**ARTICLE**

# Development of an optimizing method for the operation rule curves of a multipurpose reservoir in a Southeast Asian watershed

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## Abstract

Water scarcity and flooding constitute major problems for developing countries located within the tropical climatic region of Southeast Asia. In addition, regional water consumption is increasing, and water usage patterns have been changing recently. Therefore, an advanced water resource management framework that considers both water supply and flood control is needed. Multipurpose reservoirs are widely used to manage water resources efficiently; however, water-related problems occur with reservoirs in Southeast Asian watersheds because of inadequate operation rule curves. We developed a method for constructing optimal operation rule curves for Dau Tieng Reservoir, which is one of the largest multipurpose reservoirs in Vietnam. The reservoir is used for flood control, domestic water supply, industrial uses, environmental flows, and agricultural uses, in the order of priority. The operation rule curves of the Dau Tieng Reservoir comprise five reference water levels: the retarding water level, upper water level, lower water level, critical water level, and dead water level. Water release from the reservoir is determined based on the relationship between the reservoir level and the rule curves. In this study, the rule curves were newly determined using the shuffled complex evolution method of the University of Arizona (SCE-UA method). The objective function for optimization was defined by focusing on the improvement in insufficient supply for agricultural uses and environmental flow downstream of the Dau Tieng Reservoir. Inadequate solutions were prevented by introducing penalty functions into the objective function. Experimental results indicate that the proposed optimization method efficiently searches for optimal rule curves.

**Keywords** Optimization · SCE-UA method · Water scarcity · Flood control · Reservoir operation

## Introduction

Water scarcity is a major problem for developing countries in Southeast Asia because of tropical climatic factors, increasing populations, and saltwater intrusion into the lower reaches of large rivers (Kummu et al. 2016; Adepelumi et al. 2009). In addition, regional water consumption is increasing, and water usage patterns are changing because of changes in lifestyle and recent socioeconomic activities (ADB 2016). It is important to ensure that water demands are met, and this requires the development of a method for water resource management that can adapt to future changes in land use, climate, and the pattern of water usage. In addition, flooding occurs almost annually in the wet season and flat low-lying areas are frequently subject to substantial damage associated with inundation (WMO/GWP 2008). Accordingly, an advanced framework for water resource management is needed urgently, which considers both the demand for and supply of water and the control of flooding.

Multipurpose reservoirs are widely utilized for the efficient management of water resources. The role of a multipurpose reservoir includes flood control and the supply of water for each element of demand, e.g., domestic water, industrial water, hydropower generation water, agricultural water, and environmental water downstream of the reservoir. Environmental water refers to water used to impede saltwater intrusion into a river mouth and to maintain the river

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environment. Reservoir rule curves that define the operation regulations according to the demand for and storage of water are set for each reservoir, and the release operation is determined based on the relationship between the reservoir rule curves and the existing reservoir level. However, with regard to reservoirs in watersheds in Southeast Asia, water scarcity and floods currently occur because of the inadequacy of the reservoir rule curves (Ngoc et al. 2014).

In recent years, artificial intelligence technologies such as artificial neural networks, genetic algorithms (GAs), and fuzzy logic have been used to overcome problems related to hydrology and water resource systems. Regarding the operation of multipurpose reservoirs, there have been many cases of research using artificial intelligence technology to determine water release and storage volumes in particular. For example, Chaves and Chang (2008) optimized the release of a multipurpose reservoir using an artificial neural network. Suen and Eheart (2006), Chen and Chang (2007) and Ngoc et al. (2014) optimized the release of a multipurpose reservoir using a GA. In addition, Chang et al. (2010) determined the water storage appropriate to satisfy the various needs of a multipurpose reservoir using a GA. Many studies have addressed the optimization of water release and storage volumes of multipurpose reservoirs using artificial intelligence technology. However, only a few studies have considered the optimization of reservoir rule curves; e.g., Chang et al. (2005), Ngo et al. (2007) and Khan and Tingsanchali (2009). Therefore, the development of a more efficient optimization method for reservoir rule curves is required.

In addition, in the Southeast Asian watershed, problems such as the absence of necessary hydrological, climatic, and watershed data or predominantly low-reliability data exist. Thus, considering the problem of data scarcity, appropriate reservoir rule curves are needed. The present study was conducted to develop a method for constructing optimal reservoir rule curves for a multipurpose reservoir located in a watershed in Southeast Asia. The shuffled complex evolution method of the University of Arizona (SCE-UA method), proposed by Duan et al. (1992, 1994) and Sorooshian et al. (1993), which has been shown to have an overwhelmingly powerful global optimal solution search capability in comparison with GAs (Tanakamaru 1995), was used in this study for optimization of the reservoir rule curves.

## Study area

### Dau Tieng Reservoir

The Dau Tieng Reservoir watershed is located in southern Vietnam, approximately 90 km northwest of Ho Chi Minh City (Fig. 1). The land use of the total watershed area of 2700 km$^2$ is predominantly forest and cropland. The average
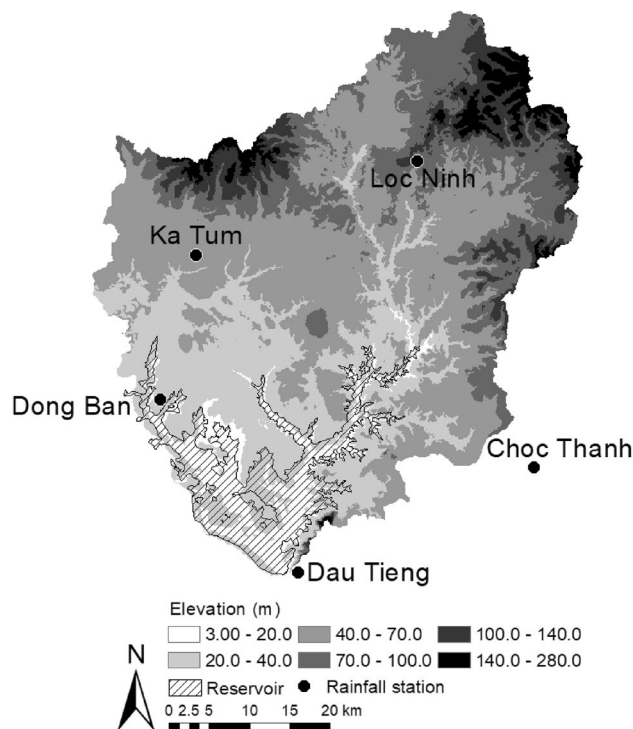


**Fig. 1** Topography and rainfall stations of the Dau Tieng Reservoir watershed, Vietnam

annual rainfall is 1800 mm, although 77% of this rainfall occurs between July and November.

The Dau Tieng Reservoir is one of the largest multipurpose reservoirs in Vietnam, with an effective storage capacity of $1.58 \times 10^9$ m$^3$. The reservoir is used for flood control, domestic water supply, industrial uses, environmental flows, and agricultural uses, in order of priority. The reservoir contributes significantly to the water resources of Ho Chi Minh City, which is located downstream. In Ho Chi Minh City, flooding often occurs during the rainy season (July to December), and there is often water scarcity during the dry season (January to June). One of the causes of these problems is the inadequacy of the operation rule curves of the Dau Tieng Reservoir. Furthermore, according to the existing reservoir operation regulations, it is also a problem that the supply of agricultural and environmental water with low priority is insufficient (Ngoc et al. 2014). Therefore, it is necessary to construct appropriate operation regulations of the Dau Tieng Reservoir.

### Reservoir operation systems

As shown in Table 1, the Dau Tieng Reservoir has set monthly demand water volumes for domestic, industrial, environmental, and agricultural water. The operation rule curves of the Dau Tieng Reservoir comprise five reference water levels from the higher level: the retarding water level

**Table 1** Monthly water demand of the Dau Tieng Reservoir

| | Monthly amount of water demand ($\times 10^6$ m$^3$) | | | | |
|---|---|---|---|---|---|
| | Domestic water | Industrial water | Environmental water | Agricultural water | Total |
| Jan | 15.5 | 71.3 | 21.4 | 213.8 | 322.0 |
| Feb | 14.0 | 64.4 | 29.0 | 235.2 | 342.6 |
| Mar | 15.5 | 71.3 | 32.1 | 342.2 | 461.1 |
| Apr | 15.0 | 69.0 | 31.1 | 141.5 | 256.6 |
| May | 15.5 | 71.3 | 16.1 | 0.0 | 102.9 |
| Jun | 15.0 | 54.3 | 0.0 | 69.3 | 138.6 |
| Jul | 15.5 | 71.3 | 0.0 | 173.0 | 259.8 |
| Aug | 15.5 | 71.3 | 0.0 | 0.8 | 87.6 |
| Sep | 15.0 | 69.0 | 0.0 | 0.0 | 84.0 |
| Oct | 15.5 | 71.3 | 0.0 | 0.0 | 86.8 |
| Nov | 15.0 | 69.0 | 0.0 | 238.6 | 322.6 |
| Dec | 15.5 | 71.3 | 0.0 | 217.7 | 304.5 |
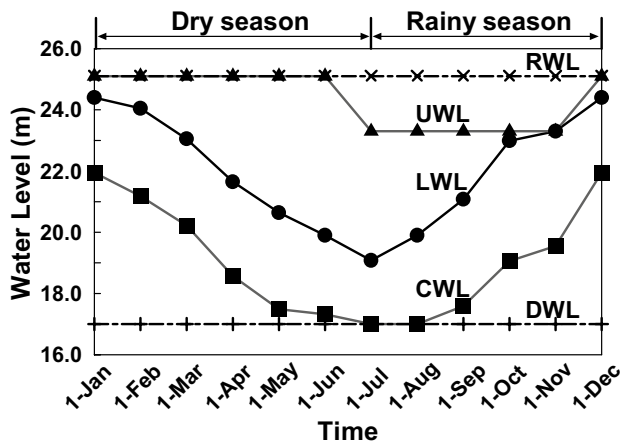


**Fig. 2** Current operation rule curves of the Dau Tieng Reservoir

(RWL), upper water level (UWL), lower water level (LWL), critical water level (CWL), and dead water level (DWL). Each curve consists of 12 reference water levels on the first day of each month (Fig. 2). The following operational regulations are set based on the reservoir rule curves and the reservoir storage level.

1. When the existing reservoir level is above the RWL, the spillway is opened immediately to its maximum in an attempt to reduce the reservoir level rapidly to the UWL.
2. When the reservoir level reaches the RWL, the spillway is opened immediately in an attempt to reduce the reservoir level rapidly to the UWL.
3. When the reservoir level exceeds the UWL, water release should be maintained at a high priority in an attempt to maintain the reservoir level at the UWL.

4. When the reservoir level is below the LWL, water release is restricted. In this case, water supply should satisfy domestic and industrial demands but be reduced for agricultural uses.
5. When the reservoir level drops to the DWL, water release is halted for the supply of all demands except domestic uses.

The RWL and DWL are indicators of high risk of flooding and extreme water scarcity, respectively, and they are inevitably determined by the dimensions of the reservoir and the dam. Therefore, in this study, the UWL, LWL, and CWL were newly determined using the optimization method.

## Optimization method for reservoir rule curves

### Optimization method

Recently, global search methods such as GAs and the SCE-UA method have been widely used as optimization methods. A global search method is a method that searches for the global minimum point by examining the entire search space, and it can cope with the problem that the solution might fall to the local minimum point (Tanakamaru 1995). The GA proposed by Holland (1975) is an algorithm based on the principles of biological evolution, e.g., selection, crossover, and mutation. Wang (1991) applied a GA to the identification of seven constants of a rainfall–runoff model and showed that GAs are effective as a global search method. Conversely, Duan et al. (1992, 1994) and Sorooshian et al. (1993) proposed the SCE-UA method, which is a global search method that incorporates the concepts of random searching, population mixing, and competitive evolution, similar to the GA in the Simplex method proposed by Nelder (1965). The SCE-UA method was applied to the identification of 6 or 13 constants of a rainfall–runoff model and its effectiveness was clarified. In addition, Tanakamaru (1995) used the local search method of the Simplex method and the Powell method, and the global search method of the GA and SCE-UA methods to identify the 16 constants of a four-stage tank model numerically, which revealed the superiority of the SCE-UA method in terms of both solution accuracy and search efficiency. Therefore, in this study, we adopted the SCE-UA method to optimize the rule curves of the Dau Tieng Reservoir. The optimization calculation was performed by repeating the procedure illustrated in Fig. 3 a preset number of times (specifically, 500 times).
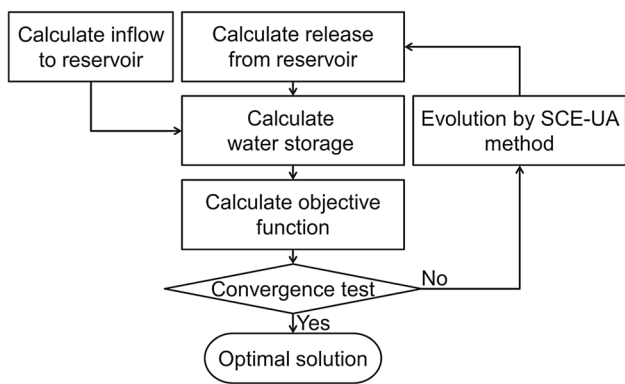
**Fig. 3** Procedure for optimization using the SCE-UA method

## Reservoir operation model

The water storage of the reservoir was calculated using Eq. (1):

$$W_{s,t+1} = W_{s,t} + In_{s,t} + R_{s,t} - E_{s,t} - Re_{s,t} \tag{1}$$

where $s$ is the calculation year ($= 1$–$10$), $t$ is the calculation day ($= 1$–$365$), $W_{s,t}$ is the water storage of the reservoir (m$^3$), $In_{s,t}$ is the inflow volume to the reservoir (m$^3$) that was calculated using the rainfall–runoff model proposed by Takada et al. (2018), $R_{s,t}$ is the rainfall to the reservoir (m$^3$), $E_{s,t}$ is the evapotranspiration from the reservoir (m$^3$), and $Re_{s,t}$ is the water released from the reservoir (m$^3$). The value of $Re_{s,t}$

$$f^{Agr} = \text{Max}_{s=1}^{N_{year}} \left\{ \sum_{t=1}^{365} S_{s,t}^{Agr2} \times K^{Agr} \right\}$$

$$S_{s,t}^{Agr} = \begin{cases} D_t^{Agr} - \left( Re_{s,t} - D_t^{Dom} - D_t^{Ind} - D_t^{Env} \right), & Re_{s,t} - D_t^{Dom} - D_t^{Ind} - D_t^{Env} < D_t^{Agr} \\ 0, & Re_{s,t} - D_t^{Dom} - D_t^{Ind} - D_t^{Env} \geq D_t^{Agr} \end{cases} \tag{4}$$

was calculated based on the operation regulations and the water demands of the Dau Tieng Reservoir listed in Table 1.

## Objective function

The objective function was set by paying attention to the insufficient agricultural and environmental water supplies with reference to Ngoc et al. (2014). Thus, Eq. (2) was set with the aims of reducing the difference between the demand and supply for both environmental and agricultural water and of satisfying the demand as much as possible:

$$F^{Obj} = f^{Env} + f^{Agr} + \sum_{i=1}^{6} f_i^{Pen}, \quad F^{Obj} \rightarrow \text{Min} \tag{2}$$

where $F^{obj}$ is the objective function, $f^{Env}$ is the sub-objective function for environmental water, $f^{Agr}$ is the sub-objective

function for agricultural water, and $f_i^{Pen}$ is the penalty function. The solution with the minimum objective function $F^{obj}$ was taken as the optimal solution.

The sub-objective function for environmental water $f^{Env}$ was calculated using Eq. (3):

$$f^{Env} = \text{Max}_{s=1}^{N_{year}} \left\{ \sum_{t=1}^{365} S_{s,t}^{Env2} \times K^{Env} \right\}$$

$$S_{s,t}^{Env} = \begin{cases} D_t^{Env} - \left( Re_{s,t} - D_t^{Dom} - D_t^{Ind} \right), & Re_{s,t} - D_t^{Dom} - D_t^{Ind} < D_t^{Env} \\ 0, & Re_{s,t} - D_t^{Dom} - D_t^{Ind} \geq D_t^{Env} \end{cases} \tag{3}$$

where $s$ is the calculation year ($= 1$–$10$), $t$ is the calculation day ($= 1$–$365$), $N_{year}$ is the number of calculated years ($= 10$), $D_t^{Env}$ is the demand volume for environmental water (m$^3$), $D_t^{Dom}$ is the demand volume for domestic water (m$^3$), $D_t^{Ind}$ is the demand volume for industrial water (m$^3$), and $K^{Env}$ is the weight coefficient of environmental water ($= 20.0$). Here, $S_{s,t}^{Env}$ represents the difference between the amount of water when deducting the demands for domestic and industrial water with higher priority than environmental water from the release volume ($=$ the amount of water that could be supplied for environmental water) and the demand for environmental water. The weighting coefficient for environmental water was set with consideration of the priority of the water demand items in relation to the Dau Tieng Reservoir.

The sub-objective function for agricultural water $f^{Agr}$ was calculated using Eq. (4):

where $D_t^{Agr}$ is the demand volume for agricultural water (m$^3$) and $K^{Agr}$ is the weight coefficient of agricultural water ($= 10.0$). Here, $S_{s,t}^{Agr}$ represents the difference between the amount of water when deducting the demands for domestic, industrial, and environmental water with higher priority than agricultural water from the release volume ($=$ the amount of water that could be supplied for agricultural water) and the demand for agricultural water. The weighting coefficient for agricultural water was set smaller than that of environmental water based on consideration of the priority of water demand items in relation to the Dau Tieng Reservoir.

## Penalty function

The six penalty functions [Eqs. (5)–(10)] were added when an inappropriate solution was derived in the optimum calculation process to prevent the generation of an inappropriate solution

(Abedian et al. [2005]). In the following, $W_{s,t}$ is the water storage of the reservoir (m$^3$), $W_t^{\text{Retard}}$ is the water storage at the RWL (m$^3$), $W_t^{\text{Upper}}$ is the water storage at the UWL (m$^3$), $W_t^{\text{Lower}}$ is the water storage at the LWL (m$^3$), $W_t^{\text{Critical}}$ is the water storage at the CWL (m$^3$), and $W_t^{\text{Dead}}$ is the water storage at the DWL (m$^3$). Each function was set with reference to Ngoc et al. [2014], and each weighting coefficient was set to a relative value in consideration of the needs of the study area.

The sub-penalty function $f_1^{\text{Pen}}$, imposed when the water level of the reservoir exceeds the RWL, was calculated using Eq. (5):

$$f_1^{\text{Pen}} = Max_{s=1}^{N_{\text{year}}} \left\{ \sum_{t=1}^{365} c_{1,s,t} \times K^{\text{Retard}} \right\}$$
$$c_{1,s,t} = \begin{cases} W_{s,t} - W_t^{\text{Retard}}, & W_t^{\text{Retard}} < W_{s,t} \\ 0, & W_t^{\text{Retard}} \geq W_{s,t} \end{cases} \quad (5)$$

Because the risk of flooding becomes extremely high when the reservoir level exceeds the RWL, the value of weighting coefficient $K^{\text{Retard}}$ was set as $1.0 \times 10^3$.

The sub-penalty function $f_2^{\text{Pen}}$, imposed when the water level of the reservoir is below the DWL, was calculated using Eq. (6):

$$f_2^{\text{Pen}} = Max_{s=1}^{N_{year}} \left\{ \sum_{t=1}^{365} c_{2,s,t} \times K^{\text{Dead}} \right\}$$
$$c_{2,s,t} = \begin{cases} W_t^{\text{Dead}} - W_{s,t}, & W_{s,t} < W_t^{\text{Dead}} \\ 0, & W_{s,t} \geq W_t^{\text{Dead}} \end{cases} \quad (6)$$

Because the risk of water scarcity becomes extremely high when the reservoir level is below the DWL, the value of weighting coefficient $K^{\text{Dead}}$ was set as $1.0 \times 10^3$.

The sub-penalty function $f_3^{\text{Pen}}$, imposed when the water level of the reservoir is below the CWL, was calculated using Eq. (7):

$$f_3^{\text{Pen}} = Max_{s=1}^{N_{year}} \left\{ \sum_{t=1}^{365} c_{3,s,t} \times K^{\text{Critical}} \right\}$$
$$c_{3,s,t} = \begin{cases} W_t^{\text{Critical}} - W_{s,t}, & W_{s,t} < W_t^{\text{Critical}} \\ 0, & W_{s,t} \geq W_t^{\text{Critical}} \end{cases} \quad (7)$$

To satisfy the water demands, it is desirable to maintain the reservoir level above the CWL; therefore, the value of weighting coefficient $K^{\text{Critical}}$ was set as 4.0.

The sub-penalty function $f_4^{\text{Pen}}$, imposed when the water level of the reservoir exceeds the UWL in the rainy season (July to December), was calculated using Eq. (8):

$$f_4^{\text{Pen}} = Max_{s=1}^{N_{\text{year}}} \left\{ \sum_{t=1}^{365} c_{4,s,t} \times K^{\text{Upper}} \right\}$$
$$c_{4,s,t} = \begin{cases} W_{s,t} - W_t^{\text{Upper}}, & W_t^{\text{Upper}} < W_{s,t} \\ 0, & W_t^{\text{Upper}} \geq W_{s,t} \end{cases} \quad (8)$$

To prevent flooding, it is desirable to maintain the reservoir level below the UWL; therefore, the value of weighting coefficient $K^{\text{Upper}}$ was set as 5.0.

The sub-penalty function $f_5^{\text{Pen}}$, imposed when the water level of the reservoir is below the LWL in the dry season (January to June), was calculated using Eq. (9):

$$f_5^{\text{Pen}} = Max_{s=1}^{N_{\text{year}}} \left\{ \sum_{t=1}^{365} c_{5,s,t} \times K^{\text{Lower}} \right\}$$
$$c_{5,s,t} = \begin{cases} W_t^{\text{Lower}} - W_{s,t}, & W_{s,t} < W_t^{\text{Lower}} \\ 0, & W_{s,t} \geq W_t^{\text{Lower}} \end{cases} \quad (9)$$

To prevent water scarcity, it is desirable to maintain the reservoir level above the LWL; therefore, the value of weighting coefficient $K^{\text{Lower}}$ was set as 2.0.

The sub-penalty function $f_6^{\text{Pen}}$, imposed when each line of the reservoir rule curves intersected, was calculated using Eq. (10):

$$f_6^{\text{Pen}} = \begin{cases} K^{\text{Rule}} \\ 0 \end{cases} \quad W_t^{\text{Dead}} \leq W_t^{\text{Critical}} \leq W_t^{\text{Lower}} \leq W_t^{\text{Upper}} \leq W_t^{\text{Retard}} \quad (10)$$

As it would be extremely inappropriate for each line of the reservoir rule curves to intersect, the value of weighting coefficient $K^{\text{Rule}}$ was set as $1.0 \times 10^{20}$.
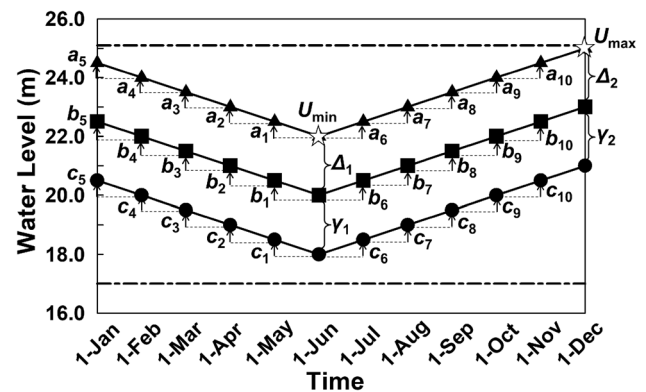


**Fig. 4** Decision variables used for optimization

## Decision variables for optimization

Optimum calculations were conducted using a total of 36 points as decision variables, i.e., 12 points of the UWL, 12 points of the LWL, and 12 points of the CWL. However, it was difficult to generate appropriate solutions because, for example, each line of the reservoir rule curves intersected at all of the generated solutions. Therefore, to obtain optimal solutions reflecting the rainy and dry seasons, represented by smooth lines without intersection, the 36 variables shown in Fig. 4 were taken as decision variables. Thus, the decision variables were the minimum and maximum values of the UWL ($U_{min}$ and $U_{max}$), the decrease in the minimum and maximum values from the UWL to the LWL ($\Delta_1$ and $\Delta_2$), the decrease in the minimum and maximum values from the LWL to the CWL ($\gamma_1$ and $\gamma_2$), and the rate of increase in the water level of each line in each month ($a_1$–$a_{10}$, $b_1$–$b_{10}$, and $c_1$–$c_{10}$). The decision variables that minimized the objective function were adopted as the optimal solutions, and the values of the UWL, LWL, and CWL were obtained.

To prevent flooding and water scarcity, the water level must be at the minimum at the time of switching from the dry season to the rainy season and at the maximum at the time of switching from the rainy season to the dry season. Optimum calculations were performed in nine ways because $U_{min}$ ranged from the latter half of the dry season to the first half of the rainy season (May to July) and because $U_{max}$ was in the latter half of the rainy season (October to December). The search space of each decision variable was set as shown in Table 2 based on the following values: crest elevation of the dam = 26.5 m, minimum water level of the reservoir = 14.0 m, and full water level = 24.5 m.

## Results

Optimum calculation of the daily steps was performed using the SCE-UA method with input data from 2000 to 2009. Conventionally, the operation rule of a multipurpose

**Table 2** Feasible space of decision variables used for optimization

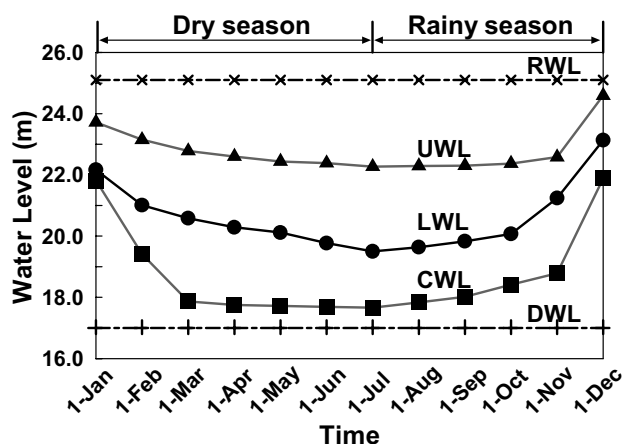| Decision variable | Feasible space |
|---|---|
| $U_{max}$ | 22.0–25.1 (m) |
| $U_{min}$ | 21.0–24.0 (m) |
| $\Delta_1$ | 2.5–6.0 (m) |
| $\Delta_2$ | 1.0–4.0 (m) |
| $\gamma_1$ | 1.5–4.0 (m) |
| $\gamma_2$ | 1.0–4.0 (m) |
| $a_1$–$a_{10}$ | 0.0–1.0 |
| $b_1$–$b_{10}$ | 0.0–1.0 |
| $c_1$–$c_{10}$ | 0.0–1.0 |

**Fig. 5** Optimum solutions of the operation rule curves

reservoir is developed based on extreme rainfall (10 years or 50 years return period) by statistical analysis. However, long-term observation data necessary for statistical analysis could not be obtained for this study area. Therefore, we used data from 2000 to 2009, which were available, as input values. As a result, the objective function showed the minimum value for the combination of the minimum value of the UWL ($U_{min}$) in July and the maximum value of the UWL ($U_{max}$) in December. The optimal solution is shown in Fig. 5. The water level of each rule curve showed a tendency to decrease toward the beginning of the rainy season and to increase toward the beginning of the dry season. It is considered that the proposed optimization method efficiently searched for the operation rule curves. It can be seen that the UWL is set lower than the current operation rule curves shown in Fig. 2. It is conceivable that the sub-penalty function when the reservoir level exceeds the RWL ($f_1^{Pen}$) with a large weight coefficient had considerable influence on this. In other words, the reservoir water level could be maintained at a low level by encouraging release from the spillway due to the decline of the UWL such that the water level of the reservoir could not exceed the RWL. In addition, it can be seen that the CWL during November to February is set higher in Fig. 5. It is conceivable that the sub-penalty function when the reservoir level is below the DWL ($f_2^{Pen}$) with a large weight coefficient had considerable influence on this. The reservoir water level is prevented from falling below the DWL by limiting release during the months of relatively high demand, shown in Table 1, due to the increase of the CWL.

However, when compared with the reservoir level calculated using the obtained rule curves, the reservoir level is lower than the DWL for all of the calculated years (Fig. 6). The calculated reservoir level is low overall, and it can be seen that there is much margin until it reaches RWL. In other words, it is conceivable that the obtained

**Fig. 6** Comparison of the obtained rule curves and calculated reservoir level
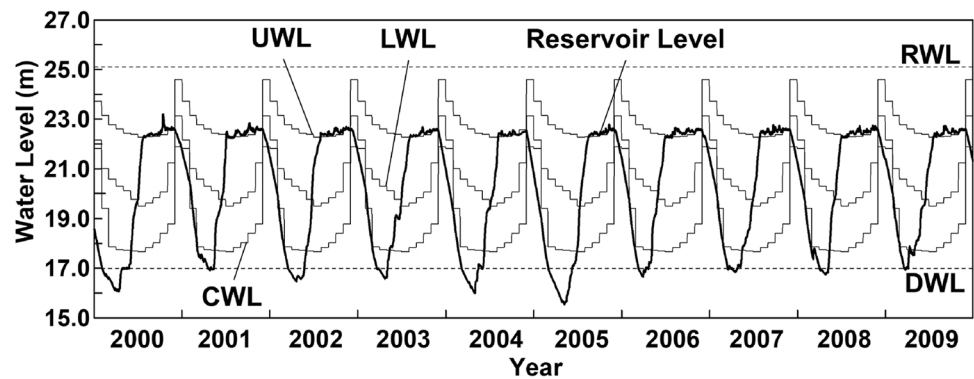


rule curves greatly affect the flood control. It is clear that the set penalty functions and the values of the weighting coefficients largely affected the result. Therefore, it is necessary to verify the diversity of the obtained rule curves from both the flood control and water supply based on the needs of the study area, and to improve the method used to set the penalty functions and weighting coefficients in further studies.

## Conclusions

The objective of this study was to propose a method for setting optimal operation rule curves for a multipurpose reservoir located in a watershed in Southeast Asia. We developed such a method for the Dau Tieng Reservoir, which is one of the largest multipurpose reservoirs in Vietnam. The reservoir is used for flood control, domestic water supply, industrial uses, environmental flows, and agricultural uses, in order of priority. We calculated the water release and reservoir storage volumes based on the monthly water demand and operation regulations of the reservoir. The objective function in relation to the Dau Tieng Reservoir was set to satisfy, as much as possible, the low-priority demands of agricultural and environmental water uses. Penalty functions were introduced to prevent generation of inappropriate solutions during the optimal calculation process. Optimum calculation using input data from 2000 to 2009 was performed using the SCE-UA method, which is a global search method. In the optimal solution, the UWL was set at a low level compared with the current operation rule curves and the CWL during the months with high demand was set at a high level to limit the release volume. It is necessary to verify the diversity of the obtained rule curves from both the flood control and water supply based on the needs of the study area, and to improve the method used to set the penalty functions and weighting coefficients in further studies.

The proposed optimization method efficiently searched for optimal operation rule curves in a watershed where the long-term observation data generally necessary for developing operation rules could not be obtained. Therefore, this method can be applied to other watersheds where long-term observation data are not available.

## References

Abedian A, Ghiasi MH, Dehghan-Manshadi B (2005) Effect of a linear-exponential penalty function on the GA's efficiency in optimization of a laminated composite panel. Int J Comput Intell 2(1):5–11

Adepelumi AA, Ako BD, Ajayi TR, Afolabi O, Omotoso EJ (2009) Delineation of saltwater intrusion into the freshwater aquifer of Lekki Peninsula, Lagos, Nigeria. Environ Geol 56(5):927–933

Asian Development Bank (ADB) (2016) Asian water development outlook 2016: strengthening water security in Asia and the Pacific. Asian Water Development Outlook

Chang FJ, Chen L, Chang LC (2005) Optimizing the reservoir operating rule curves by genetic algorithms. Hydrol Process 19:2277–2289

Chang LC, Chang FJ, Wang KW, Dai SY (2010) Constrained genetic algorithms for optimizing multi-use reservoir operation. J Hydrol 390:66–74

Chaves P, Chang FJ (2008) Intelligent reservoir operation system based on evolving artificial neural networks. Adv Water Resour 31:926–936

Chen L, Chang FJ (2007) Applying a real-coded multi-population genetic algorithm to multi-reservoir operation. Hydrol Process 21:688–698

Duan Q, Sorooshian S, Gupta VK (1992) Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resour Res 28(4):1015–1031

Duan Q, Sorooshian S, Gupta VK (1994) Optimal use of the SCE-UA global optimization method for calibrating watershed models. J Hydrol 158:3–4

Holland JH (1975) Adaptation in natural and artificial systems. University of Michigan Press, Ann Arbor

Khan NM, Tingsanchali T (2009) Optimization and simulation of reservoir operation with sediment evacuation: a case study of the Tarbela Dam, Pakistan. Hydrol Process 23:730–747

Kummu M, Guillaume JHA, de Moel H, Eisner S, Flörke M, Porkka M, Siebert S, Veldkamp TIE, Ward PJ (2016) The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Scientific Reports, Nature Publishing Group 6

Nelder JA (1965) A simplex method for function minimization. Comput J 7:308–313

Ngo LL, Madsen H, Rosbjerg D (2007) Simulation and optimisation modelling approach for operation of the Hoa Binh reservoir, Vietnam. J Hydrol 336:269–281

Ngoc TA, Hiramatsu K, Harada M (2014) Optimizing the rule curves of multi-use reservoir operation using a genetic algorithm with a penalty strategy. Paddy Water Environ 12(1):125–137

Sorooshian S, Duan Q, Gupta VK (1993) Calibration of rainfall-runoff models: application of global optimization to the Sacramento soil moisture accounting model. Water Resour Res 29(4):1185–1194

Suen JP, Eheart JW (2006) Reservoir management to balance ecosystem and human needs: incorporating the paradigm of the ecological flow regime. Water Resour Res 42:W03417

Takada A, Hiramatsu K, Ngoc TA, Harada M, Tabata T (2018) Development of a mesh-based distributed runoff model incorporated with tank models of several land utilizations in a Southeast Asian watershed. In: Proceedings of the 21st congress of International Association for Hydro-Environment Engineering and Research (IAHR) Asia Pacific Division (APD), vol 1, pp 539–547

Tanakamaru H (1995) Parameter estimation for the tank model using global optimization. Trans Jpn Soc Irrig Drain Reclam Eng 178:103–112 **(in Japanese)**

Wang QJ (1991) The genetic algorithm and its application to calibrating conceptual rainfall-runoff models. Water Resour Res 27(9):2467–2471

World Meteorological Organization (WMO) and Global Water Partnership (GWP) (2008) Urban flood risk management—a tool for integrated flood management. Associated programme on flood management