Water Resources Management (2019) 33:1591–1607
https://doi.org/10.1007/s11269-019-2186-7

Analyzing the Impacts of Climate Change on Hydro-Environmental Conflict-Resolution Management

Yuni Xu[1] · Xiang Fu[1] · Xuefeng Chu[2]

Received: 24 July 2018 / Accepted: 1 January 2019 /
Published online: 12 January 2019

Abstract

Conflict-resolution methods have been applied to water resources management to balance conflicting interests of stakeholders. Due to the climate change impacts on hydrologic processes, the strategy selections of conflict-resolution methods can be influenced, resulting in different selection rules for historical and future periods. This study aims to quantify the impacts of climate change on the strategy-selection rules of the conflict-resolution methods for better long-term strategic decision-making. The methodology of this study consists of climatic, hydrological, environmental and multi-objective optimization models, two fuzzy social choice methods (FSCMs) and four game-theoretical bargaining methods (GTBMs). The hydro-environmental conflict-resolution management in the Yangtze River of China is selected as the case study. The results show that the strategy selection of GTBMs is more stable and results in a better balance between hydropower and environmental objectives, compared to that of FSCMs. Moreover, considering climate change, under the appropriate environmental flow pattern, the stabilities of the strategy selections of FSCMs and GTBMs are slightly influenced, and the average satisfied degrees of both objectives obtained by FSCMs and GTBMs in the future period (2021-2080) are lower than those in the base period (1950-2012). The findings from this study provide guidance for hydro-environmental conflict-resolution management from a sustainable development perspective.

Keywords Conflict-resolution method · Multi-objective optimization model · Climate change · Environmental protection · Hydropower generation

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11269-019-2186-7) contains supplementary material, which is available to authorized users.

✉ Xiang Fu
xfu@whu.edu.cn

Yuni Xu
ynxu@whu.edu.cn

Xuefeng Chu
xuefeng.chu@ndsu.edu

1 State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China

2 Department of Civil and Environmental Engineering (Dept 2470), North Dakota State University, PO Box 6050, Fargo, ND 58108-6050, USA

1 Introduction

Hydropower is an important type of renewable energy that is provided through reservoir operations. Because hydropower demand is increasing, the current focus on reservoir operation is the best mechanism to improve hydropower generation. However, due to the changed flow condition of the hydrological system induced by reservoir operations, the habitats of organisms living in the river or its adjacent riparian areas, e.g., the spawning habitats of fish species, are potentially influenced (Yi et al. 2010). With limited water resources, conflicts between the flow requirements of hydropower generation and environmental protection occur (Cai et al. 2013). For sustainable river management, conflict resolution is critical to mitigate or avoid the environmental deterioration induced by hydropower demand.

Social choice methods (SCMs) are concerned with the interactions among stakeholders with conflicting preferences. By combining individual preferences into a collective decision in some sense, SCMs can provide effective strategies for conflicting situations (Arrow 1952). SCMs have been widely applied to conflict-resolution problems. Kangas et al. (2006) reviewed applications of the voting theory in sustainable forest management. Madani et al. (2014) combined the voting method and Monte-Carlo selection and applied it to water export conflict management in the Sacramento-San Joaquin Delta. Fraser and Hauge (1998) proposed a multicriteria approval method and demonstrated the feasibility of the proposed method in solving a multicriteria decision making problem with minimal information. Ghodsi et al. (b) presented a pairwise voting method for water quality-quantity conflict-resolution management in Iran. Alizadeh et al. (2017a) investigated the effectiveness of four SCMs for groundwater allocation in Iran and indicated that the four SCMs were applicable to resolve conflicts among stakeholders. Fuzzy social choice methods (FSCMs) are extensions of SCMs, which consider uncertainty in the decision behaviors of stakeholders (Nurmi 1981). García-Lapresta and Martínez-Panero (2002) incorporated fuzzy preference into the Borda counting method (BCM; Borda 1781) and the approval voting method (Brams and Fishburn 1978). Kacprzyk et al. (2008) used fuzzy preference to offset the difference between group decision-making and social choice, alleviating the voting paradoxes. Zarghami (2011) extended BCM by the ordered weighted averaging operator and demonstrated that the proposed method could be used to address human-based uncertainties. Alizadeh et al. (2017b) utilized four FSCMs to balance the groundwater supply and demands in Iran and determined the preferred FSCM by unanimity fallback bargaining based on stakeholders' preferences under different fuzzy levels.

Game-theoretical bargaining methods (GTBMs) are other effective tools to resolve conflicts among stakeholders who prefer their own utilities. Through bargaining based on game theory, the socio-optimal strategies accepted by all stakeholders are determined. GTBMs have been widely used in conflict resolution for water resources management. Shirangi et al. (2008) introduced the Young theory (Young 1993) for conflict resolution related to the quality and quantity of water allocation. Kerachian et al. (2010) coupled fuzzy sets with Rubinstein bargaining theory (Rubinstein 1982) to address the uncertainties of stakeholder behaviors in surface and groundwater conflict-resolution management. Ghodsi et al. (2016a) extended a noncooperative bargaining model from the modeling method proposed by Carraro and Sgobbi (2008) and utilized it to identify the socio-optimal strategy from several urban runoff management strategies. Brams and Kilgour (2001) modified fallback bargaining by introducing an "impasse", which sets a limit on stakeholders' preference rankings. Due to this limit, stakeholders were inclined to disagree with any lower-ranking options. Raei et al. (2017) applied fallback bargaining with impasse to identify a socio-optimal strategy supported by the departments of energy, environment, and disaster management for groundwater contamination problems. Xu et al. (2018) incorporated the Stackelberg theory into the operation of multi-reservoir system to balance hydropower needs between upstream and downstream reservoirs.

Although FSCMs and GTBMs have been widely used for conflict-resolution problems, the rules of strategy selection, which are generally obtained from long-term experiments, for both methods have not been investigated. For hydro-environmental conflict-resolution problems, climate change impacts on the hydrographic basin can influence strategy selections of conflict-resolution methods, resulting in different selection rules for historical and future periods. Therefore, it is necessary to quantify the impacts of climate change on the strategy-selection rules of FSCMs and GTBMs for better long-term strategic decision-making. In this study, the upstream of the Yangtze River (YR) in China was selected as the study area. As a world-class hydropower project, the Three Gorges Dam (TGD) is located in the study area. For more hydropower generation, water is stored to elevate the water level of TGD as high as possible. Due to reservoir operation, however, the natural physical and ecological features of the upstream of the YR have been changed, which has induced many environmental problems (Yi et al. 2010; Cai et al. 2013). This study focuses on resolving the conflicts between hydropower generation and environmental protection and providing guidelines for future decision-making. The specific objectives are to (1) investigate the strategy-selection rules of FSCMs and GTBMs for the hydro-environmental conflict-resolution problems and (2) quantify the difference of such rules between historical and future periods.

To achieve both objectives, the climate model, hydrological model, environmental model, multi-objective optimization model, and conflict-resolution methods are utilized in this study. In the remainder of the paper, these models and methods, as well as the study area are described in detail in Section 2. Then, the results and discussion are provided in Section 3. Finally, the conclusions are presented in Section 4.

2 Materials and Methods

The methodological flowchart for this study is shown in Fig. 1. The methodology includes five main components: (1) climate model to simulate future climate scenarios, (2) hydrological model to predict future streamflow process, (3) environmental flow model to define environmental flow, (4) multi-objective optimization model to optimize the reservoir operation considering hydropower generation (HG) and environmental protection (EP), and (5) conflict-resolution methods to select the socio-optimal strategies from the non-dominated strategies. Each component is described in the following sections.

2.1 Study Area

The YR originates from the main peak of the Tanggula Mountain on the Qinghai-Tibetan Plateau, China. As the longest river in Asia, the YR has a length of 6397 km. Due to the abundance of water energy resources, a series of hydropower projects has been constructed in the YR basin to satisfy society's needs, such as hydropower generation and flood control (Fu et al. 2014). As the world-class hydropower project, TGD is located on the YR basin (shown in Fig. 2). The construction of TGD was completed in 2003, and it started testing operations in the same year. The catchment area of TGD is approximately 1.0 million km^2, accounting for 55.5% of the entire YR basin. As the world's largest capacity hydropower station, the total storage and

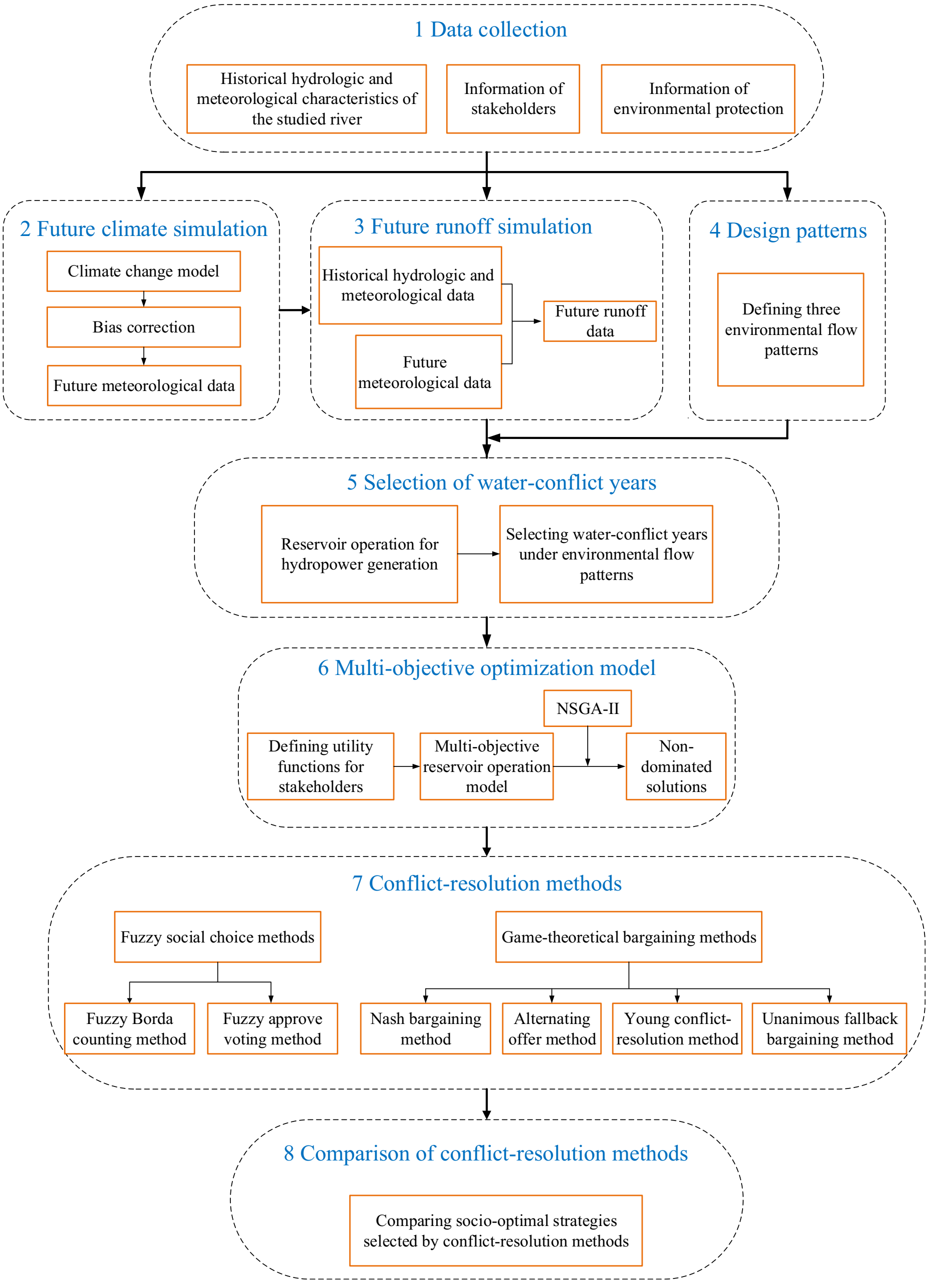

Fig. 1 Methodological flowchart for this study

installed capacity of TGD are 393 billion m^3 and 22,500 MW, respectively. The power output coefficient of TGD is 8.8. According to the current operation rules of TGD, the water level is controlled at 145 m (flood limited water level) in flood seasons (June 1 to September 31). In October, the water level of TGD is increased to 175 m (normal pool water level). Considering the navigation requirement, the minimum release from TGD is set to 5000 m^3/s.

The observed daily streamflow time series from 1950 to 2012, acquired from the Yichang hydrological station, were regarded as the inflow to TGD. Because the testing operation of TGD started in 2003, the natural streamflow conditions of the river have been altered since 2003. To eliminate the impacts of the TGD operation on the hydrologic processes, the observed daily streamflow data after 2003 were modified using a simple water balance method (Li et al. 2013).

The observed daily precipitation and maximum and minimum temperature data from 1950 to 2012 at 92 meteorological stations (shown in Fig. 2) were acquired from the National Meteorological Information Center (http://data.cma.cn/). The daily precipitation and maximum and minimum temperature data simulated by BCC-CSM1.1 were obtained from the database of the Coupled Model Intercomparison Project Phase 5 for the 1970 - 1999 period (past) and the 2021 - 2080 period (future).

2.2 Climate Model

General circulation models (GCMs) are important tools to simulate atmospheric processes and predict future climate conditions. As one of the GCMs, the Beijing Climate Center Climate System Model (BCC-CSM) has been widely used in China (Xin et al. 2013; Hao et al. 2016; Yang et al. 2016). In this study, the BCC-CSM1.1 is selected to predict the future meteorological data. The BCC-CSM1.1 simulation is under a greenhouse gas emissions scenario of the representative concentrations pathway (RCP) 4.5 with a horizontal resolution of 2.8 × 2.8 (Wu et al. 2010). The BCC-CSM1.1 outputs include daily precipitation and maximum and minimum temperature data. The gridded meteorological data within and surrounding the study area are averaged to a single time series using the Thiessen polygon method.

Due to their coarse resolution and systematic bias, the BCC-CSM1.1 outputs cannot be used as direct inputs for a hydrologic model. Quantile mapping (QM) has

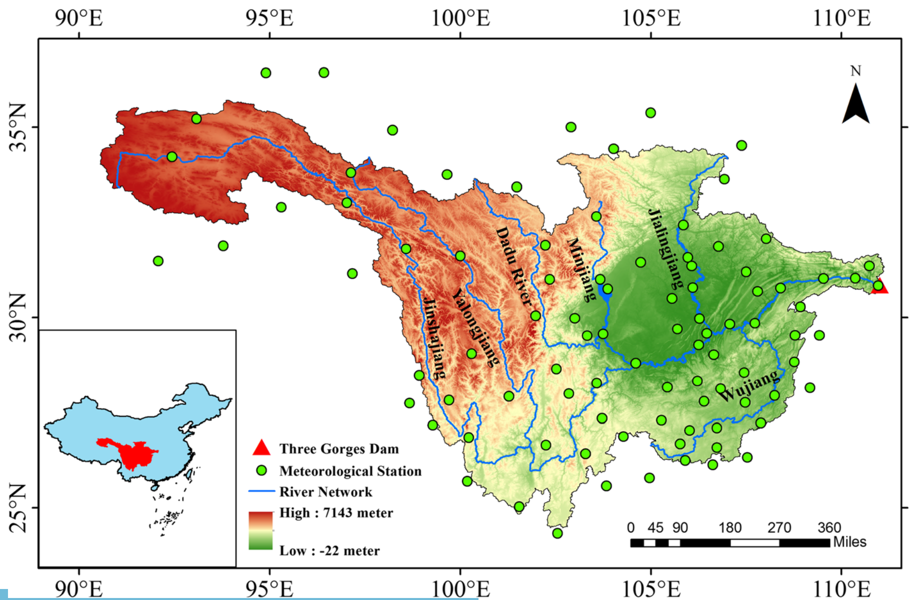

Fig. 2 Locations of the upstream of Yangtze River and the meteorological stations (Notes: the geographic coordinate system is WGS1984; and the datum is D_WGS_1984)

been used to downscale GCM simulations (Camici et al. 2013; Sangelantoni et al. 2018). QM targets mapping the GCM cumulative distribution function (CDF) based on the difference between the simulated and observed CDF in the historical period. Through the distribution correction for all variables in the GCM outputs, the systematic bias can be eliminated. In this study, QM is selected to downscale the BCC-CSM1.1 outputs. To evaluate the performance of QM, the relative errors (RE) between the observed and downscaled datasets are calculated.

2.3 Hydrological Model

Future daily precipitation and maximum and minimum temperature data are summed (for precipitation) or averaged (for temperature) to obtain monthly values. The monthly meteorological data are used as the input for the hydrological model to predict the hydrological processes for the study area. Xiong and Guo (1999) proposed the two-parameter monthly water balance (TPMWB) model that is a lumped hydrological model, and demonstrated that it can be effectively applied to the humid and semi-humid regions of China. In this study, the TPMWB model is applied for future streamflow simulation in the YR basin, based on the interrelation among monthly precipitation, evapotranspiration and streamflow. To evaluate its performance, the Nash-Sutcliffe efficiency (NSE) coefficient and RE between the observed and simulated series are calculated.

2.4 Environmental Flow Model

Environmental flow (EF) is necessary to maintain the functionality of a riverine ecosystem. The basic flow method (BFM; Palau 1994) is an effective method for determining EF based on hydrological series (daily mean flows). Instead of a unique minimum flow value, the BFM provides a flow regime, including the basic flow (BF) and maintenance basic flow (MBF), to indicate the variability and magnitude of EF at a temporal scale. In addition, the appropriate environmental flow (AEF) is proposed in this study to satisfy the flow demands of specific species living in the upstream of the YR.

2.4.1 Base Flow

BF indicates the minimum channel flow that is usually from groundwater. To obtain BF, the irregularities of daily streamflow series are analyzed by the BFM based on moving averages (Alcázar and Palau 2010; Palau and Alcázar 2012). Because the analysis is influenced by the number of low-flow periods, the daily streamflow series should start from the beginning of a month that does not include the minimum monthly average flow and the minimum annual daily flow (see Eqs. (1)-(5) in Appendix).

2.4.2 Maintenance Basic Flow

MBF is the minimum flow that maintains the natural conditions of a river. MBF can be calculated using the BFM on a monthly scale (Alcázar and Palau 2010; Palau and Alcázar 2012). The calculated MBF is used to describe the temporal variability of BF. Compared to BF, MBF can better reflect the natural conditions of the river ecosystem (see Eq. (6) in Appendix).

2.4.3 Appropriate Environmental Flow

Due to the construction of TGD, the spawning route of fish in the upstream of the YR has been obstructed. Thus, the spawning of fish is negatively impacted, and the population of fish has decreased (Zhang et al. 2012; Hu et al. 2015). To maintain the species diversity of a river, the flow demands of the fishes living in the river need to be considered.

In this study, four major commercial fishes and one endangered fish (Acipenser sinensis) are regarded as the representation of the fish living in the YR (Yi et al. 2010). The relevant information about the spawn time and flow requirements of the representative fish was gathered by Wang et al. (2013). Moreover, due to saline water intrusion caused by the impoundment of TGD, the survival of the fish living in the river is threatened by high concentrations of sodium chloride. To relieve this threat for the representative fish, the minimum flow requirement is considered to control salinity (Wang et al. 2013).

AEF is proposed considering the ecological requirements, which is more amenable to the representative fish than BF and MBF. Based on the modifications of MBF, AEF can be described as follows:

$$Q_i^* = \begin{cases} \underline{Q_i} & Q_i \le \underline{Q_i} \\ Q_i & \underline{Q_i} \le Q_i \le \overline{Q_i} \\ \overline{Q_i} & Q_i \ge \overline{Q_i} \end{cases} \tag{1}$$

where Q_i^* is the AEF in month i; Q_i is the MBF in month i; and $\underline{Q_i}$ and $\overline{Q_i}$ are the minimum and maximum flow requirements, respectively, for the species living in the river.

2.5 Multi-Objective Optimization Model

2.5.1 Definition of Water-Conflict Years

In this study, the water-conflict year is defined based on the water supply capability of the upstream of the YR in each operation year. To assess whether the streamflow is sufficient to satisfy HG and EP simultaneously, a reservoir operation model for optimizing HG is developed (see Eqs. (7)-(12) in Appendix). Without considering the EF demands, HG is maximized for each operation year. If BF (MBF/AEF) can be satisfied by the reservoir releases, then there is no conflict between HG and EP in the year, and the year is defined as a water-free year. Otherwise, the year is defined as a water-conflict year.

2.5.2 Objective Functions and Constraints

The multi-objective optimization model focuses on maximizing the hydropower benefits and minimizing the water deficit in maintaining the EF demands, and provides non-dominated strategies for the two objectives in water-conflict years. The hydropower and environmental objectives in this model are formulated as:

$$u_1 = \max \sum_{t=1}^{12} N_t \times \Delta t \qquad t = 1, 2, \ldots, 12 \tag{2}$$

$$u_2 = \min\left\{ \sum_{t=1}^{12} \left[\max(0, Q_t - R_t) \times \Delta t\right] \right\} \qquad t = 1, 2, \ldots, 12 \tag{3}$$

The relevant constraints are expressed as follows:

$$V_{t+1} = V_t + (I_t - R_t) \times \Delta t \quad t = 1, 2, \ldots, 12 \tag{4}$$

$$V_t^{\min} \le V_t \le V_t^{\max} \quad t = 1, 2, \ldots, 12 \tag{5}$$

$$R_t^{\min} \le R_t \le R_t^{\max} \quad t = 1, 2, \ldots, 12 \tag{6}$$

$$N_t^{\min} \le N_t \le N_t^{\max} \quad t = 1, 2, \ldots, 12 \tag{7}$$

$$V_1 = V_{12} \tag{8}$$

where u_1 and u_2 are the maximum HG and the minimum water deficit in maintaining EF demands, respectively; Q_t is the EF at the tth period; V_t and V_{t+1} are the storages of TGD at the tth and $(t+1)$th periods; I_t is the inflow of TGD at the tth period; $V_t^{\min}$ and $V_t^{\max}$ are the minimum and maximum storages of TGD at the tth period; $R_t^{\min}$, $R_t^{\max}$, and R_t are the minimum, maximum, and actual average releases, respectively, from TGD at the tth period; $N_t^{\min}$, $N_t^{\max}$, and N_t denote the minimum, maximum, and actual average power outputs, respectively, of TGD at the tth period; and Δt is the time-step.

2.5.3 Multi-Objective Optimization Algorithm

The non-dominated sorting genetic algorithm (NSGA-II; Deb et al. 2002) has been applied to optimize multi-objective reservoir optimizations (Zhou et al. 2018). Different from other evolutionary algorithms, NSGA-II applies fast non-dominated sorting to reduce computational efforts and elitism crowded comparison to preserve the diversity of strategies. Through the optimization of the proposed multi-objective model by NSGA-II, the non-dominated strategies for HG and EP can be obtained in this study. The following parameter settings of NSGA-II are: population size = 100, iterations = 1500, mutation rate = 0.1, and crossover rate = 0.8.

2.6 Conflict-Resolution Methods

In this paper, two FSCMs and four GTBMs are used to select the socio-optimal strategies from the non-dominated strategies. FSCMs are based on the social choice theory, including the fuzzy Borda counting method (FBCM) and the fuzzy approval voting method (FAVM). GTBMs are based on the game theory, including the Nash bargaining method (NBM), alternating offer method (AOM), Young conflict-resolution method (YCRM), and unanimity fallback bargaining method (UFBM).

2.6.1 Fuzzy Borda Counting Method

In the FBCM (García-Lapresta and Martínez-Panero 2002), stakeholder preference degrees are represented by using fuzzy binary relations, which range from 0 to 1. Considering pairwise comparisons, stakeholders independently assign scores to each strategy to show how much they prefer one strategy to the others. For each strategy, the final score is equal to the summation of the assigned scores more than 0.5. The strategy with the highest score is the balanced strategy for all involved stakeholders (see Eqs. (13)-(15) in Appendix).

2.6.2 Fuzzy Approval Voting Method

The FAVM (García-Lapresta and Martínez-Panero 2002) is based on collective decision-making. Different from the FBCM, the socio-optimal strategy selected by the FAVM does not need pairwise comparisons. In the FAVM, all stakeholders assign fuzzy preference scores to each strategy. For each strategy, the fuzzy preference scores given by all stakeholders are added to obtain the total fuzzy preference score. The strategy with the highest score is supported by all stakeholders (see Eqs. (16) and (17) in Appendix).

2.6.3 Nash Bargaining Method

The NBM (Nash 1953) describes a 2-player bargaining game over sharing a resource based on cooperative game theory. The NBM introduced disagreement points to the conflict-resolution process. For each strategy, the differences between the utility values of objectives and their disagreement points are identified and then multiplied. The strategy with the maximum product is regarded as the most preferred strategy by both stakeholders (see Eqs. (18)-(20) in Appendix).

2.6.4 Alternating Offer Method

In the AOM (Carraro and Sgobbi 2008), stakeholders propose their best strategy according to their own preference in the first round of bargaining. Then, for each proposed strategy, the values of the utility functions of all stakeholders are calculated. Next, the excepted utility value, which is regarded as the constraint for the second round of bargaining, of each stakeholder is obtained based on all proposed strategies. In the second round, the suboptimal strategy of each stakeholder that maximizes the utility value to the stakeholder and yields a utility value for the other stakeholder that is at least equal to the other stakeholder's expected value is provided. This process is continued until the convergence criterion is satisfied (see Eq. (21) in Appendix).

2.6.5 Young Conflict-Resolution Method

The YCRM (Young 1993) is a 2-player bargaining method, in which partial experience with previous bargaining is owned by each stakeholder. According to the previous experience, stakeholders propose strategies that maximize their utility values. Two assumptions should be considered in the YCRM: first, all strategies are absolutely homogeneous; second, the utility functions of stakeholders are weakly concave and strictly increasing. By normalizing the utility values between 0 and 1 to eliminate the limitation brought by different utility units, the YCRM can be practically applied in real-world confliction-resolution problems (see Eqs. (22)-(24) in Appendix).

2.6.6 Unanimity Fallback Bargaining Method

In the UFBM (Brams and Kilgour 2001), all strategies are ranked in descending order by each stakeholder according to the preference of the stakeholder. In the first round, each stakeholder proposes the best strategy according to its utility value. If the proposed strategies are the same, then an agreement for all stakeholders is reached, and the bargaining stops at a depth of 1.

Otherwise, each stakeholder proposes a suboptimal strategy in the second round. For all proposed strategies in the two rounds, if one or several strategies can be accepted by all stakeholders, agreement is reached, and the bargaining stops at a depth of 2. Otherwise, the bargaining is continued until the compromise set is first non-empty (see Eqs. (25) and (26) in Appendix).

2.7 Evaluation Criteria

In this study, the satisfied degree (SD) is proposed to evaluate stakeholder satisfaction with the socio-optimal strategy selected from the non-dominated strategies. SD is defined as follows:

$$SD_{1,i} = \frac{u_{1,i} - u_{1,i}^{\min}}{u_{1,i}^{\max} - u_{1,i}^{\min}} \quad i = 1, 2, \ldots, n \tag{9}$$

$$SD_{2,i} = 1 - \frac{u_{2,i} - u_{2,i}^{\min}}{u_{2,i}^{\max} - u_{2,i}^{\min}} \quad i = 1, 2, \ldots, n \tag{10}$$

where $u_{1,i}$ and $u_{2,i}$ are the HG and water deficit, respectively, according to the selected strategy in water-conflict year i; n is the number of water-conflict years; $u_{1,i}^{\min}$ and $u_{1,i}^{\max}$ are the minimum and maximum HG according to the non-dominated strategies in water-conflict year i; and $u_{2,i}^{\min}$ and $u_{2,i}^{\max}$ are the minimum and maximum water deficit according to the non-dominated strategies in water-conflict year i.

The stabilities of the strategy-selection rules of conflict-resolution methods are reflected by the standard deviations of SD (SSD) of different stakeholders:

$$SSD_1 = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(SD_{1,i} - \overline{SD_1} \right)^2} \quad i = 1, 2, \ldots, n \tag{11}$$

$$SSD_2 = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(SD_{2,i} - \overline{SD_2} \right)^2} \quad i = 1, 2, \ldots, n \tag{12}$$

where SSD_1 and SSD_2 are the standard deviations of HG' and EP' SD values, respectively; $\overline{SD_1}$ and $\overline{SD_2}$ are the averages of $SD_{1,i}$ and $SD_{2,i}$, respectively.

3 Results and Discussion

3.1 Climate Input

To downscale the daily meteorological data predicted by BCC-CSM1.1, QM was calibrated over the 1970-1999 period. The RE values for daily precipitation, maximum temperature, and minimum temperature are 0.0011, 0.0003, and 0.0006, respectively, which demonstrates that QM is effective for downscaling the BCC-CSM1.1 outputs. The observed meteorological data (1950-2012) and the predicted meteorological data (2021-2080) that have been downscaled by QM are summed (for precipitation) or averaged (for temperature) to obtain monthly values. Figure 3a–c show the monthly average precipitation and minimum and maximum temperature

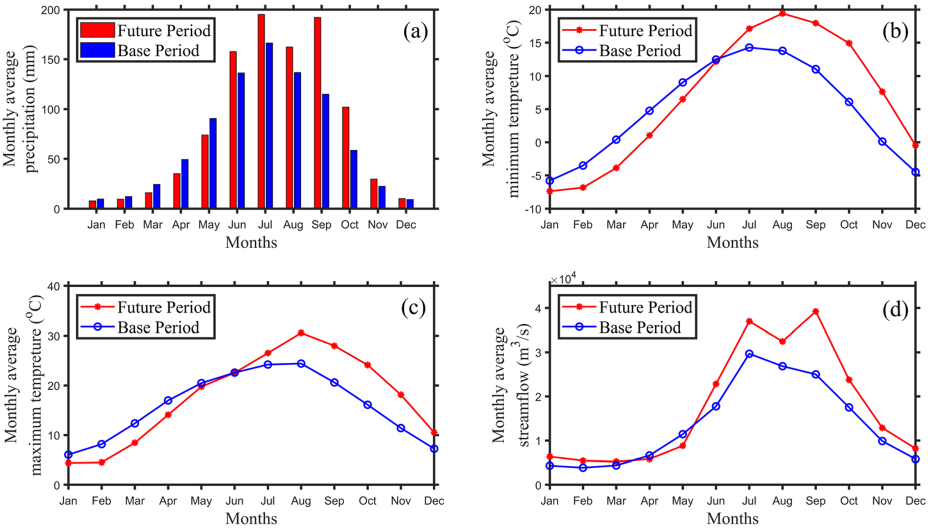

Fig. 3 Comparison of the monthly meteorological data and streamflow in the base and future periods: **a** monthly average precipitation; **b** monthly average minimum temperature; **c** monthly average maximum temperature; **d** monthly average streamflow

data in the base and future periods. Figure 3a indicates that the monthly average precipitation moderately decreased from January to May and increased in the other months for the future period, compared to that in the base period. Figure 3b and c show a similar changing trend of the monthly minimum and maximum temperatures in the future period.

The observed and predicted monthly meteorological data and the observed monthly streamflow data were used as the inputs of the TPMWB model to predict the future monthly streamflow. In this study, TPMWB was calibrated over the 1961-1980 period and validated over the 1981-2000 period. The NSE value for the calibration period is 0.91, and that for the validation period is 0.93. The RE values for both periods are 0.01. These results indicate that the TPMWB model is effective for streamflow prediction. Figure 3d shows the comparison of the inflows to TGD in the base (1950-2012) and future periods (2021-2080). It is observed that the future inflow (2021-2080) to TGD increased during the dry seasons compared to that in the base period, which would mitigate the conflicts between HG and EP in the dry seasons. Overall, the TGD would be more likely to utilize the potential of its comprehensive benefits for the future period.

3.2 Impacts of Climate Change on Conflict Resolution

The BF, MBF and AEF for EP are presented in Table 1. Figure 4 shows the results of the selection for water-conflict years for the base period (1950-2012) and future period (2021-2080) under the BF, MBF, and AEF patterns. In Fig. 4, each point indicates the water deficit in maintaining the EF demands when the HG is maximized for a certain year. The water-free years and the water-conflict years are indicated by the blue and red points, respectively. Compared to the base period, in the future period, due to the increased inflow in the dry seasons, the water deficit in maintaining the EF demands is decreased. It can be observed that there is no conflict between HG and EP under the BF pattern for the future period. Based on the statistics of the red points, the number of water-conflict years for the base period are 23, 47, and 62 under the BF, MEF and AEF patterns, respectively, while those for the future period are 19 and 59 under the MBF and AEF patterns, respectively.

Table 1 The BF, MBF, and AEF for the upstream of the Yangtze River

Month	EF Patterns			Month	EF Patterns		
	BF(m^3/s)	MBF(m^3/s)	AEF(m^3/s)		BF(m^3/s)	MBF(m^3/s)	AEF(m^3/s)
Jan	3573.07	4259.75	5500	Jul	3573.07	11,093.95	11,093.95
Feb	3573.07	4030.91	5500	Aug	3573.07	10,596.88	10,596.88
Mar	3573.07	4292.87	5500	Sep	3573.07	10,213.75	10,213.75
Apr	3573.07	5265.69	11,000	Oct	3573.07	8553.43	12,000
May	3573.07	6909.02	11,000	Nov	3573.07	6432.6	12,000
Jun	3573.07	8620.65	11,000	Dec	3573.07	4927.42	5500

EF environmental flow, *BF* base flow, *MBF* maintenance basic flow, and *AEF* appropriate environmental flow

The multi-objective optimization model was applied to the water-conflict years, and the non-dominated strategies for each water-conflict year are shown in Fig. 5. The six conflict-resolution methods were applied to select the balanced strategies from the non-dominated strategies. Unlike the FBCM, FAVM, NBM, and YCRM, the number of selected strategies in the water-conflict year using the AOM or UFBM could be more than one. Because the strategies selected by the hydropower and environmental stakeholders were similar (see Fig. 1 in Appendix), the SD values of HG and EP obtained by the AOM (or UFBM) were regarded as the mean values of the corresponding SD values related to both selected strategies.

Figure 6 shows the box plots of the SD values of HG and EP related to the selected strategies using the six conflict-resolution methods for the base and future periods under different EF patterns. As the EF demands increase, the ranges of HG' and EP' SD values obtained by the FBCM and FAVM are significantly narrowed, while those obtained by the NBM, AOM, YCRM, and UFBM remain within a small scale. It is indicated that the stabilities of the strategy selections of two FSCMs are sensitive to EF demands, while those of the four

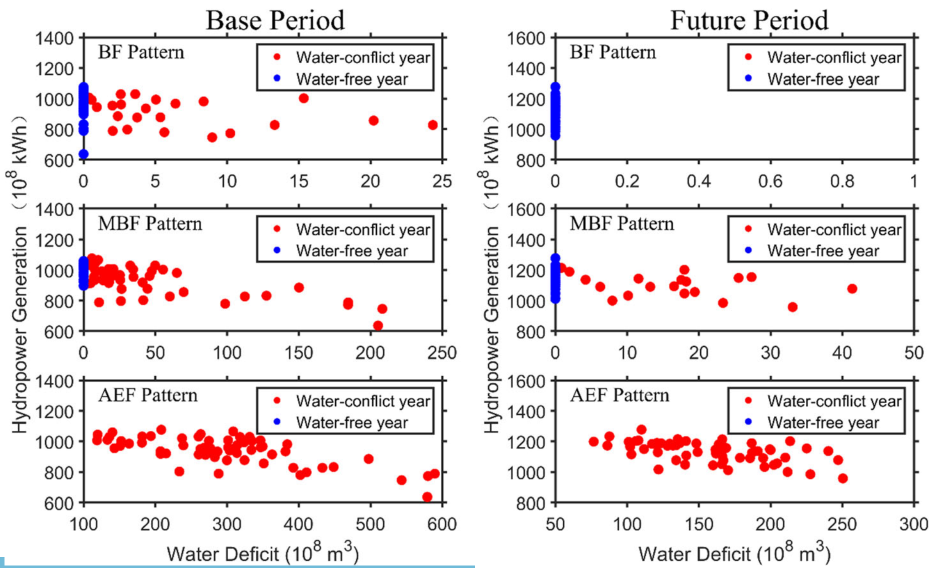

Fig. 4 Water-conflict years selected from the base period (1950-2012) and future period (2021-2080) under three EF patterns

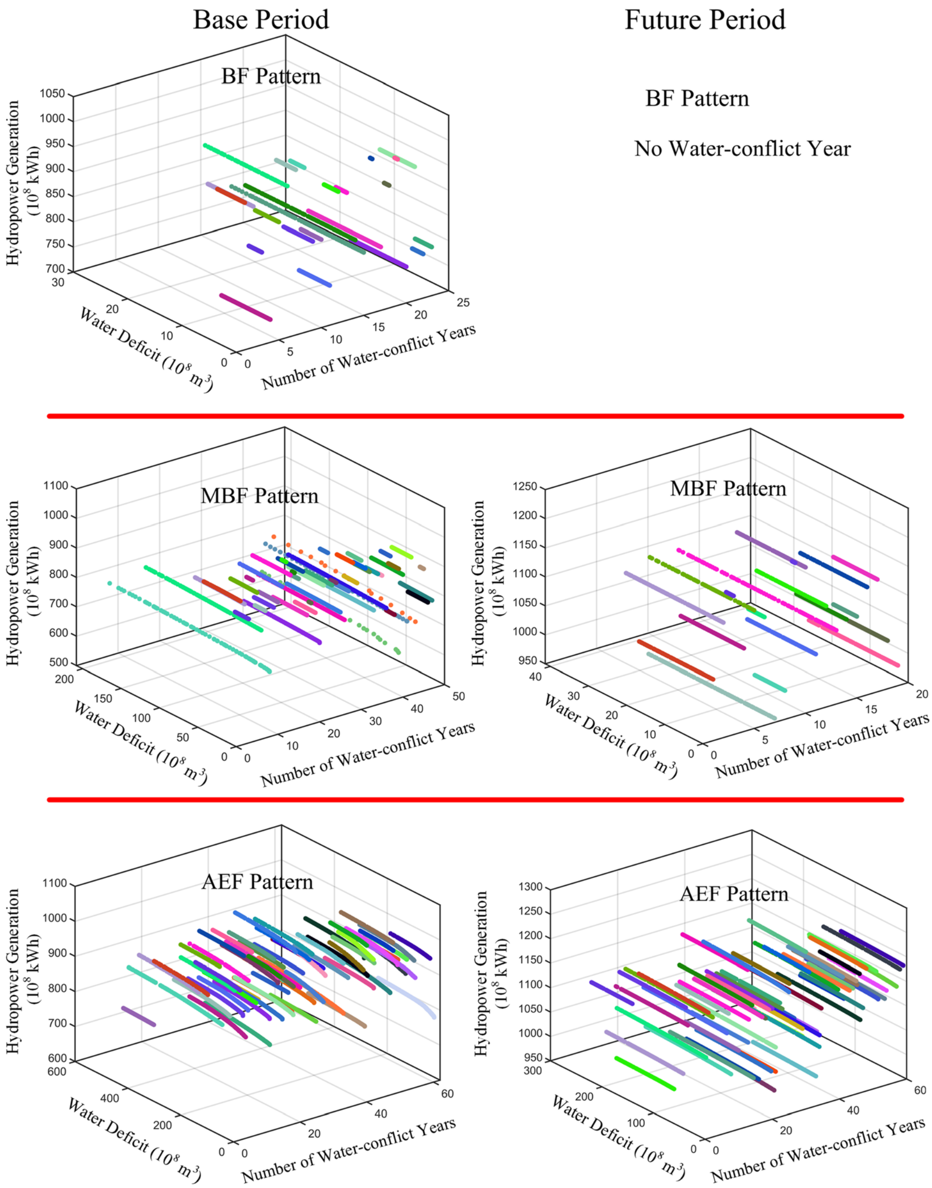

Fig. 5 The non-dominated solutions for each water-conflict year under BF, MBF and AEF patterns in the base and future periods (different colors indicate different water-conflict years)

GTBMs are relatively insensitive to EF demands. Moreover, it is observed that the NBM, AOM, YCRM, and UFBM provide smaller ranges of HG' and EP' SD values than those of the FBCM and FAVM in the base and future periods. It is indicated that the strategy selections of the four GTBMs are more stable than those of the two FSCMs. As shown in Table 2, compared to the base period under the AEF pattern, in the future period, the SSD of both objectives obtained by the FAVM, NBM, AOM, YCRM and UFBM would be slightly reduced, while those provided by the FBCM would be increased by 0.08 and 0.09.

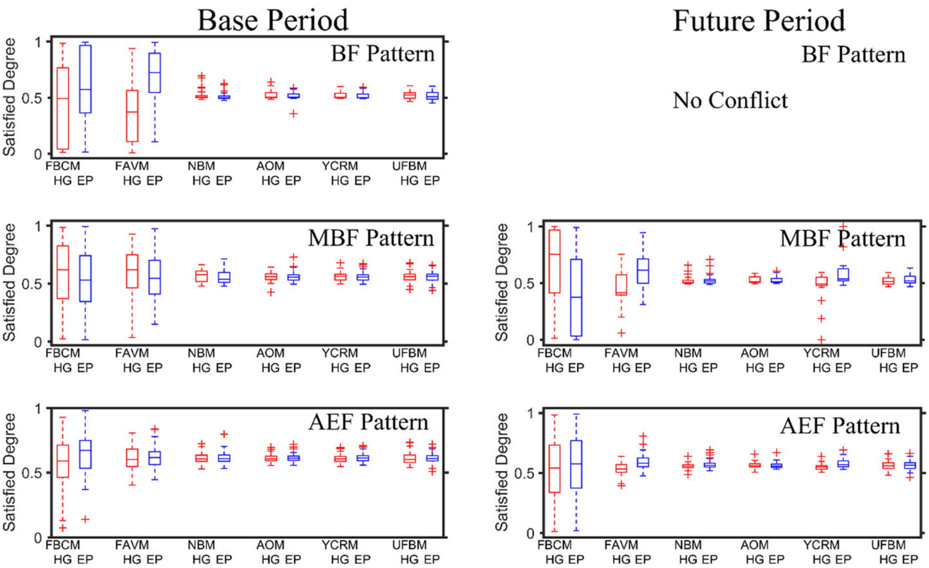

Fig. 6 Box plots of the SD values of HG and EP according to the selected strategies using six conflict-resolution methods for the base and future periods under different EF patterns

Table 2 also shows the annual average SD values of HG and EP obtained by six conflict-resolution methods under different EF patterns for the base and future periods. It is observed that the difference between the average SD values of HG and EP obtained by two FSCMs is more apparent than those obtained by four GTBMs. It is indicated that the FBCM and FAVM tend to select a strategy with apparent preference, while the NBM, AOM, YCRM, and UFBM tend to select a strategy that strikes a balance between both objectives. Considering climate change, under the MBF pattern, the application of the FBCM with the cost of reducing the average SD value of EP by 0.14 could improve the average SD value of HG by 0.06, while the applications of the FAVM and

Table 2 The results of strategy-selection using six conflict-resolution methods in the water-conflict years for the base and future periods

Periods	Pattens	FBCM		FAVM		NBM		AOM		YCRM		UFBM	
		HG	EP	HG	EP	HG	EP	HG	EP	HG	EP	HG	EP
Base period	Average_BF	0.45	0.60	0.37	0.68	0.53	0.52	0.53	0.52	0.52	0.52	0.52	0.52
	SSD_BF	*0.37*	*0.36*	*0.28*	*0.25*	*0.06*	*0.04*	*0.04*	*0.04*	*0.03*	*0.03*	*0.04*	*0.05*
	Average_MBF	0.58	0.54	0.59	0.54	0.57	0.56	0.56	0.56	0.56	0.56	0.56	0.56
	SSD_MBF	*0.29*	*0.28*	*0.22*	*0.21*	*0.06*	*0.06*	*0.04*	*0.04*	*0.04*	*0.04*	*0.04*	*0.05*
	Average_AEF	0.56	0.65	0.61	0.62	0.61	0.62	0.61	0.61	0.61	0.61	0.61	0.61
	SSD_AEF	*0.18*	*0.18*	*0.09*	*0.08*	*0.04*	*0.04*	*0.03*	*0.03*	*0.03*	*0.03*	*0.04*	*0.04*
Future period	Average_MBF	0.64	0.40	0.45	0.61	0.52	0.54	0.53	0.53	0.47	0.59	0.52	0.53
	SSD_MBF	*0.36*	*0.38*	*0.18*	*0.16*	*0.04*	*0.06*	*0.03*	*0.03*	*0.15*	*0.13*	*0.04*	*0.04*
	Average_AEF	0.53	0.57	0.54	0.59	0.56	0.57	0.56	0.56	0.55	0.58	0.56	0.56
	SSD_AEF	*0.27*	*0.27*	*0.05*	*0.06*	*0.02*	*0.03*	*0.02*	*0.02*	*0.02*	*0.03*	*0.03*	*0.03*

FBCM fuzzy Borda counting method, *FAVM* fuzzy approval voting method, *NBM* Nash bargaining method, *AOM* alternating offer method, *YCRM* Young conflict-resolution method, *UFBM* unanimity fallback bargaining method, *HG* hydropower generation, *EP* environmental protection; Average_BF, Average_MBF, and Average_AEF = the annual average satisfied degree of objective obtained by conflict-resolution method under BF, MBF and AEF patterns; SSD_BF, SSD_MBF, and SSD_AEF = the stability of the strategy-selection rule of conflict-resolution method under BF, MBF and AEF patterns

YCRM with the cost of reducing the average SD values of HG by 0.14 and 0.09, respectively, could improve the average SD values of EP by 0.07 and 0.03, respectively. In addition, compared to the base period, in the future period, the applications of the NBM, AOM, and UFBM under the MBF pattern and the applications of the six conflict-resolution methods under the AEF pattern would result in a decrease in the average SD values of HG and EP.

4 Conclusions

This study aims to quantify the impacts of climate change on the strategy-selection rules of conflict-resolution methods for hydro-environmental management. The major conclusions can be summarized as follows:

(1) The performances of the four GTBMs in terms of strategy selection were more stable than those of the two FSCMs. In addition, the two FSCMs tended to resolve the conflicts between hydropower generation and environmental protection with apparent preferences, while the four GTBMs showed a good balance between the two objectives.
(2) Considering climate change, under AEF pattern, the stabilities of the FAVM, NBM, AOM, YCRM and UFBM in terms of strategy selection slightly increased, while the stability of the FBCM reduced. Moreover, the average SD values of both objectives obtained by the six conflict-resolution methods in the future period were lower than those in the base period.

Although the conclusions are drawn from the case study of the upstream of the YR of China, the methodology of this study is objective and rational. Therefore, the findings from this study can be used to improve hydro-environmental management of other hydropower projects. As demonstrated in this study, appropriate conflict-resolution methods can be selected for the future period to balance the conflicting benefits of the involved stakeholders. Moreover, the socio-optimal strategies selected by the conflict-resolution methods and the satisfied degrees of the involved stakeholders according to the selected strategies can be predicted for a future period, which contributes to long-term strategic decision-making. Future studies should focus on a comprehensive hydro-environmental modeling with a consideration of water quality and other environmental and ecohydrological variables.

Acknowledgments This study was supported by the National Key Research and Development Program (No. 2016YFC0401306) and National Natural Science Foundation of China (No. 91647204).

Compliance with Ethical Standards

Conflict of Interest None.

References

Alcázar J, Palau A (2010) Establishing environmental flow regimes in a Mediterranean watershed based on a regional classification. J Hydrol 388(1):41–51

Alizadeh MR, Nikoo MR, Rakhshandehroo GR (2017a) Developing a multi-objective conflict-resolution model for optimal groundwater management based on fallback bargaining models and social choice rules: a case study. Water Resour Manag 31(5):1457–1472
Alizadeh MR, Nikoo MR, Rakhshandehroo GR (2017b) Hydro-environmental management of groundwater resources: a fuzzy-based multi-objective compromise approach. J Hydrol 551:540–554
Arrow KJ (1952) Social choice and individual values. J Polit Econ 60(5):422–432
Borda JCD (1781) Memoire sur les elections au Scrutin. Histoire de I'Academie Royale des Sciences, Paris
Brams SJ, Fishburn PC (1978) Approval voting. Am Polit Sci Rev 72(3):831–847
Brams SJ, Kilgour DM (2001) Fallback bargaining. Group Decis Negot 10(4):287–316
Cai W, Zhang L, Zhu X et al (2013) Optimized reservoir operation to balance human and environmental requirements: a case study for the Three Gorges and Gezhouba dams, Yangtze River basin, China. Ecol Inform 18(9):40–48
Camici S, Brocca L, Melone F et al (2013) Impact of climate change on flood frequency using different climate models and downscaling approaches. J Hydrol Eng 19(8):04014002
Carraro C, Sgobbi A (2008) Modelling negotiated decision making in environmental and natural resource management: a multilateral, multiple issues, non-cooperative bargaining model with uncertainty. Automatica 44(6):1488–1503
Deb K, Pratap A, Agarwal S et al (2002) A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans Evol Comput 6(2):182–197
Fraser NM, Hauge JW (1998) Multicriteria approval: application of approval voting concepts to MCDM problems. J Multi-Criteria Decis Anal 7(5):263–273
Fu X, Li AQ, Wang H (2014) Allocation of flood control capacity for a multireservoir system located at the Yangtze River basin. Water Resour Manag 28(13):4823–4834
García-Lapresta JL, Martínez-Panero M (2002) Borda count versus, approval voting: a fuzzy approach. Public Choice 112(1-2):167–184
Ghodsi SH, Kerachian R, Estalaki SM et al (2016a) Developing a stochastic conflict resolution model for urban runoff quality management: application of info-gap and bargaining theories. J Hydrol 533:200–212
Ghodsi SH, Kerachian R, Zahmatkesh Z (2016b) A multi-stakeholder framework for urban runoff quality management: application of social choice and bargaining techniques. Sci Total Environ 550:574–585
Hao Y, Jiang Z, Li L et al (2016) Biases and improvements in an ensemble of dynamical downscaling climate simulations over China. Clim Dyn 47(9-10):1–17
Hu M, Hua Q, Zhou H et al (2015) The effect of dams on the larval abundance and composition of four carp species in key river systems in China. Environ Biol Fish 98(4):1201–1205
Kangas A , Laukkanen S , Kangas J (2006) Social choice theory and its applications in sustainable forest management—a review. For Policy Econ 9(1):77-92.
Kacprzyk J, Zadrożny S, Fedrizzi M et al (2008) On group decision making, consensus reaching, voting and voting paradoxes under fuzzy preferences and a fuzzy majority: a survey and some perspectives. In: Studies in fuzziness and soft computing. Springer Berlin 220, pp 263–295
Kerachian R, Fallahnia M, Bazargan-Lari MR et al (2010) A fuzzy game theoretic approach for groundwater resources management: application of Rubinstein bargaining theory. Resour Conserv Recycl 54(10):673–682
Li S, Xiong L, Dong L et al (2013) Effects of the Three Gorges reservoir on the hydrological droughts at the downstream Yichang station during 2003–2011. Hydrol Process 27(26):3981–3993
Madani K, Read L, Shalikarian L (2014) Voting under uncertainty: a stochastic framework for analyzing group decision making problems. Water Resour Manag 28(7):1839–1856
Nash J (1953) Two person cooperative games. Econometrica 21(1):128–140
Nurmi H (1981) Approaches to collective decision making with fuzzy preference relations. Fuzzy Sets Syst 6(3): 249–259
Palau A, Alcázar J (2012) The basic flow method for incorporating flow variability in environmental flows. River Res Appl 28(1):93–102
Raei E, Nikoo MR, Pourshahabi S (2017) A multi-objective simulation-optimization model for in-situ bioremediation of groundwater contamination: application of bargaining theory. J Hydrol 551:407–422
Rubinstein A (1982) Perfect equilibrium in a bargain model. Econometrica 50(1):91-109
Sangelantoni L, Russo A, Gennaretti F (2018) Impact of bias correction and downscaling through quantile mapping on simulated climate change signal: a case study over Central Italy. Theor Appl Climatol 5:1–16
Shirangi E, Kerachian R, Bajestan MS (2008) A simplified model for reservoir operation considering the water quality issues: application of the Young conflict resolution theory. Environ Monit Assess 146:77–89
Wang XM, Zhou JZ, Ouyang S et al (2013) TGC eco-friendly generation multi-objective optimal dispatch model and its solution algorithm. J Hydraul Eng 44(2):154–163 (in Chinese)
Wu T et al (2010) The Beijing climate center atmospheric general circulation model: description and its performance for the present-day climate. Clim Dyn 1(123):34

Xin X, Zhang L, Zhang J et al (2013) Climate change projections over East Asia with BCC_CSM1.1, climate model under RCP scenarios. J Meteorol Soc Jpn 91(4):413–429
Xiong L, Guo S (1999) A two-parameter monthly water balance model and its application. J Hydrol 216(1–2): 111–123
Xu Y, Fu X, Qin J (2018) Qualifying coordination mechanism for cascade-reservoir operation with a new game-theoretical methodology. Water 10(12):1857
Yang G, Guo S, Li L et al (2016) Multi-objective operating rules for Danjiangkou reservoir under climate change. Water Resour Manag 30(3):1183–1202
Yi YJ, Wang ZY, Yang ZF (2010) Impact of the Gezhouba and Three Gorges Dams on habitat suitability of carps in the Yangtze River. J Hydrol 387(3–4):283–291
Young HP (1993) An evolutionary model of bargaining. J Econ Theory 59(1):145–168
Zarghami M (2011) Soft computing of the Borda count by fuzzy linguistic quantifiers. Appl Soft Comput 11(1): 1067–1073
Zhang G, Wu L, Li H et al (2012) Preliminary evidence of delayed spawning and suppressed larval growth and condition of the major carps in the Yangtze River below the Three Gorges Dam. Environ Biol Fish 93(3): 439–447
Zhou Y, Guo S, Chang FJ et al (2018) Methodology that improves water utilization and hydropower generation without increasing flood risk in mega cascade reservoirs. Energy 143:785–796