ratio during a time period is defined as the quotient obtained by dividing the difference between the corresponding inflow demand and total effective inflow by that demand. For a reservoir node, the water shortage ratio is defined by dividing the difference between the corresponding storage demand and actual storage by the storage demand.

Cooperative Game Theoretic Approaches for Water and Net Benefits Reallocation

The second step of CWAM comprises three submodels: the Irrigation Water Planning Model (IWPM), the Hydrologic-Economic River Basin Model (HERBM), and the Cooperative Reallocation Game (CRG) of the net benefit of a given coalition. IWPM is a model for deriving benefit functions of irrigation water for all time periods, which maximizes the total profit of irrigated crop productions within an irrigation demand node by adopting quadratic empirical crop yield-water and salinity functions. HERBM is the core component of the coalition analysis, which is a tool for finding optimal water allocation schemes and net benefits of various coalitions of stakeholders. The inputs include hydrologic and water demand data, initial water rights, water demand curves and benefit functions, stakeholders, coalitions and owner-use relationships. CRG adopts cooperative game theoretic approaches to perform equitable allocation of the net benefits of a given coalition. The economically efficient use of water under a given coalition is achieved through water transfers (water reallocation) based on initial water rights.

In CWAM, constant price-elasticity water demand functions are adopted to derive the monthly net benefit functions of municipal and industrial demand sites and hydropower stations, while quadratic gross benefit functions are used to find the monthly net benefit functions of agriculture water uses, stream flow demands and reservoir storage (Wang *et al.*, 2008a).

Given a set of stakeholders or players under consideration for reallocation, a subgroup of stakeholders entering into a cooperative agreement and working together forms a coalition. Reallocation of water and net benefits through cooperation of stakeholders can be viewed as an *n*-person cooperative game. Simplifications are made to reduce the problem size in order to keep the computational load within a reasonable limit. The value of a coalition is defined as the maximum total net benefit that the coalition can gain based on the coalition members' water rights over the entire planning period, subject to not decreasing the water flows and not increasing the pollutant concentrations in the flows to other stakeholders not taking part in that coalition. For details of the formulation, refer to Wang (2005). Solution concepts, including nucleolus, weak nucleolus, proportional nucleolus, normalized nucleolus and Shapley value, are adopted to solve the reallocation game. It is noted that the various nucleolus solution concepts are perfectly equitable, because they lexicographically minimize the maximum coalition excess (Owen, 1995).

The allocation approaches of CWAM have sustainability implications embedded in their formulations. They introduce environmental sustainability consideration by treating environmental requirements as demands and allowing the inclusion of water quality constraints. The lexicographic method enforces the water sharing among users during shortage times and attempts to secure a sustainable economy and society.

SOUTH SASKATCHEWAN RIVER BASIN CASE STUDY

The South Saskatchewan River Basin (SSRB) located in southern Alberta, Canada, shown in Figure 4, comprises four sub-basins: the Red Deer, Bow and Oldman River sub-basins and the portion of the South Saskatchewan River sub-basin located within Alberta. The SSRB drains about 120,000 square kilometers and possesses a primarily semi-arid climate (Dyson *et al.*, 2004). The South Saskatchewan River originates in the Rocky Mountains of Canada and summer flows are highly dependent upon snowmelt from the mountains. More than 1.5 million people lived in the SSRB in 2004, about 81% residing in urban centers including Calgary (about one million residents), Lethbridge, Red Deer, and Medicine Hat.

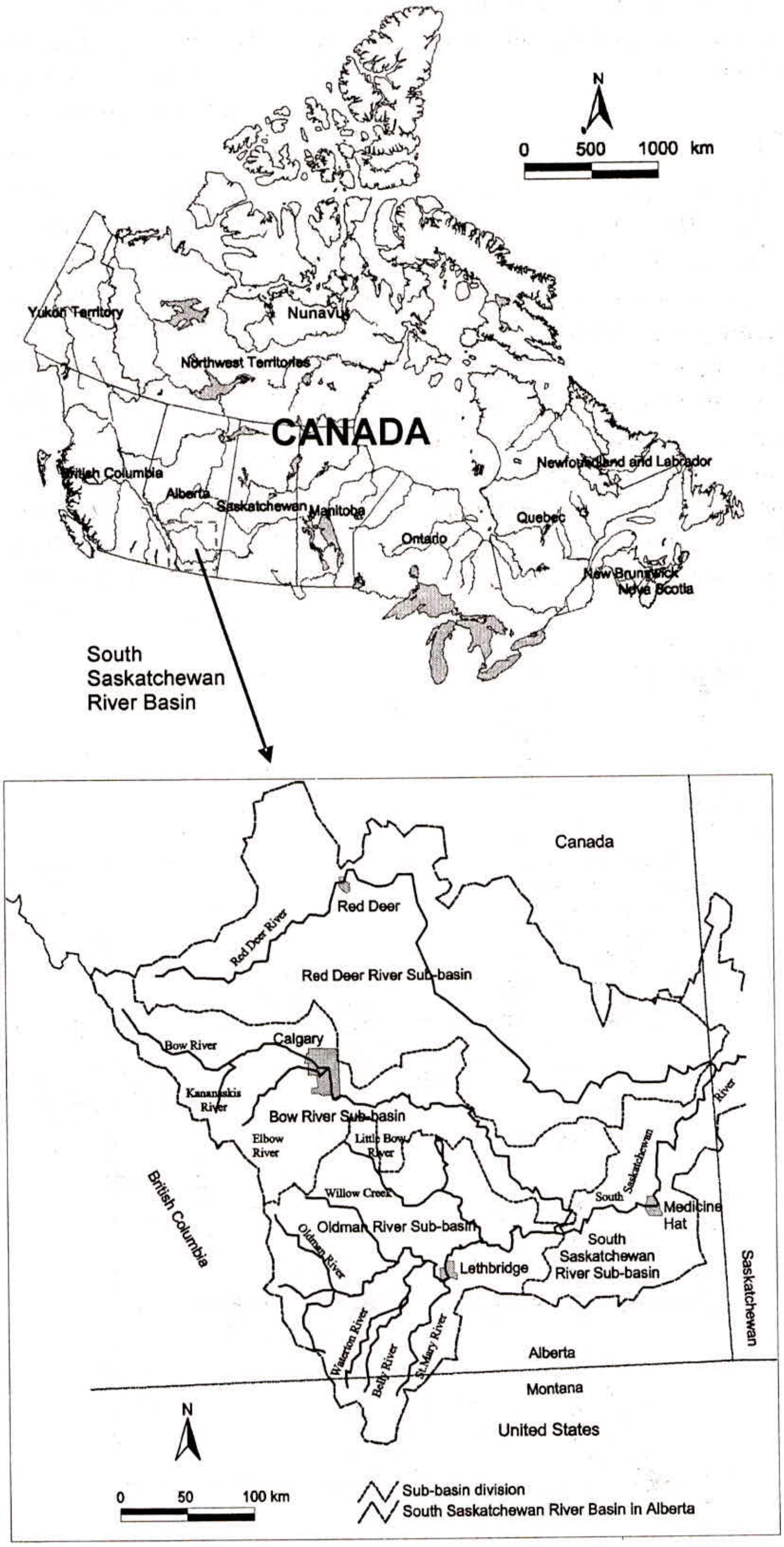

Fig. 4: The South Saskatchewan River Basin within the Canadian Province of Alberta

Under the *Water Act*, the Government of Alberta owns the rights to all waters within its borders. Licenses assign to water uses the maximum amounts of withdrawals and priorities on a first-in-time, first-in-right basis (Alberta Environment, 2003). According to the SSRB Water Management Plan approved in August 2006, Alberta Environment will no longer accept new water license applications for the Bow, Oldman, and

South Saskatchewan sub-basin systems. New water allocations have to be obtained through water allocation transfers (Alberta Environment, 2006).

MODELING SCENARIOS

The SSRB network is plotted in Figure 5, which has 55 nodes in total, including 10 inflow (IN1 to IN10), 1 outlet (O1), 17 reservoirs (R1 to R17), 9 irrigation (A1 to A9), 4 domestic (D1 to D4), 4 general (G1 to G4), 4 industrial (I1 to I4), 2 hydropower plants (H1, H2), and 4 instream flow requirement (S1 to S4) demand nodes. In this case study, the general demand refers to municipal, excluding domestic, demand. The directed links to offstream irrigation, domestic, general and industrial demand nodes are diversion canals, while the reversely directed links from them to nodes on streams represent the return flow routes. Thirteen irrigation districts and smaller privately-owned irrigation systems in the SSRB are aggregated into 9 irrigation nodes according to surface water sources and agroclimate zones. Groundwater supplies are not considered.

The time horizon of the modeling in this study is one year having 12 monthly time periods. Water demands of irrigation regions are assumed to occur during the growing season. Monthly irrigation demands are determined by the Irrigation Water Planning Model (IWPM), a sub-model of CWAM, as the difference between crop potential evapotranspiration and effective precipitation utilizing soft wheat, hard spring wheat, barley, canola, potatoes and alfalfa, as representative crops for the six crop categories. Salinity is considered in this study in order to explore the effects of water allocation on the salt concentrations in the river system and on the benefits of crop production.

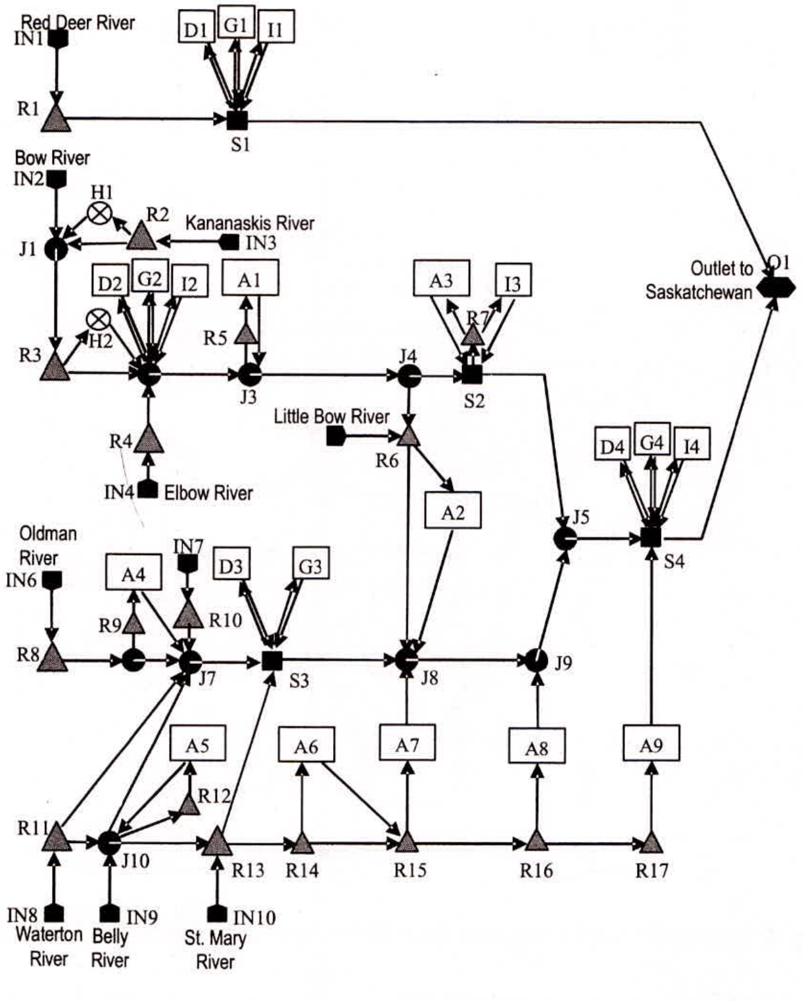

Fig. 5: Network of the South Saskatchewan River Basin in southern Alberta

Six case scenarios are investigated according to the combinations of water demands, hydrologic conditions, and methods for initial water rights allocation. In Cases A, B and C, initial water rights are allocated by the PMMNF method, reflecting Alberta's existing prior water rights system. In Cases D, E and F, initial water rights are assigned by the LMWSR method, which reflects allocations under an assumed public regime. Case A (1995 wet & PMMNF) and Case D (1995 wet & LMWSR) represent the actual situations of water demands, tributary inflows and node adjustments in 1995. Case B (2021 normal & PMMNF) and Case E (2021 normal & LMWSR) consider the forecasted water demands in 2021, and the long term mean (1912–2001) tributary inflows and node adjustments. Case C (2021 drought & PMMNF) and Case F (2021 drought & LMWSR) explore water allocations under the forecasted water demands in 2021 and the hydrologic conditions of an assumed drought year. Since Case A represents the actual situation as of 1995, it is also used for calibrating model parameters such as water loss coefficients and node adjustments.

In the PMMNF method, ten priority ranks are assigned to all the demands in the SSRB: all domestic water demands have the highest priority rank; licensed withdrawals for satisfying irrigation, municipal, industrial and hydropower generation water demands and stream flow requirements are assigned priority ranks according to the "First come first in right" rule and their license application dates. In the LMWSR method, weights of water uses are set based on the "equivalent weighted shortages" rule, whereby water shortages are shared subject to equivalent weighted water shortage ratios. The higher the social utility or the lower the water-shortage endurance that the use has, the larger is the weight.

The modeling results show that in the wet and normal hydrologic years, all offstream and hydropower generation water demands are satisfied if PMMNF is used, and are nearly satisfied when LMWSR is utilized. Hence, there is little need or incentive for water reallocation. The upcoming discussion concentrates on the results of the two drought cases.

INITIAL WATER RIGHTS ALLOCATION IN THE SOUTH SASKATCHEWAN RIVER BASIN

In Case C, water shortages appear at various locations, with the annual satisfaction ratios ranging from 0.966 (96.6%) to 0.475 (47.5%) as shown in Figure 6. For the large municipality of Calgary, all monthly domestic demands are satisfied even if there is severe drought, because under Alberta's existing prior water rights system they are always assigned to the highest priority no matter when an application for withdrawals is submitted. The monthly satisfaction ratios of Calgary's general (G2) and industrial (I2) water demands are found to be constant, at 0.695 and 0.475, respectively, because the demands required by future development are licensed with lower priority ranks. Calgary would have to yield the rights to utilize these withdrawal licenses with lower priority in the drought scenario.

Compared to the PMMNF method, the allocation by the LMWSR method under the drought Case F leads to more evenly distributed satisfaction ratios for offstream and the hydropower generation water demands varying from 0.802 to 1, as shown in Figure 6. As the LMWSR method for water rights allocation searches for the vector of lexicographic minimax fair distribution of weighted shortage ratios by iteratively finding the minimax water shortage ratios and then fixing their upper bounds, the demands possessing higher weights have the privilege to receive water, and all demands of the same weight are equitably treated no matter if they are located upstream or downstream.

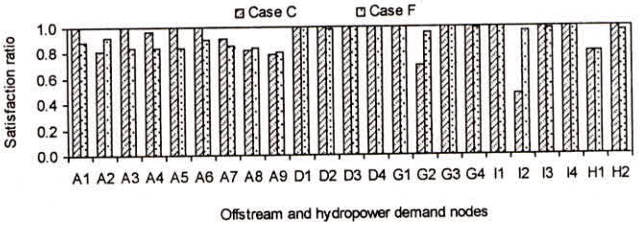

Fig. 6: Distributions of annual satisfaction ratios under Cases *C* and *F*

WATER AND NET BENEFITS REALLOCATION IN THE SOUTH SASKATCHEWAN RIVER BASIN

Due to data limitations, the values of stream flows and reservoir storages are not explicitly included in the objective functions of the hydrologic-economic river basin modeling and coalition analysis. Instead their water rights are preserved through hydrologic constraints.

Net Benefits of Initial Water Rights

The economic analysis of the allocated initial rights demonstrates that the differences of water values for different water uses can be shown by the different monthly marginal net benefits of raw water based on withdrawal rights to non-storage demand sites. For example, in drought Case C, the marginal values of raw water withdrawn from the junction node J2 to the general (G2) and industrial (I2) demands of Calgary are more than $1.8 per cubic meter during all months, and are significantly higher than other uses. The marginal values of irrigation withdrawals are between $0.015 and $0.051 per cubic meter.

For drought Case F, the total annual inflow of non-storage demand sites in the SSRB based on the initial rights allocations by the LMWSR method is a little smaller than those allocated by the PMMNF method, and more water is left in the river system for satisfying stream flow requirements and is passed unto the downstream Province of Saskatchewan. However, the total net benefit based on the results of LMWSR is even greater than that obtained by PMMNF. This means that the LMWSR method can produce water allocations that are not only equitable but also as economically efficient as PMMNF.

Basin-wide Optimal Water Allocation

Annual net benefits of stakeholders under the initial and basin-wide optimal scenarios in Case C are summarized in Figure 7, which shows water trade (including both intra- and inter-stakeholder trade) will lead to an increase in the total net benefit of the SSRB in the amount of 170.5 million dollars. Marginal net benefits of raw water withdrawals under the basin-wide optimal allocation scenario in Case C are evenly distributed among months due to the economic optimization covering all time periods.

Under the basin-wide optimal allocation scenario in Case F, large amounts of water are exchanged among irrigation regions, rather than being assigned to a more valuable user, the City of Calgary, and the gain of water trade is only $15.53 million. This is caused by the more evenly-spread water satisfaction ratios of initial water rights obtained by the LMWSR method.

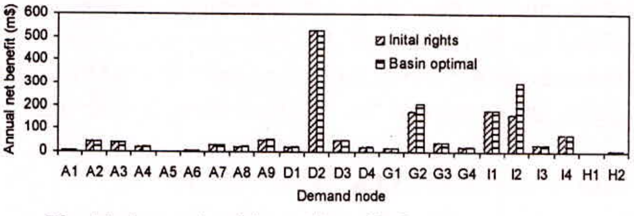

Fig. 7: Annual net benefits of inflows allocated to demand sites (Case C)

Reallocation of Net Benefits among Stakeholders

Eight stakeholders are considered in the hydrologic-economic river basin modeling and coalition analysis. However, the comparative analysis of the initial rights and basin-wide optimal scenarios under both Cases C and F demonstrates that only four stakeholders (BH, CA, BIR and OIR) have significant changes of inflows and net benefits, while others are either nil or very small. Thus, the coalition analysis just needs to consider these four players. The reduction of stakeholders drastically decreases the coalition number to only 15. For every coalition, the multistart global optimization algorithm for coalition analysis utilizes the OQNLP solver to generate hundreds of scatter trial points, select good starting points, and summon the gradient-based nonlinear solver MINOS for further optimization and final solution determination.

Stakeholders may have different capacities of water withdrawal and different gains of water uses when participating in different coalitions. For example, under Case C, if BH and CA pursue the intra-optimal allocation, they may only get nil and $28.110 million more than those obtained by their initial rights, respectively. But they can gain an increase of $38.642 million if they work cooperatively. The different capability of gains for a stakeholder involved in different coalitions makes it necessary to analyze all the possible coalitions of stakeholders in order to promote the grand coalition and equitably allocate the net benefits (side payments). The cores of the cooperative net benefit reallocation games under both Cases C and F are nonempty, which means there are infinite possible allocations satisfying the equity rationalities as long as they are located in the cores. The allocations by various nucleolus and Shapley values can be used for reference and comparison purposes.

Value of participation in the grand coalition for each stakeholder is represented as the additional gain over the independent optimal (intra-stakeholder optimal) net benefit that can be produced based on his or her initial water rights. The additional gains under Case C after reallocation of water and net benefits with different cooperative game solution concepts are summarized in Figure 8. Under Case C, Calgary is normally allocated most of the additional gain over the intra-optimal scenario benefit, ranging from 67 to 138 million dollars, since it is the major contributor to the grand coalition. The Bow River Irrigation Regions (BIR) make additional gains from about 3 to 60 million dollars, by receiving a side payment from Calgary for the water trade among them. For participation in the grand coalition under Case F, the total additional gain over the intra-optimal allocation is only $13.815 million. Most of the gain is allocated to Calgary due to its significant contribution to the grand coalition. BIR's gains range from $0.553 to $2.421 million, since it withdraws more water under the grand coalition scenario than its initial water rights. Bow River hydropower stations (BH) make additional gains of about 2 to 3 million dollars, by receiving side payments from Calgary and the Bow River Irrigation Regions (BIR) for water rights transferred to them.

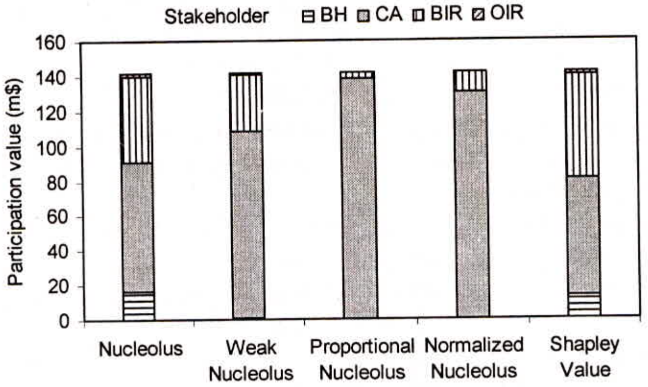

Fig. 8: Values of participation in the grand coalition for stakeholders under Case C reallocated with different cooperative game solution concepts

FUTURE CHALLENGES

As exemplified by the SSRB application in the previous section, the Cooperative Water Allocation Model (CWAM) constitutes a fine example of a comprehensive systems methodology for tackling complex issues in water allocation. However, as is also emphasized by Hipel and Fang (2005) and Hipel *et al.* (2007), a rich range of systems thinking approaches needs to be developed for addressing many types of complex water resources and environmental problems facing humankind at the present time and in the foreseeable future. For instance, how can the world community develop fair policies to allocate costs in reducing greenhouse gas emission as well as adapting to the impacts of climate change. Perhaps some of the key ideas embedded within CWAM can be appropriately revised and extended for resolving this kind of problem. Another connected challenge is to design systems thinking methods for handling issues related to providing reliable fresh water supplies and other types of infrastructure security. Because negative and unforeseen emergent properties can arise from a given complex system of systems, real time adaptive and integrative decision making may be required in certain situations based upon vast amounts of data being continuously measured over time (Hipel *et al.*, 2007). For instance, unsuspected health effects caused by synthetic pharmaceutical chemicals present in our water supply may require immediate action to rectify the situation.

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