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# LOGICAL GENETIC PROGRAMMING (LGP) DEVELOPMENT FOR IRRIGATION WATER SUPPLY HEDGING UNDER CLIMATE CHANGE CONDITIONS†

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## ABSTRACT

Traditional genetic programming (TGP) is herein enhanced by the addition of logical operators to form logical genetic programming (LGP). The LGP approach is applied to calculate hedging reservoir-operation rules for the Aidoghmoush single-purpose reservoir (north-eastern Iran) to supply irrigation water during a 14-year baseline operation period (1987–2000) and a climatically changed condition (2026–2039). The objective function of the hedging rule is to minimize the long-term shortage ratio (LSR). Our results show that the LGP-obtained hedging rule compares favourably with that obtained with the TGP approach, so that the former approach's objective function is 25 and 6% better than the latter's approach with the baseline and climate change conditions, respectively. The results obtained concerning the reliability, vulnerability and resiliency of water supply indicate that the LGP hedging operating rule decreases the water supply reliability by 34%, increases the vulnerability by 58%, and decreases the resiliency by 29% during climate change conditions compared with baseline conditions. 

KEY WORDS: genetic programming; hedging rule; reservoir operation; climate change

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## RÉSUMÉ

La programmation génétique traditionnelle (TGP) est ici améliorée par l'ajout d'opérateurs logiques pour former une programmation génétique logique (LGP). L'approche LGP est appliquée pour calculer les règles de couverture des réservoirs pour le réservoir à usage unique de Aidoghmoush (nord-est de l'Iran) pour fournir de l'eau d'irrigation pendant une période de fonctionnement de 14 ans (1987–2000) et sous contrainte de changement climatique (2026–2039). La fonction objective de la règle de couverture est de minimiser le ratio de pénurie à long terme (LSR). Nos résultats montrent que la règle de couverture obtenue par LGP se compare favorablement à celle obtenue avec l'approche TGP, soit 25 et 6% de mieux avec les conditions de référence et de changement climatique, respectivement. Les résultats obtenus concernant la fiabilité, la vulnérabilité et la résilience de l'approvisionnement en eau indiquent que la règle de fonctionnement de couverture LGP diminue de 34% la fiabilité de l'approvisionnement en eau, augmente la vulnérabilité de 58% et diminue la résilience de 29% dans les conditions de changement climatique par rapport aux conditions de base. 

MOTS CLÉS: programmation génétique; règle de couverture; fonctionnement d'un réservoir; changement climatique

## INTRODUCTION

Hedging rules for reservoir operation avoid severe water shortages by managing short-term water deficits. Several approaches have been reported in water resources concerning the calculation of hedging rules for reservoir operation with different modelling approaches. Sargent (1979) applied a dynamic programming method to determine a decision policy for reservoir release during drought conditions. Tu *et al.* (2003) developed a mixed integer linear programming (MILP) model that considered simultaneously traditional rule curves and hedging rules to manage and operate a multi-purpose, multi-reservoir system in Taiwan. Hsu *et al.* (2004) applied evolution algorithms

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†Développement de la programmation génétique logique (LGP) pour la couverture de l'approvisionnement en eau d'irrigation dans des conditions de changement climatique.

to optimize reservoir operation. Furthermore, the study detected the drought events by the prediction data and water resource system model, and optimized the double-group rule curves for the LiYuTan reservoir in Taiwan. The main objective of their paper was to devise a methodology for the rational selection of actions of the Contingency Plan in relation to long-term process measures (and not a hedging rule approach). Shiau and Lee (2005) calculated optimal hedging rules for simultaneously minimizing short- and long-term shortages in the Shihmen Reservoir in Taiwan. The results indicated that the suggested method effectively achieved the reservoir operation goal. Tu *et al*. (2008) employed hedging rules for a multi-reservoir system in southern Taiwan with a mixed-integer quadratic programming model. The results showed that the optimized new hedging rules improved the efficiency of reservoir operations of the water distribution system. You and Cai (2008) developed a conceptual two-period model for reservoir operation with hedging that explicitly includes uncertain future reservoir inflow. Karamouz *et al*. (2012) developed a contingency planning scheme for operation of reservoirs in drought periods using hedging rules with the objective of decreasing the maximum water deficit. The results indicated that the proposed methodology led to less water deficit in the study area. Taghian *et al*. (2014) reported a hybrid model to optimize simultaneously the conventional rule curve and the hedging rule. The compound model coupled a simple genetic algorithm (GA) 7 with a simulation program including a linear programming (LP) algorithm. The results indicated that the model had good performance in extracting the optimum policy for reservoir operation under normal and drought conditions. Spiliotis *et al*. (2016) presented a methodology to achieve the identification of optimal hedging rules for operating reservoir systems seeking to mitigate drought impacts. The procedure was successfully applied to four water resource systems in Spain.

Genetic programming (GP) has not being used to calculate hedging rules because it has no logical operators in its function set. However, most recently the GP has been extended to meet specific objectives. For example, Fallah-Mehdipour *et al*. (2012) applied GP to calculate reservoir operating rules. These operational rules related water release to deterministic and stochastic variables such as storage volume and inflow. Fallah-Mehdipour *et al*. (2013) calculated a fixed-length gene genetic programming (FLGGP) rule based on GP to compute an effective operation rule that yields a better objective function value than that calculated with the GA for the same conditions. The FLGGP rules were employed in an aquifer–dam system with two subsystems. Ashofteh *et al*. (2015a) applied GP for determining irrigation allocation policy under climate change. These allocation policies related water release to variables such as storage, inflow and demand volume. In other research by Ashofteh *et al*. (2015b) multi-objective genetic programming (MO-GP) was implemented to calculate optimal reservoir-operating rules under baseline and climatic change conditions. The objective functions were the maximization of the reliability of meeting irrigation demand and the minimization of the vulnerability to irrigation deficits under baseline condition and future conditions.

Other studies have shown that climate change made it necessary to modify existing operating rules. For example, previous studies showed that climate change will increase water shortage and, thus, operating rules must be modified to face the challenge of changing conditions.

This study extends traditional genetic programming (TGP) by adding logical operators and functions, giving rise to logical genetic programming (LGP). GP is a type of evolutionary algorithm (EA) (see other examples of EAs in Ahmadi *et al*., 2015; Akbari-Alashti *et al*., 2014). This study applies the LGP approach (this study's innovation) to calculate multi-conditional hedging reservoir-operation rules for the Aidoghmoush Reservoir System (north-eastern Iran) during a 14-year reservoir operation period that serves as a baseline condition (1987–2000) and under climate change conditions (2026–2039).The objective function used to calculate the hedging rule is to minimize the long-term water-shortage ratio (LSR*)*. The performance of the LGP approach in calculating reservoir-operation rules is compared with that of the TGP approach for baseline and climate change conditions. Lastly, the results obtained from the calculated hedging rules with the LGP and the TGP are compared, based on efficiency indices under baseline and climate change conditions. It is noted that in order to simplify, this study has two assumptions, including (i) unchanging evaporation in the future period relative to the baseline period and (ii) consideration of the average value for demand.

## METHODOLOGY

This paper's methodology includes the processing of climatic data, the estimation of reservoir inflow, analysis of water use under climate change conditions, the calculation of a hedging reservoir-operation rule under baseline and climate change conditions with the TGP and LGP approaches, and evaluation of the hedging reservoir-operation rules using efficiency indices.

This paper's LGP approach is an extended TGP approach whereby logical operators and functions have been added to the former approach. Figure 1 depicts a flowchart of the LGP algorithm.

### *Climate scenarios and hydrologic simulation*

The Hadley Centre's coupled model version 3 (HadCM3) model with A2 greenhouse gas emissions scenario was

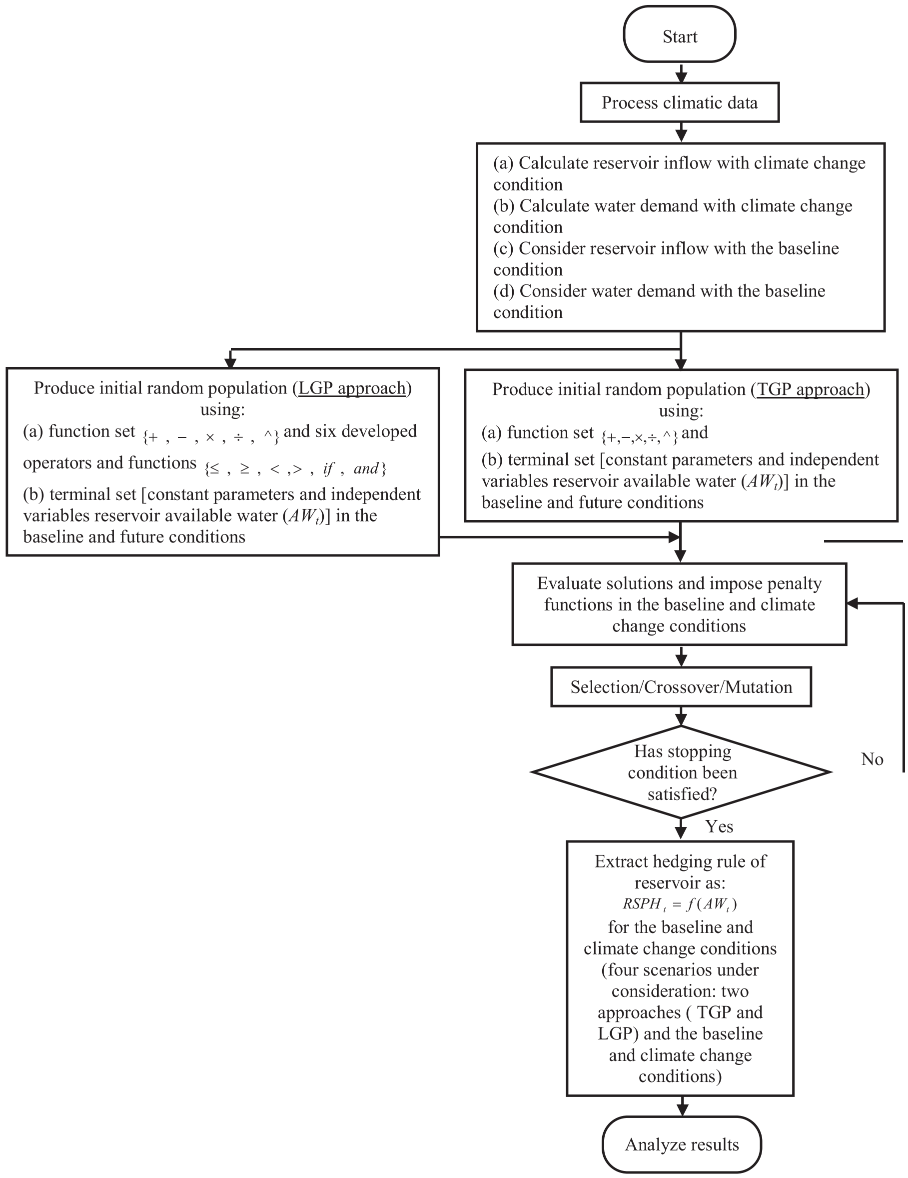


Figure 1. Flowchart of this work's implemented methodology

implemented to process the climatic scenario. The HadCM3 model provides some of the most robust predictions of climatic variables, as shown by the good match between simulated and observed climatic variables in the baseline interval (Ashofteh *et al*., 2016). The semi-conceptual hydrologic model IHACRES (Jakeman and Hornberger, 1993; Jakeman *et al*., 1990) is employed to simulate reservoir inflow under climate change (Ashofteh *et al*., 2013). Inputs to the IHACRES model are climatic variables simulated by HadCM3 and basin data (such as drainage area). IHACRES simulates runoff that is used an inflow for reservoir operation. IHACRES converts climatic variables (such as rainfall and temperature) to effective rainfall by a nonlinear loss module, and the effective rainfall is converted to runoff (or reservoir inflow) by a unit hydrograph linear module. Crop water use for the study area under climate change conditions was determined based on the cultivated area and its cropping pattern, employing the Food and Agriculture Organization's FAO-24 method based on the Penman–Monteith equation coded in the CROPWAT software (Ashofteh *et al*., 2013). Figure 2 shows the flowchart of the methodology for generating climate scenarios and conducting hydrologic simulation.

## *The reservoir hedging rule*

The purpose of using hedging rules in reservoir operation is to reduce the damage caused by a severe water shortage

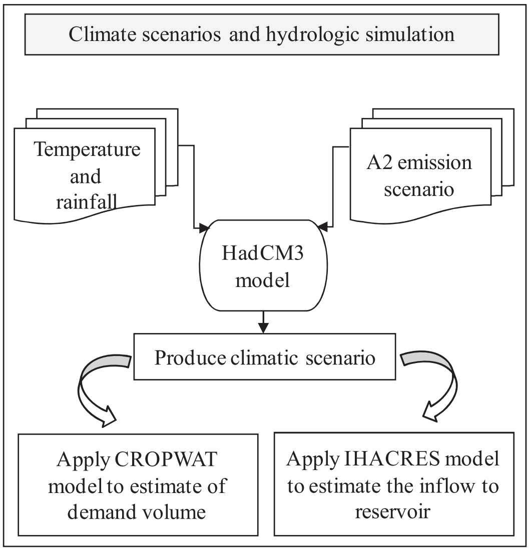


Figure 2. Flowchart of climate scenarios and hydrological simulation

in exchange for accepting more frequent but less severe shortage periods. The hedging rule of reservoir operation dictates the curtailment of water releases when reservoir storage falls below a specified threshold in order to conserve water for future uses. A graphical representation of the hedging curve is depicted in Figure 3. It is seen in Figure 3 that hedging occurs when the available water (AW) is between SH and EH. The SH and EH are the starting and ending hedging limits, respectively. The SH and EH range between 0 and $D$ and $D$ and $D + S_{\max}$, respectively, where $D$ and $S_{\max}$ denote average water demand met by the reservoir and the maximum reservoir storage, respectively. The operating policy for SH = EH = $D$

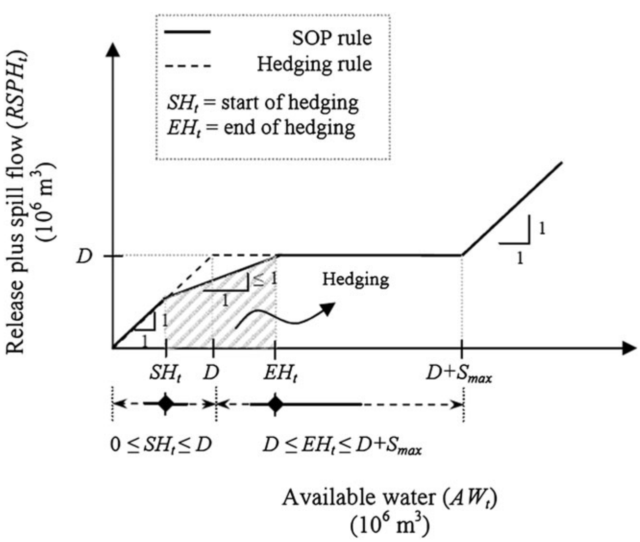


Figure 3. Schematic of the standard operating policy (SOP) and hedging rules

is called the standard operating policy (SOP), in which case hedging does not occur.

The objective of the reservoir operation problem herein applied to manage water supply for irrigation minimizes the long-term shortage ratio (LSR) [this index is similar to the index introduced by Shiau and Lee (2005):

$$\text{Minimize LSR} = \frac{1}{T}\sum_{t=1}^{T}|D - \text{RSPH}_t| \tag{1}$$

The decision variables in Equation (1) are the parameters that define the hedging rule for reservoir release introduced in Equation (2); LSR = the long-term shortage ratio; $\text{RSPH}_t$ = reservoir release (regulated release plus spill flow) calculated based on hedging rule during period $t$; $T$ = length of the operation interval; and $D$ = average water demand during the operation interval.The hedging release rule depends on the reservoir's water availability according to Equation (2):

$$\text{RSPH}_t = f(\text{AW}_t) \quad t = 1, 2, \ldots, T \tag{2}$$

in which $f(\text{AW}_t)$ = hedging rule calculated with the TGP and LGP approaches; and $AW_t$ = available water during period $t$, which is calculated with Equation (3) assuming linear approximation of reservoir evaporation (Fallah-Mehdipour *et al*., 2014; Ashofteh *et al*., 2015a, b):

$$\text{AW}_t = S_t + Q_t - \frac{e_t \cdot (aS_t + b)}{1000} \quad t = 1, 2, \ldots, T \tag{3}$$

in which $S_t$ = reservoir storage at the beginning of period $t$; $Q_t$ = reservoir inflow during period $t$; $e_t$ = depth of reservoir evaporation during period $t$; and $a$ and $b$ = constants in the surface storage function of the reservoir.

The constraints of the hedging problem are given by Equations (4)–(7):Constraint on water balance:

$$S_{t+1} = \text{AW}_t - \text{RSPH}_t \quad t = 1, 2, \ldots, T \tag{4}$$

Constraint on minimum storage:

$$S_t \geq S_{\min} \quad t = 1, 2, \ldots, T \tag{5}$$

Constraint on reservoir release:

$$RSPH_t = \min[\max(\text{RSPH}_t, 0), D] \quad t = 1, 2, \ldots, T \tag{6}$$

Constraint on reservoir release when storage exceeds the maximum storage:

$$\begin{cases} \text{RSPH}_t = \text{AW}_t - S_{\max} \\ S_{t+1} = S_{\max} \end{cases} \text{if } S_{t+1} \geq S_{\max} \;\; \text{t} = 1, 2, \ldots, \text{T} \tag{7}$$

in which $S_{t+1}$ = storage volume of reservoir at the ending of period $t$; $S_{min}$ = reservoir dead volume; and $S_{max}$ = reservoir maximum capacity.The constraints expressed by

 

Equations (5)–(6) are enforced via penalty functions (PF) that are added to the objective function:

$$PF1_t = C_1.[|S_{\min} - S_t|/S_{\max} - S_{\min}]^2 + C_2 \quad t = 1, 2, \ldots, T \tag{8}$$

$$PF2_t = C_3.[|\mathrm{RSPH}_t|/D] + C_4 \quad t = 1, 2, \ldots, T \tag{9}$$

$$PF3_t = C_5.[(\mathrm{RSPH}_t - D)/D]^2 + C_6 \quad t = 1, 2, \ldots, T \tag{10}$$

in which $PF1_t$ = penalty function applied to violation of the constraint given by Equation (5); $PF2_t$ and $PF3_t$ = penalty function applied to violation of the constraint given by Equation (6); and $C_1$ through $C_6$ = positive coefficients of the penalty functions.

### *Approaches under consideration*

Four approaches of analysis were entertained in this work: the first develops the reservoir release rules for the baseline period using the TGP approach; the second approach develops the reservoir release rules for the baseline period using the LGP approach; the third approach develops the reservoir release rules for the future period (under climate change) using the TGP approach; the fourth develops the reservoir release rules for the future period using the LGP approach.Reservoir releases are functions of the decision parameters, such as water availability under the baseline and climate change conditions as written in Equations (11)–(14):

$$\mathrm{RSPH}_{tb-\mathrm{TGP}} = f_{b-\mathrm{TGP}}(\mathrm{AW}_{tb-\mathrm{TGP}}) \quad t = 1, 2, \ldots, T \tag{11}$$

$$\mathrm{RSPH}_{tb-\mathrm{LGP}} = f_{b-\mathrm{LGP}}(\mathrm{AW}_{tb-\mathrm{LGP}}) \quad t = 1, 2, \ldots, T \tag{12}$$

$$\mathrm{RSPH}_{tf-\mathrm{TGP}} = f_{f-\mathrm{TGP}}(\mathrm{AW}_{tf-\mathrm{TGP}}) \quad t = 1, 2, \ldots, T \tag{13}$$

$$\mathrm{RSPH}_{tf-\mathrm{LGP}} = f_{f-\mathrm{LGP}}(\mathrm{AW}_{tf-\mathrm{LGP}}) \quad t = 1, 2, \ldots, T \tag{14}$$

zin which $\mathrm{AW}_{tb-\mathrm{TGP}}$ and $\mathrm{RSPH}_{tb-\mathrm{TGP}}$ = reservoir water availability and reservoir release under baseline conditions, respectively, with the TGP approach (state 1); $\mathrm{AW}_{tb-\mathrm{LGP}}$ and $\mathrm{RSPH}_{tb-\mathrm{LGP}}$ = reservoir water availability and reservoir release under baseline conditions, respectively, with the LGP approach (state 2); $\mathrm{AW}_{tf-\mathrm{TGP}}$ and $\mathrm{RSPH}_{tf-\mathrm{TGP}}$ = reservoir water availability and reservoir release under climate change conditions, respectively, with the TGP approach (state 3); and $\mathrm{AW}_{tf-\mathrm{LGP}}$ and $\mathrm{RSPH}_{tf-\mathrm{LGP}}$ = reservoir water availability and reservoir release under climate change conditions, respectively, based on the LGP approach (state 4).

### *Reservoir efficiency indexes*

Hashimoto *et al.* (1982) introduce reliability, vulnerability and resiliency indices to evaluate the performance of water resources systems, which were adopted in this work.The reliability index is defined by Equation (15):

$$\alpha = \frac{N(\mathrm{RSPH}_t \geq D)_{t=1,2,\ldots,T}}{T} \tag{15}$$

in which $\alpha$ = reliability index; and $N(\mathrm{RSPH}_t \geq D)_{t=1,2,\ldots,T}$ = the number of time periods in which water demand is met.The vulnerability index is defined by Equation (16):

$$\upsilon = \frac{\sum_{t=1}^{T} (\mathrm{RSPH}_t - D|\mathrm{RSPH}_t < D)}{\mathrm{TD}} \tag{16}$$

in which $\upsilon$ = vulnerability index; $\sum_{t=1}^{T}(\mathrm{RSPH}_t - D|\mathrm{RSPH}_t < D)$ = total shortages in the operation interval; and TD = total volume of water demand in the entire operation interval. The resiliency index is defined by Equation (17):

$$\beta = \frac{N(\mathrm{RSPH}_{t+1} \geq D|\mathrm{RSPH}_t < D)_{t=1,2,\ldots,T}}{N(\mathrm{RSPH}_t < D)_{t=1,2,\ldots,T}} \tag{17}$$

in which $\beta$ = resiliency index; $N(\mathrm{RSPH}_{t+1} \geq D|\mathrm{RSPH}_t < D)_{t=1,2,\ldots,T}$ = the number of periods in which water demand is supplied after each shortage of water supply; and $N(\mathrm{RSPH}_t < D)_{t=1,2,\ldots,T}$ = number of time periods with shortage of water supply.

## CASE STUDY

This section describes the reservoir system and the LGP and TGP approaches.

### *Reservoir system*

The Aidoghmoush basin and reservoir are located in the province of East Azerbaijan (Figure 4). The reservoir system and basin characteristics are depicted in Figure 4.

Fourteen years of reservoir inflow data and 14 yr of reservoir downstream demand data were used in the baseline interval (1987–2000). Also, average water demand in the baseline period equals $12.0 * 10^6$ $m^3$. The average irrigation water demand to be met by reservoir operation is implemented in this study.

### *Parameters of the TGP and LGP approaches*

The GPLAB toolbox was used in MATLAB 9.0 (Silva, 2007) as a programming environment in this work. The TGP functions involve five arithmetic operators (+, −, /, ×, ^) whereas the LGP functions feature six additional

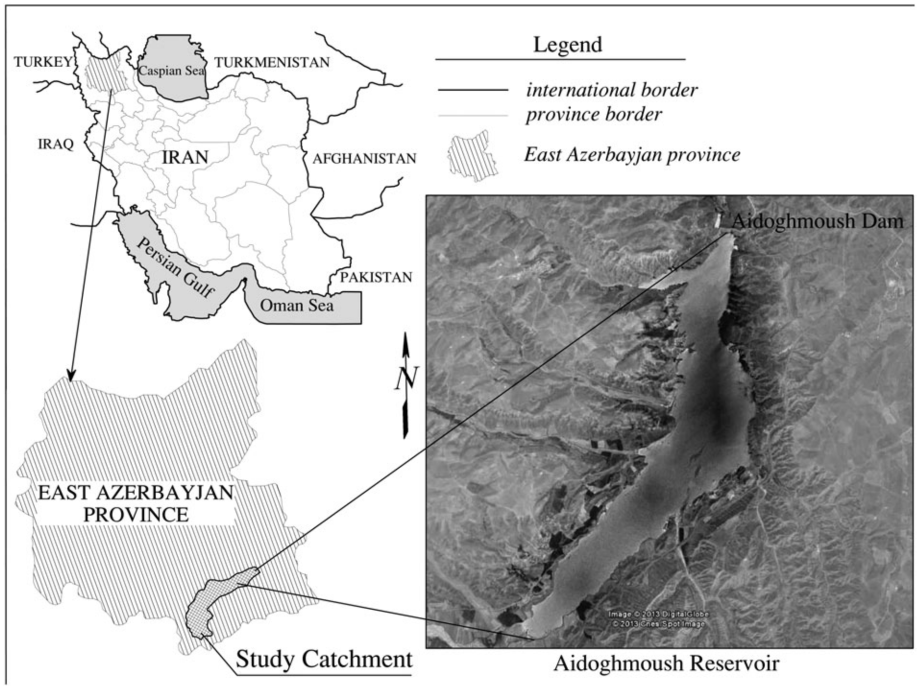


Figure 4. Location of the reservoir system under consideration

mathematical operators (≤, ≥, <, >, *if*, *and*). The TGP and LGP approaches apply a solution tree. The solution tree is a tree composed of nodes and connections. The connections include all independent parameters and constants, and nodes include all the operators or mathematical expressions. Generally, the steps to solve a problem by two approaches are as follows: (i) generate an initial population randomly (selection of variables and operators applied in solutions by the user); (ii) evaluate each of the solutions with the objective function; (iii) produce the next generation by crossover operator; (iv) impose the mutation operator randomly; (v) repeat steps (ii)–(iv) to stabilize the objective function; and (vi) satisfy the stopping criterion based on the specified number of iterations.

The most influential parameters in the resolution process are the crossover rate, the mutation rate, the maximum number of iterations, the maximum initial height of the solution tree, the number of trees and the reproduction rate. The values of the TGP and LGP parameters applied to obtain the hedging rule for reservoir operation are listed in Table I.

## RESULTS AND DISCUSSION

Figure 5 shows that basin temperature is predicted to increase between 0.5 and 2.7°C compared to the baseline conditions, whereas the rainfall increases or decreases depending on the month. The climatic scenarios shown in Figure 5 were applied to historic monthly values to obtain the future scenarios of streamflow and rainfall. Specifically, the predicted changes in monthly temperature were added to historic values, and the historic monthly precipitation was multiplied by the predicted percentages of change in precipitation to calculate the predicted future monthly precipitation (this approach has been used in previous climate change studies of hydrologic response; see Loáiciga *et al*., 2000). The predicted temperature and rainfall were input to the IHACRES hydrologic model with which reservoir inflow was simulated. The 14-yr time series of

Table I. Parameters of the TGP and LGP used with the hedging rule of reservoir operation

| Parameter | Maximum number of iterations | Crossover rate | Mutation rate | Maximum initial height of the tree | Number of trees | Reproduction rate |
|---|---|---|---|---|---|---|
| Value | 2500 | 0.9 | 0.1 | 9 | 100 | 0.1 |

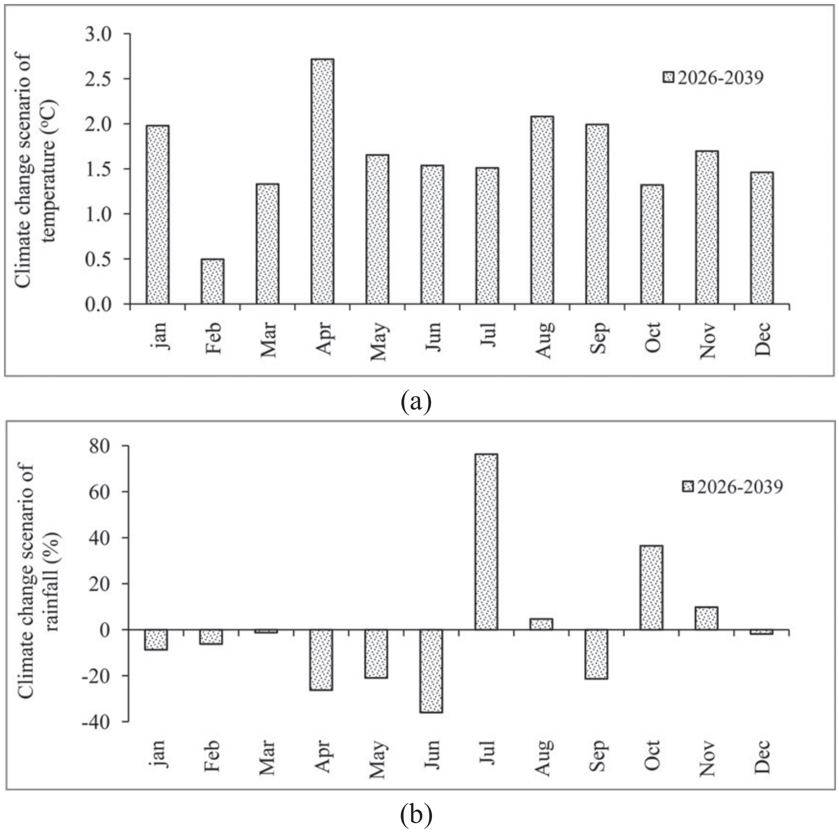


Figure 5. Climatic scenarios resulting from HadCM3 model for (a) temperature and (b) rainfall

predicted future reservoir inflow (period 2026–2039) is shown in Figure 6 (Ashofteh *et al*., 2013).

Crop evapotranspiration was determined and the water demand of different crops calculated with CROPWAT simulations based on the predicted climatic variables (Ashofteh *et al*., 2013). The average demand under climate change conditions was calculated to equal 13.9 * $10^6$ $m^3$ and is shown in Figure 6 with other fluxes.

Figures 7(a)–(f) show the calculated hedging rules for reservoir operation calculated with the TGP and the LGP under the baseline conditions. Figures 8(a)–(f) show the same type of results under climate change conditions. Figures 7(a)–(b) and Figures 8(a)–(b) show the convergence of the LGP to the objective function equal to 3.82 and 4.22% under baseline and climate change conditions, respectively, which are compared to the results obtained with the TGP whose objective function values were 5.09 and 4.47% corresponding to the baseline and climate change conditions, respectively. Therefore, the LGP approach improves the objective function about 25 and 6% relative to the TGP approach in calculating the hedging rule under the baseline and climate change conditions, respectively.

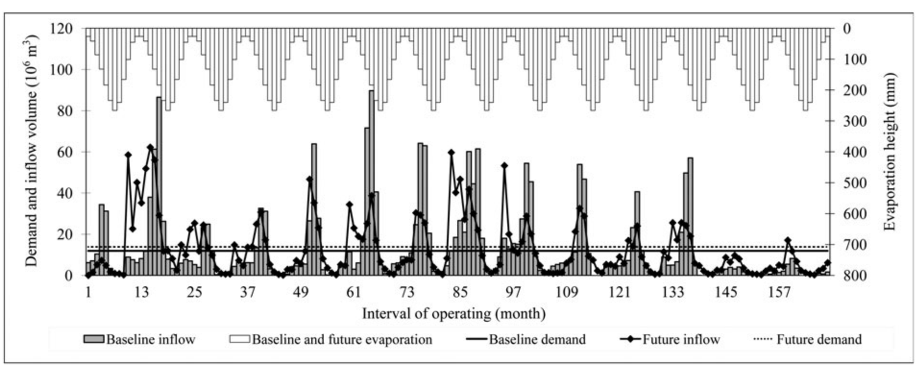


Figure 6. Reservoir inflow, average water demand and evaporation depth in the baseline and future periods

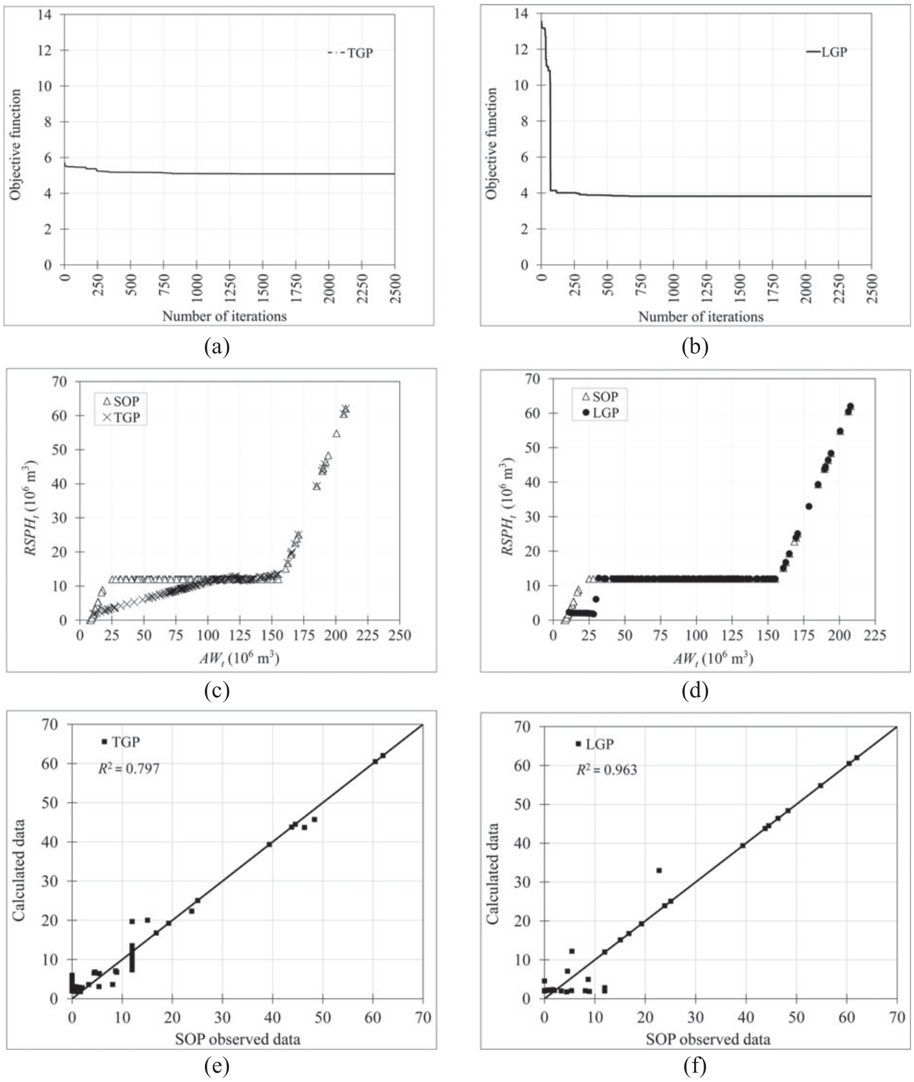


Figure 7. Results for the hedging rule calculated with the TGP and LGP approaches under baseline condition: (a) and (b) the related objective functions, (c) and (d) hedging curves, and (e) and (f) comparison of calculated and observed values

Comparison of the results obtained with the LGP approach and the SOP observed data (with determination coefficients equal to 96 and 77% under baseline and climate change conditions, respectively) relative to results calculated with the TGP (with determination coefficient equal to 80 and 71% under baseline and climate change conditions, respectively) in Figures 7(e)–(f) and Figures 8(e)–(f) show that the LGP approach exhibited better performance than the TGP. This indicates that the LGP-based reservoir release would lead in the future to a better supply of irrigation water.Equations (18)–(19) are rules developed by the TGP and LGP (in a format of multi-conditional relations developed through adding logical operators and functions) for the baseline condition with minimal objective function values, respectively, and Equations (20)–(21) are rules developed with the LGP and TGP approaches for climate change conditions, respectively:

$$\begin{aligned}\mathrm{RSPH}_t = {} & 3.151 + 8.831\times10^{-7}\cdot\mathrm{AW}_t^{\,4} \\ & + 8.370\times10^{-11}\cdot\mathrm{AW}_t^{\,6} \\ & - 1.538\times10^{-13}\cdot\mathrm{AW}_t^{\,7} \\ & - 1.484\times10^{-8}\cdot\mathrm{AW}_t^{\,5}\end{aligned}$$

$$\mathrm{RSPH}_t = \begin{cases} \mathrm{AW}_t - 145.7 & 159.51 \le \mathrm{AW}_t \\ 11.97 & 30.60 \le \mathrm{AW}_t < 159.51 \\ 5.05 & 29.02 \le \mathrm{AW}_t < 30.60 \\ 2.05 & \mathrm{AW}_t < 29.02 \end{cases} \tag{19}$$

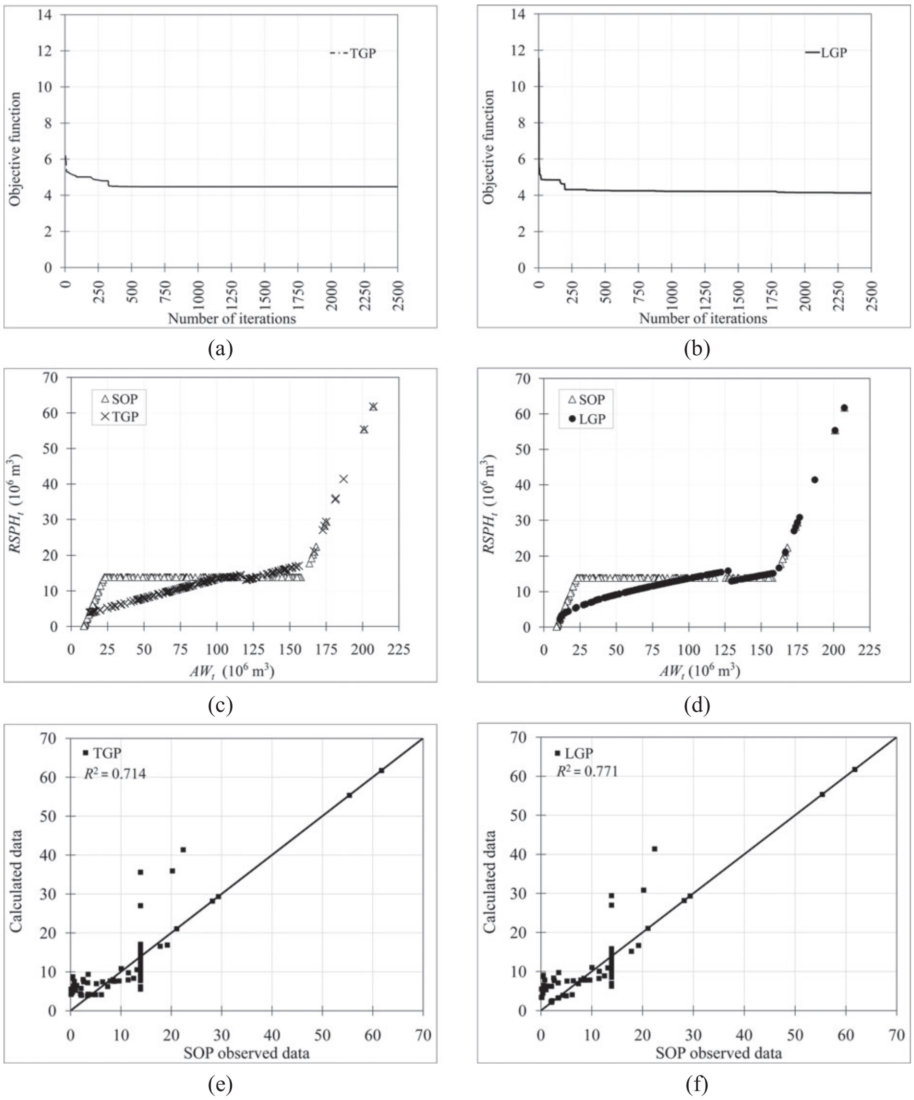


Figure 8. Results of the hedging rule calculated with the TGP and LGP approaches under climate change condition: (a) and (b) the objective functions, (c) and (d) hedging curves, and (e) and (f) comparison of calculated and observed values

$$\begin{aligned}\mathrm{RSPH}_t = {} & 1.504{\cdot}\mathrm{AW}_t + 0.00097{\cdot}\mathrm{AW}_t^{\,3} \\ & + 3.601{\times}10^{-8}{\cdot}\mathrm{AW}_t^{\,5} - 9.196 \\ & - 5.660{\times}10^{-11}{\cdot}\mathrm{AW}_t^{\,6} - 0.054{\cdot}\mathrm{AW}_t^{\,2}\end{aligned} \quad (20)$$

$$\mathrm{RSPH}_t = \begin{cases} \mathrm{AW}_t - 145.7 & 165.32 \le \mathrm{AW}_t \\ 0.109\mathrm{AW}_t & 118.74 \le \mathrm{AW}_t < 165.43 \\ 0.158\mathrm{AW}_t + 7.28 & 105.21 \le \mathrm{AW}_t < 118.74 \\ 0.109\mathrm{AW}_t + 2.51 & \mathrm{AW}_t < 105.21 \end{cases} \quad (21)$$

The optimal rules calculated with the TGP and LGP approaches were compared and the results are depicted in Figure 9(a) for the baseline condition and in Figure 10(a) for climate change conditions. Changes of storage volume and water supply shortage associated with the rules calculated with the TGP and LGP were calculated with the four analysis states and compared with the average water demand and are portrayed in Figures 9(b)–(c) for the baseline condition and in Figures 10(b)–(c) for climate change conditions.

Figures 9(a) and 10(a) show that the performance of the LGP-calculated release rules with the baseline and climate change conditions was better than that calculated with the TGP. The LGP-based releases was more consistent in meeting the water demand than that obtained with the TGP under baseline and climate change conditions.

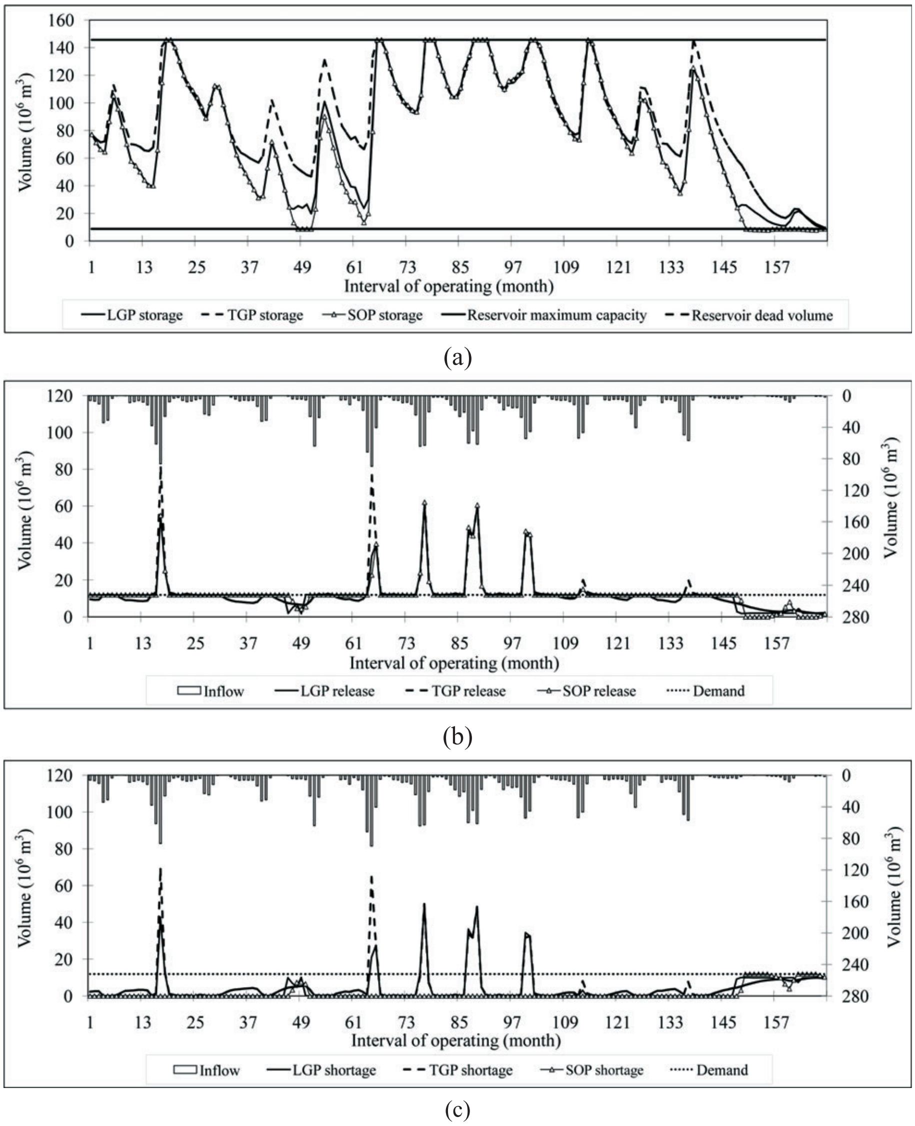


Figure 9. The changes of (a) additional release volume, (b) storage volume and (c) shortage volume based on release rules calculated with the TGP and LGP approaches for the first and second approaches with average water demand under baseline conditions. [Colour figure can be viewed at wileyonlinelibrary.com]

Table II lists the efficiency indices corresponding to the four analysis approaches.

Comparison of the first and second approaches in Table II shows that using the LGP approach leads to increase of reliability (30%), decrease of vulnerability (29%) and increase of resiliency (21%) relative to applying the TGP approach with the baseline condition. Under climate change conditions (third and fourth approaches) the use of the LGP increases reliability (15%) and decreases vulnerability (5%).

Meanwhile, the results listed in Table II establish that use of the LGP approach (second and fourth approaches) decreases reliability (34%), increases vulnerability (58%) and decreases resiliency (29%) under climate change conditions relative to the baseline condition. The TGP method (first and third approaches) decreases reliability (25%), increases vulnerability (18%) and decreases resiliency (14%), respectively. In other words, the reservoir efficiency indices with both approaches under climate change are worse than those of the baseline.

## CONCLUDING REMARKS

The calculation of hedging rules assists planners and operators who can apply those hedging rules in the allocation of water in situations where, for example, assessment indices indicate drought events, thus minimizing damage during drought periods.

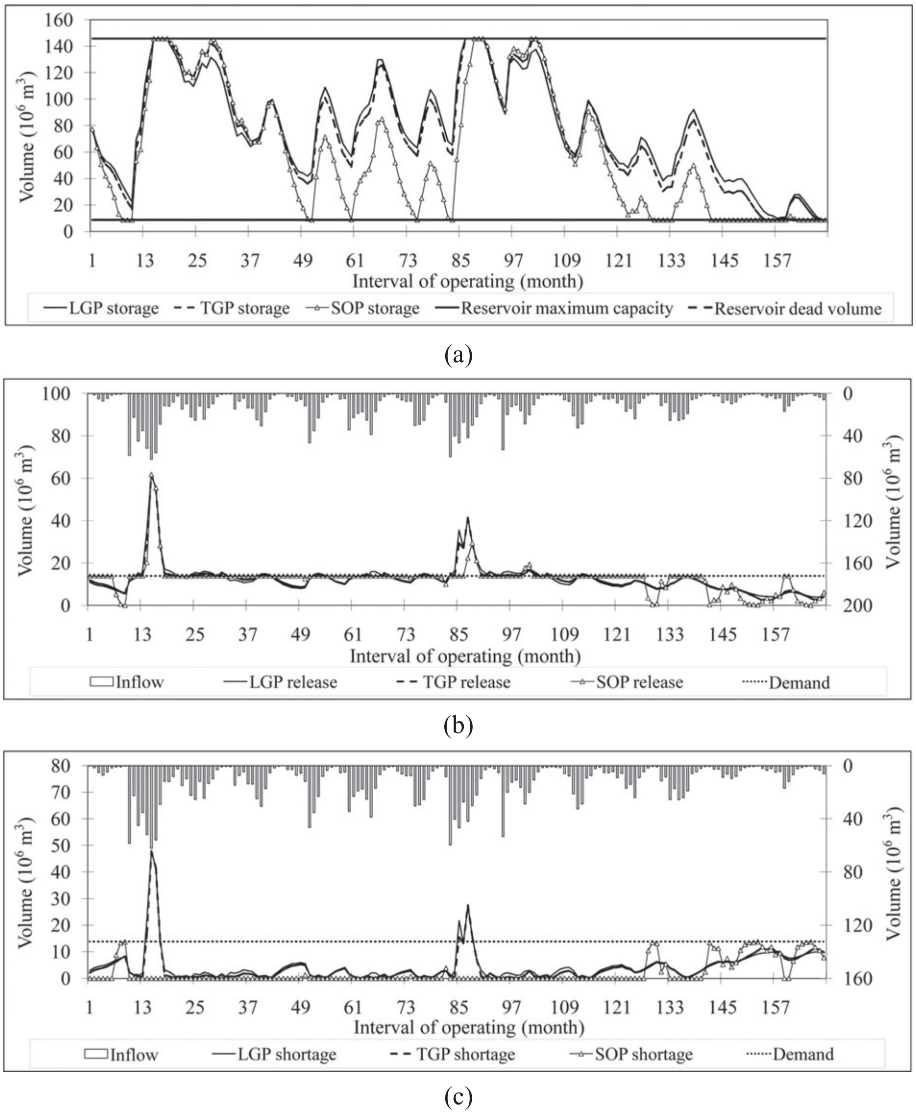


Figure 10. The changes of (a) release volume, (b) storage volume and (c) shortage volume based on release rules calculated with the TGP and LGP approaches for the third and fourth approaches with average water demand under climate change conditions

Multi-conditional functions, logical operators and a Boolean function were added to the TGP in this work to form the LGP approach. The LGP was applied to derive optimal hedging rules under baseline and climate change conditions for a one-reservoir system with the purpose of minimization of the LSR.

Table II. Comparison of the efficiency indices for the four approaches under consideration

| Approaches | Reliability (%) | Vulnerability (%) | Resiliency (%) |
|---|---|---|---|
| First (TGP, baseline) | 36 | 17 | 14 |
| Second (LGP, baseline) | 47 | 12 | 17 |
| Third (LGP, climate change) | 27 | 20 | 12 |
| Fourth (TGP, climate change) | 31 | 19 | 12 |

Comparison of the calculated results with the LGP approach and the SOP observed data (with determination coefficient equal to 96 and 77%, respectively, under baseline and climate change conditions) indicated that the LGP had better performance than the TGP approach (with determination coefficient equal to 80 and 71%, respectively, under baseline and climate change conditions).

Comparison of performance indices corresponding to the four approaches demonstrated that applying the LGP approach increased the reliability (30%), decreased the vulnerability (29%) and increased the resiliency (21%) relative to the TGP in the baseline condition. The LGP increased the reliability (15%) and decreased the vulnerability (5%) under climate change conditions relative to baseline conditions.

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