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Article

Optimization–based Solution for Reducing Water Scarcity in the Greater Chao Phraya River Basin, Thailand: Through Re–operating the Bhumibol and Sirikit Reservoirs Using Non–linear Programming Solver

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Abstract. Water scarcity problem in Thailand has been intensively addressed over decades to realize its impact and to promote a systematic modernization framework and technological advancement for effective and sustainable water resources management. Accordingly, the optimization–based solution with three scenarios was conducted by aiming to reduce water scarcity in the Greater Chao Phraya River Basin through re–operating the Bhumibol (BB) and Sirikit (SK) Reservoirs using non–linear programming solver. The results reveal that water deficit can be definitely reduced by the implementation of Fmincon optimization. Water allocation between BB and SK Dams was shared in the existing 0.44:0.56 ratio for scenario 1 and current operation and 0.45:0.55 ratio for scenario 2 and 3. The proportion of water released from SK Dam in dry years and normal years is still higher than BB Dam for all scenarios and higher than the current operation particularly in normal years. However, Fmincon optimization proposes to supply water from BB Dam higher than SK Dam in wet years with the average water sharing ratio of 0.54:0.46, 0.55:0.45, and 0.55:0.45 for scenario 1, 2, and 3, respectively. This leads to the increase in water storages of two main dams for a long–term reservoir operation.

Keywords: Bhumibol and Sirikit Reservoirs, Fmincon optimization algorithm, Greater Chao Phraya River Basin, multi–reservoir reoperation system, reservoir performance indices (RPI).

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1. Introduction

Operating the reservoir system in the perspective views of sustainable water resources management has been a challenging task due to the rising population and economic growth and impacts of climate changes [1–5]. A broad range of the reservoir operation studies considering importance and concern of the operational practices of reservoir systems has been broadly addressed to realize unforeseen damages and to ensure water security in both short–term and long–term operation. Water scarcity has been regarded as the water crisis facing the world globally at every level. It arises in the situations where water demand exceeds over water availability supplied to a specific area [6]. The water scarcity is generally described in two specific manners: (1) physical water scarcity and (2) economic water scarcity. The physical water scarcity is commonly occurred because of the natural phenomena and human–induced influences [7]. The economic water scarcity is caused by a lack of investment or human capacity to satisfy the demand for water [8]. In Thailand, the physical water scarcity has been considered as national treats not only affecting for agricultural sector which is accounted for over 70% of water use, but also trucking the drinking water to some specific areas particularly in the worst dry years. It is reported that the rapid growth of population and development of industrial sector as well as the urbanization have sent the water demand soaring in recent years which have heightened the risk of water scarcity [9]. The situations of worst drought have been frequently found in a wide area of the Chao Phraya River Basin (CPYRB) due to an unusually low rainfall leading to unusually low water levels in major reservoirs and rivers [9]. CPYRB is the major artery for land and water resources development situated in the central region of Thailand. In the recent years, CPYRB is in the transition from water richness to water scarcity due to large fluctuations of water supply sources and growing water demands. Consequently, a systematic modernization framework and technological advancement to water resources management are certainly needed to achieve the equitability, sustainability, and efficiency in this region [10].

The reservoir simulation and optimization algorithms have been extensively introduced to overcome water scarcity and its risk and to optimize the beneficial uses of limited water supply [11–14]. A diverse range of optimization techniques such as continuous and discrete optimizations, unconstrained and constrained optimizations, deterministic and stochastic optimizations, single and multi–objective optimizations have been widely used to solve the real–world problems. Generally, the optimization problems can be solved by linear and non–linear programming through numerous optimization algorithms. The optimization algorithm is a sort of mathematical algorithms used in machine learning to find the best alternative under the given constraints [15] such as simplex algorithm, gradient–based algorithms, derivative–free algorithms, and metaheuristics. A broad array of computerized optimization techniques and problem solving, and algorithms have been adopted for modelling of the multi–reservoir system operation aiming to deal with the imbalance between water supply and water demand. It is evidenced that optimization can be a powerful tool particularly for large–scale non–linear optimization problems to achieve the optimality of operational problems for multi–purpose reservoir system [16–19]. Moreover, it is stated that the constrained optimization such as constrained genetic algorithm, constrained particle swarm optimization algorithm, and constrained gravitational search algorithm provide better operational results for solving multi–reservoir optimization problems [20–23].

Fmincon (Find minimum of constrained non–linear multivariable function) optimization algorithm which is a non–linear programming solver provided in MATLAB's optimization toolbox, is commonly used to find the minimum of the specific problems. It is capable of finding the minimum value of an objective function subject to linear inequality constraints, linear equality constraints, non–linear constraints, and bound constraints. In addition, Fmincon can also incorporate gradient evaluation in the objective function for faster or more reliable computations [24]. Fmincon optimization has been used in water resources management system to minimize the major water problems. For example, MATLAB programming by Fmincon algorithm was demonstrated to optimize the optimal operation schedule of a hydroelectric dam [25]. Fmincon optimization was also established to find the optimal water allocation of low–cost water distribution networks [26]. In addition, programming method by Fmincon was deployed for conflict resolutions over water resources allocation in a river basin [27]. Therefore, this study aims to find the optimization–based solution for reducing water scarcity in the Greater Chao Phraya River Basin (GCPYRB), Thailand to help assist the current operation of the Bhumibol (BB) and Sirikit (SK) Dams in supplying water to GCPYRB. As a variety of non–linear multivariable problems with linear and non–linear constraints can be solved well by Fmincon algorithm, the multi–reservoir re–operation system model in GCPYRB was accordingly developed through MATLAB programming using Fmincon optimization algorithm and visually displayed and analyzed the simulation results using Simulink. The optimum daily releases of these two dams were solved to minimize the long–term water deficit in the region.

2. Study Area

The Greater Chao Phraya River Basin is termed for this study to describe the principal river basin cluster for cooperative management of water resources in the central region of Thailand. GCPYRB covers the drainage area of approximately 30% of the country's area [28] composing seven basins namely, Ping (34,468 km^2), Wang (10,789 km^2), Yom (24,000 km^2), Nan (34,557 km^2), Pasak (16,291 km^2), Sakae Krang (5,191 km^2), and Tha Chin (13,681 km^2) river basins as shown in Fig. 1a [29]. There are two large multipurpose dams; Bhumibol (BB) and Sirikit (SK) Dams and two medium multipurpose dams; Khwae Noi Bumrung Dan (KNB) and Pasak Jolasid (PS) Dams supplying water to satisfy the local demand and joint demand in the basin as shown in Fig. 1b. More than 70% of water supply sources has been provided for agricultural water sector occupying the irrigation service area of more than 10 million rai along the Chao Phraya, Lower Ping, and Lower Nan Rivers in the Greater Chao Phraya Irrigation Scheme (GCPYIS). BB and SK Dams have been acted as the principal water supply sources not only to supply water for non-agricultural and agricultural water uses but also to prevent the massive floods and the hazardous droughts in the region. BB Dam is the first multipurpose concrete arch dam built across the Ping River in the north. It was constructed and completed in 1964 with the storage capacity of 13,462 MCM. SK Dam was designed as a multipurpose embankment dam with the storage capacity of 9,510 MCM. It was constructed across the Nan River in the north and completed in 1972. Both BB and SK Dams can be also served for hydropower generation with the average power energy of 1,037 and 1,000 GWHr per year, respectively. Operating these two reservoirs has been undertaken by the Electricity Generating Authority of Thailand (EGAT) through collaboration with the Royal Irrigation Department (RID) in supplying water for multiple uses downstream. While, the Office of National Water Resources (ONWR) has acted as the command center for water resources management in this region.

It is reported that the natural disaster occurrences of floods and droughts have been frequently occurred in GCPYRB over the past decades. In 2011 and 2021, this region was struck by the major flood creating a huge agricultural and economic losses of the country [30–31]. In addition, some irrigation area in GCPYIS particularly in the Lower Ping Water Distribution Zone was struggled with water scarcity in few consecutive years from 2018 to 2020 due to impact of climate change, leading to the significant reduction in crop yield production. The sign of drought has been visible since 2018 when weak El Niño has emerged. The total rainfall was approximately 5%–10% below average in 2018 and 2019. It is explored that a large fraction of rainfall fell outside watersheds of dam–reservoir system which led to the decrease in water supply stored in reservoirs at the end of 2019. This made the impact of the shortfall in water supply in 2020 inevitably [32]. Moreover, it is reported that the probability to operate the dam–reservoir system under the risks of flooding in wet years and drought in dry years reached up to 40% [33]. This signifies the current situation of water stress in this region that needs to be addressed for climate change adaptation in future.

3. Methodology

3.1. Data Collection

The daily reservoir data of BB and SK Dams from 2000 to 2020 were collected to develop the reservoir re–operation model using the water balance–based approach. The daily target water demand in GCPYRB were generated in the same period corresponding to seasonal and yearly water allocation plans established by RID and EGAT from 2000 to 2020. The reservoir re–operation model, which is kind of system simulation, was embedded into the optimization model to find the optimality of daily long–term released water through Fmincon optimization algorithm. In this study, determining the volume of water released from dams at the specified time periods was manipulated by considering not only the existing states of water storages stored in reservoirs but also the potential side flow downstream of BB and SK Dams. The potential side flow at key gauged stations namely, W.4A, Y.17, and N.22A contributing from the Wang, Yom, and Khwae Noi Rivers which are main tributaries of the Chao Phraya River, were accordingly used as influencing inputs to help reduce the volume of dam release and store some water in the reservoirs for subsequent use in the later periods.

3.2. Formulation of Optimization Models in GCPYRB and Scenario Analysis

Firstly, the optimization model for re–operating the BB and SK reservoirs was developed through MATLAB programming by using Fmincon optimization algorithm. A single objective optimization was selected instead of multi–objective optimization in the way of finding the best solution mainly for reducing water scarcity in GCPYRB in a specified time period. The daily optimal releases of joint operations of the BB and SK Dams of three scenarios were accordingly solved by aiming to minimize the long–term water deficit in GCPYRB. Secondly, the potential in increasing water storage volumes of BB and SK Dams at the end of wet season on the 30th of November was diagnosed and compared with current operation to explain the capability in coping with water scarcity problem over the dry season in the region. The potential side flow at W.4A station was used to reduce the volume of dam release of BB Dam, meanwhile, side flow at Y.17 and N.22A stations were used to reduce some extent of release amount of SK Dam. The water sharing ratios of BB and SK Dams were considerably explored in both short–term and long–term operations to investigate the manageability of Fmincon optimization for multi–reservoir re–operation system in GCPYRB. In the last step, reservoir operational performances in terms of reliability, vulnerability, and resiliency were investigated and compared with the current operation.

3.2.1. Background of Non–linear Optimization with Fmincon Algorithm

Fmincon is generally used in finding the minimum of non–linear multivariable problems for both the linear and non–linear constraints. The objective function and associated constraints of the Fmincon function can be performed as follows:

Objective function: *Minimize F(x)*

$$\text{Constraints:}\quad c(x) \le 0,\quad ceq(x) = 0,\quad A.x \le b,\quad Aeq.x = beq,\quad lb \le x \le ub \tag{1}$$

Variable: $x = Fmincon\ (fun, x0, A, b, Aeq, beq, lb, ub, nonlcon, options)$

where $F(x)$ is an objective function that returns a scalar. $c(x)$ is non–linear inequality function and $ceq(x)$ is equality function that return vectors. A and Aeq are coefficient matrices of linear inequality and linear equality functions, respectively. b and beq are constant vector inequality and equality functions, respectively. lb and ub are lower and upper bounds that can be adopted as vectors or matrices. It can be explained that Fmincon can find a constraint minimum function of multivariable "fun" starting at the initial estimate *"x0"* subject to the linear inequality "$A.x \le b$" and linear equality "$Aeq.x = beq$" and a set of lower and upper bounds on the decision variables x. Therefore, the solution is in a range "$lb \le x \le ub$". In addition, it can be minimized with the non–linear inequality "$(c(x) \le 0)$" and equality "$ceq(x) = 0$" defined in *"nonlcon"* and specified optimization parameters in the model structure *"options"*. The result *"x"* is obtained by using the Fmincon function which can be varied corresponding to objective function, constraints, and options of algorithm. The option is used to observe the Fmincon solution process in the constraint optimization and the Quadratic Programming (QP) is then adopted to solve at each iteration. The iterative process begins with an initial estimate by the algorithm and stops when all the setup criteria are met. Accordingly, the important criteria for the Fmincon function in the optimization problem is that the initial estimate of variable *(x0)* should be predefined [25].

3.2.2. Implementation of Non–linear Optimization with Fmincon Algorithm for the Multi–reservoir Re–operation System in GCPYRB

The simplified structure of optimization model formulated by the Fmincon function in MATLAB for the development of multi–reservoir re–operation system in GCPYRB is shown in Fig. 2. Starting the modelling process involved with the preparation of data inputs of two main dams namely, the reservoir inflow ($I(t)$), evaporation losses ($E(t)$), the observed values of spilled water ($SW(t)$), and target water demand ($D(t)$). The initial water storage of the reservoir can be defined as the initial estimate ($x0$). If the first–order optimization is fulfilled by the last iteration, the result is considered as a local minimum that satisfies system needs. The description of main features of this algorithm is explained in Fig. 2.

3.2.2.1. Objective Function

Setting up the objective function for multi–reservoir re–operation model was referred to the minimization of the water scarcity evaluated in term of water deficit in GCPYRB due to the joint operation of BB and SK Dams. Consequently, it can be computed by minimizing the sum of squared residuals between the total water released from reservoirs and target water demands. The following expresses the mathematical equation of objective function identified in this study:

$$Minimize \sum_{t=1}^{T} \sum_{i=1}^{n} (R_i(t) - D(t))^2 \tag{2}$$

where *'t'* is the simulation time steps, *'n'* is the total number of reservoirs, and *'i'* is the reservoir i. $R_i(t)$ refers to the release (MCM) from reservoir *'i'* at the time step t. $D(t)$ is the total target demand (MCM) at the time step t considering local and joint demands in GCPYRB. T is the total time step.

3.2.2.2. Constraints

Formulating the Fmincon optimization for multi–reservoir re–operation model of BB and SK Dams is constrained by several limitations corresponding to the decision variable and physical system in GCPYRB as expressed in the following equations

3.2.2.2.1. Release Constraint

The minimum and maximum releases in each time step can be determined by the lower and upper bound constraints equation:

$$Rmin_i \le R_i(t) \le Rmax_i \tag{3}$$

where *Rmin* and *Rmax* are defined as the minimum and maximum permissible releases. In this study, the minimum water releases of BB and SK Dams are determined to achieve the ecological needs of 2.5 and 3.0 MCM per day, respectively. The maximum water release is specified in accordance with the maximum turbine discharge of a hydropower system of BB and SK Dams. In addition, the total amount of water released in each time step should be greater than the target water demand as expressed in the linear inequality constraint equation:

$$\sum_{i=1}^{n} R_i(t) \geq D(t) \tag{4}$$

If the observed side flow from main tributaries was considered as potential source to help reduce the volume of dam release, consequently, the linear inequality constraints of water release was changed into:

$$\sum_{i=1}^{n} R_i(t) + SF(t) \geq D(t) \tag{5}$$

where $R_i(t)$ is the water released from the reservoir *'i'* in time step t. $D(t)$ is the total target demand at the time step t, and $SF(t)$ is the total side flow from main tributaries at time step t.

3.2.2.2.2. Mass Balance Constraint

The mass balance constraint of each reservoir was then determined as the foundation of conservation of mass in reservoirs. In the equation, the reservoir water storage at the beginning of the subsequent time interval can be calculated and expressed by the linear equality constraint equation as follows:

$$S(t+1) = S(t) + I(t) - E(t) - R(t) - SW(t) \tag{6}$$

where $S(t+1)$ represents the water storage of the reservoir at time step t+1; $S(t)$ is the initial storage of the reservoir at time step t; $I(t)$ is the reservoir inflow volume at time step t; $E(t)$ is the evaporation loss from the reservoir at time step t; $R(t)$ is the water release volume or the reservoir outflow discharging into the hydropower turbines; and $SW(t)$ is the spilled water from the reservoir at time step t.

3.2.2.2.3. Reservoir Storage Constraint

The water storage, $S(t)$ is dynamically changed due to the associated reservoir data and amount of released water. The reservoir water storage at time step t is constrained by the maximum water storage (*Smax*) and minimum water storage (*Smin*) of the reservoir. The available water storage of the reservoir *'i'* in each time step can be determined by the bound constraints as expressed in the following equation:

$$Smin_i \leq S_i(t) \leq Smax_i \tag{7}$$

where $S_i(t)$ is the storage volume from the reservoir *'i'* at time step t.

3.2.2.2.4. Spilled Water Constraint

When the final water storage, $S(t+1)$, exceeds the maximum defined limit of the reservoir storage capacity, the spilled water at time step, $SW(t)$ is overflowed through the spillway structures which can be mathematically computed by the following equation:

$$SW(t) = S(t+1) - Smax \tag{8}$$

In addition, the spilled water constraints from the reservoir *'i'* is represented by the bound constraints equation as follows:

$$SW_i(t) \geq 0 \tag{9}$$

where $SW_i(t)$ is the spilled water from the reservoir *'i'* at time step t.

3.2.3. Model Setting for Multi–reservoir Re–operation System in GCPYRB

The system consists of two main reservoirs; BB and SK as previously shown in Fig. 1. However, the influence on the released water from KNB Dam where additional flow is adjoined to the Nan River, is considered in a form of potential side flow. Therefore, the river flow at N.22A gauged station was used. The optimization model for multi–reservoir re–operation system in GCPYRB was developed from 2000 to 2020. The initial estimates of water storages of BB and SK Dams were determined at full reservoir levels as expressed in the following equation:

$$[S_{BB}(0) \quad S_{SK}(0)] = [9{,}505 \quad 9{,}070] \tag{10}$$

where $S_{BB}(0)$ and $S_{SK}(0)$ are initial storages of BB and SK Dams, respectively at the beginning of time step. The objective function of the optimization model was formulated as the minimization of the total water deficit over the operational period which was specified as the differences between the total amount of water released from two reservoirs and the amount of downstream water demand as expressed in the equation. The storage capacity and reservoir inflow were the state variables describing the mathematical state of reservoir operation system. The reservoir water released from BB and SK Dams in each time step were considered as decision variables aiming to be solved. Therefore, the objective function of this study can be written in the following equation.

$$Minimize \sum_{t=1}^{T} (R_{BB}(t) + R_{SK}(t) - D(t))^2 \tag{11}$$

where $R_{BB}(t)$ and $R_{SK}(t)$ are water released from BB and SK Dams, respectively, and $D(t)$ is the target water demand for GCPYRB at the time step t. T is the total time step.

Constraints of multi–reservoir re–operation system in GCPYRB are expressed in the following equations. Release constraint imposed on the minimum and maximum releases from BB and SK Dams as follows:

$$\begin{bmatrix} 2.5 \\ 3.0 \end{bmatrix} \leq \begin{bmatrix} R_{BB}(t) \\ R_{SK}(t) \end{bmatrix} \leq \begin{bmatrix} 69.76 \\ 63.24 \end{bmatrix} \tag{12}$$

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To satisfy the downstream water demand, the total amount of water supply from these two reservoirs should be greater than or equal to the target water demand for GCPYRB as follows:

$$R_{BB}(t) + R_{SK}(t) \geq D(t) \tag{13}$$

If the side flow from main tributaries was considered, the total water supply constraint should be transformed into the following equation:

$$R_{BB}(t) + R_{SK}(t) + SF(t) \geq D(t) \tag{14}$$

Reservoir storage capacity constraint limiting the minimum and maximum water storages of BB and SK Dams was defined as follows:

$$\begin{bmatrix} 3,800 \\ 2,850 \end{bmatrix} \leq \begin{bmatrix} S_{BB}(t) \\ S_{SK}(t) \end{bmatrix} \leq \begin{bmatrix} 13,462 \\ 9,510 \end{bmatrix} \tag{15}$$

In addition, the spilled water from BB and SK Dams was constrained in the following equation:

$$\begin{bmatrix} S_{BB}(t) \\ S_{SK}(t) \end{bmatrix} \geq \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{16}$$

where $SW_{BB}(t)$and $SW_{SK}(t)$ are spilled water from BB and SK Dams, respectively at time step t.

3.2.4. Scenario Setting for Ultimate Use of Optimization Models

To achieve the ultimate aim of this study in view of increasing the reservoir water storage and reducing the water deficit, three scenarios of optimization model for multi–reservoir re–operation in GCPYRB were established under the reasoned assumption that seeking potential water supply sources to satisfy rising water demand and assessing its viability has become necessary for sustainable water resource management in future. For this reason, the potential side flow downstream of BB and SK Dams is considered to reduce the redundant water released from dams as follows:

(1) Scenario 1: re–operating the dams without considering potential side flow. The total water demand in GCPYRB can be supplied by two main dams only.

(2)Scenario 2: re–operating the dams by considering 25% of potential side flow. The 25% of total water demand can be partially satisfied by the side flow and the remaining will be supplied by BB and SK Dams. Therefore, some amount of water can be saved and stored in reservoirs.

(3)Scenario 3: re–operating the dams by considering 50% of potential side flow. In other words, the total water demand can be potentially satisfied by the side flow when it reaches a level much higher than the daily target demand at the specified times. Therefore, the dam release becomes zero and can be stored for later use in reservoirs.

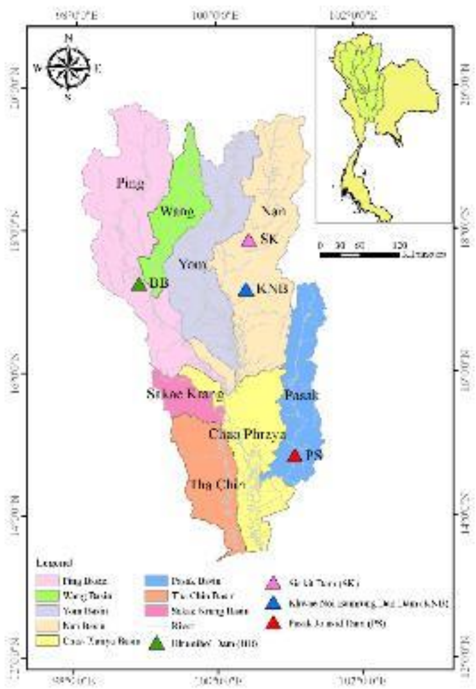

Fig. 1a. The location of the study area showing the Bhumibol and Sirikit Dams in the Greater Chao Phraya River Basin.

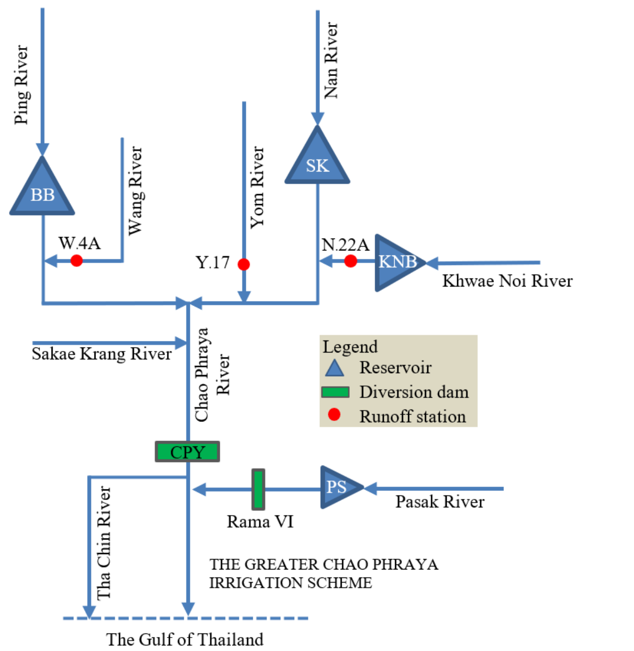

Fig. 1b. The schematic diagram of the Greater Chao Phraya River Basin.

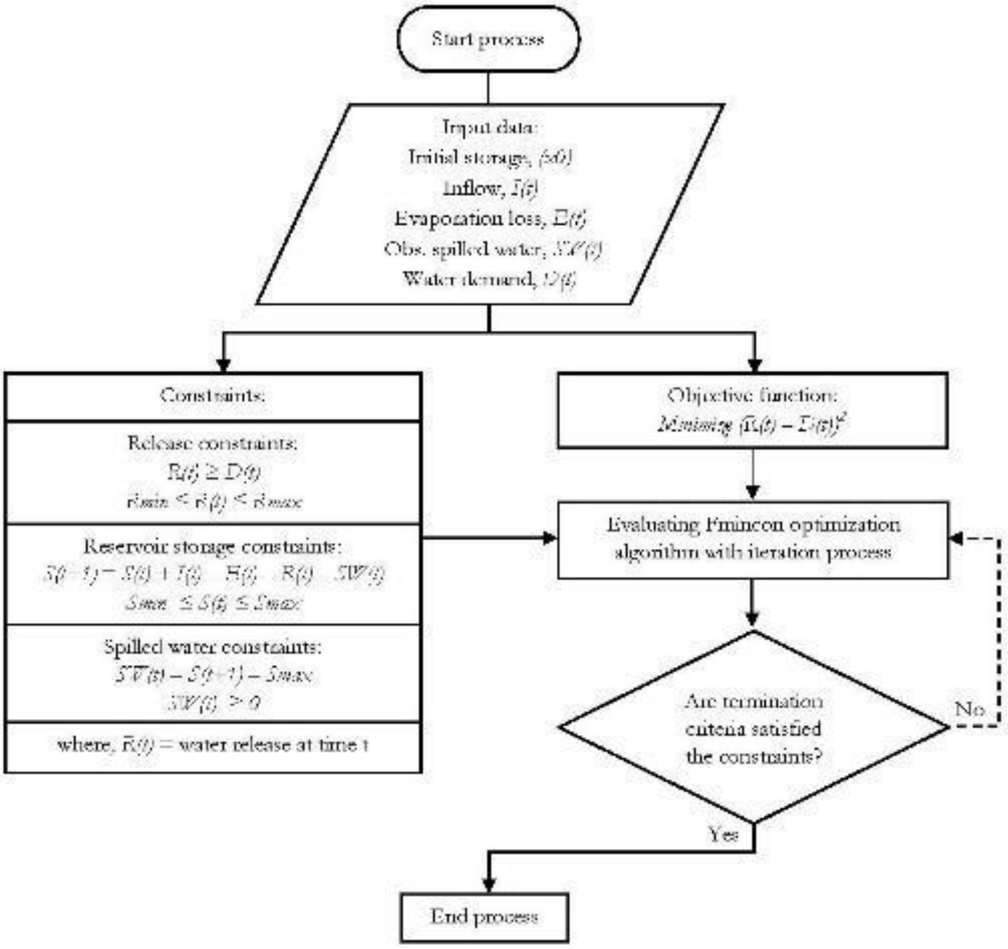

Fig. 2. Flow diagram of multi–reservoir re–operation model using the Fmincon algorithm.

3.3. Evaluation of Reservoir Performance Indices (RPI)

A large number of reservoir performance indices (RPI) have been introduced and applied to assess the performances of the reservoir operation system for more than a decade [34–35]. In this study, three famous reservoir performance indices were used namely, reliability, resiliency, and vulnerability, to assess the performance of the multi–reservoir re–operation performed by the Fmincon optimization algorithm.

3.3.1. Reliability index

The reliability index measures how much the system is accessible or the system performs unsatisfactorily within the simulation time periods [34–35]. It can be mathematically computed using the following equation:

$$Reliability\ (\%) = \frac{events\ that\ water\ demand\ are\ satisfied}{total\ events} x100 \tag{17}$$

3.3.2. Vulnerability index

The vulnerability index describes the severity of deficit occurrence throughout the simulation time periods [34–35]. The expression of vulnerability is given in the equation:

$$Vulnerability\ (\%) = \frac{total\ amount\ of\ water\ deficit}{total\ amount\ of\ target\ demand} x100 \tag{18}$$

3.3.3. Resiliency index

The resiliency explains how long the system is likely to recover from the failure events to satisfied events [34–35]. Therefore, continuous consequences of unsatisfied events are counted over the entire simulation time periods and divided by the total unsatisfied events as expressed in the following equation:

$$Resiliency\ (\%) = \frac{continuous\ consequences\ of\ unsatisfied\ events}{total\ unsatisfied\ events} x100 \tag{19}$$

4. Results and Discussions

4.1. Current Status of Water Supply and Water Demand in GCPYRB

To exhibit the water scarcity in the system due to the current dam operation in GCPYRB, the monthly, seasonal and yearly status of water supply and water demand sides from 2000 to 2020 was evaluated and compared as presented in Fig. 3, Fig. 4 and Table 1. The reservoir inflows of BB and SK Dams and potential side flow from main tributaries downstream of these two main dams were used to describe the water supply potential in the system. The results of preliminarily analysis of long–term average observed data illustrate that the yearly inflows of BB and SK Dams were approximately 5,444 and 6,103 MCM, respectively. It is obviously appeared that the reservoir inflows into BB and SK Dams have become significantly decreased since flooding event occurred in 2011 [36–38] as shown in Fig. 4. The average inflows of the BB and SK Dams from 2012 to 2020 have been declined by approximately 55% and 26% of the average long–term record (2000–2020), respectively. Moreover, high temporal and spatial variability of hydrological changes in the basin such as rainfall and climate data has considerably influenced the volume of reservoir inflows of these two dams. For the analysis of seasonal data, the reservoir inflows into BB and SK Dams in wet season (May–Oct) were amounted to 4,552 and 5,203 MCM, respectively which were much higher than in dry season (Nov–Apr) amounted to 892 and 900 MCM, respectively. By comparing the water availability from these two dams with the target water demand in GCPYRB, it is exhibited that the average yearly demand generated from water allocation plan from 2000 to 2020 was accounted for 10,557 MCM which is very close to the total amount of reservoir inflows of BB and SK Dams in normal years. More than 60% of water demand was supplied to target demand nodes in dry season. Although the average yearly inflows of BB and SK Dams was higher than the average target water demand in the system, however, the seasonal and year to year variability were definitely high. It is apparent that the percentage difference of total reservoir inflows and target water demand in dry season climbed up to –72.46% and slightly declined to –51.33% when the side flow and reservoir inflows were considered as potential water supply sources. It is explored that joint operation of BB and SK Dams from 2000 to 2020 could be handled with water deficit reduction at some extent in GCPYRB. The available excessive water at the end of wet season was utilized to supply water over the dry season. The released water was accordingly shared by BB and SK Dams with the proportion of 0.44:0.56. However, the sharing ratio of dam releases varies greatly on the daily and seasonal basis. In addition, there is no precise operational rule in identifying the sharing water releases between BB and SK Dams in clear picture on the sustainability view. Therefore, recognizing the effectively operational tool for re–operating the multiple dams is essentially needed to specify the proper portion of dam releases corresponding to the temporal variability of water supply data and water demand in the system.

4.2. Optimization Results Accomplished by Fmincon Algorithm for the Multi–reservoir Re–operation System in GCPYRB

4.2.1. Dam releases and water storages

The optimization results of these three scenarios for the multi–reservoir re–operation system in GCPYRB were obtained when all the optimality conditions and constraint tolerances were successfully met. The capability of the Fmincon optimization for dam re–operation was proven through qualitative and quantitative comparison of dam releases and changes in reservoir water storages. It is exhibited that the amount of daily dam releases of BB and SK Dams accomplished by the Fmincon optimization lie between minimum and maximum ranges of the corresponding reservoirs as presented in Fig. 5(a) and Fig. 5(b). In addition, the release patterns for all three scenarios also conform to the current releases of BB and SK Dams. The water storages of scenario 1 performed by Fmincon optimization seems to be very close to the current operation in the initial period from 2000–2012 and is slightly lower in the later period from 2013–2020. This is because the variability of reservoir inflows which was much lower than the average values after 2012. However, considering the potential side flow for the determination of dam releases with scenario 2 and scenario 3 can be well operated to increase the water storages of BB and SK Dams particularly since 2012 as illustrated in Fig. 6.

4.2.2. Manageability of Fmincon optimization to water scarcity

In this study, the "Total Water Supply (TWS)" was termed as the combination of water released from BB and SK Dams and potential side flow for the assessment of the water deficit as the results of the Fmincon optimization model. The monthly and yearly extent of water deficit was computed to describe the water scarcity at the aggregate level by comparing TWS with the "Target Water Demand (TWD)" which was generated from the water allocation plan established by RID and EGAT covering all water demand sectors namely, agriculture, municipality, industry, and ecological needs. The total water supply accomplished by Fmincon optimization with three scenarios is presented and compared with the current operation in Table 2 and the distribution of monthly and yearly water deficit is illustrated in Fig. 7 and Fig. 8. It is revealed that TWS for scenario 1 is a bit higher than TWD of +2.25% for the entire year which is very close to TWS undertaken for the current operation of +5.58%. The water deficit for the current operation is found mostly in critical dry years in 2010, 2012, 2015, 2016, 2017, and 2020 when the reservoir inflows of two main dams are extremely low but water demand is expected to increase significantly. The average amount of total water deficit for the current operation from 2000 to 2020 is approximately 73.71 MCM per year which is found in the late dry season to the initial wet season from May to June and in September. This might be because the delay in the arrival of monsoon rain which is actually the main supply source of water in the region. In addition, expanding the areas of cultivation by farmers both in dry and wet seasons when the water supply is limited, is sometimes out of control leading to high water consumption. Moreover, groundwater is used as supplementary source during critical dry years to reduce water deficit in the region. The amount of water deficit for scenario 1 can be definitely reduced to nearly zero. This is because the Fmincon optimization attempts to determine the released water to meet the target water demand at all possible time steps when water storages in the reservoirs can be accessible. As a result of Fmincon optimization, water storages of BB and SK Dams are lower particularly in the end of dry season since 2012 as the dam delivers maximum extent of released water throughout dry season to reduce water deficit. However, considering potential side flow for the scenario 2 and scenario 3 can help increase the volume of TWS of nearly 335 and 833 MCM per year. Consequently, there are no water deficit occurred throughout the simulation periods. All in all, TWS for all scenarios is higher than TWD in both dry and wet seasons. These results signify that Fmincon optimization can be an optional tool in moderating the severity of water scarcity when the optimal dam releases between BB and SK were solved.

4.2.3. Potential of increasing reservoir water storages

The potential in increasing water storages of BB and SK Dams at the end of wet season was investigated to describe capacity in supplying water over dry season and coping with water deficit for the next coming years by Fmincon optimization. The net amount of dam releases and water sharing ratio of BB and SK Dams supplied to the target demand in GCPYRB were considerably evaluated. The results are summarized in Table 3 and Fig. 9. It is indicated that the average annual released water of scenario 1 is slightly lower than the current operation by –3.13% and –3.65% for BB and SK Dams, respectively. Consequently, raising up water storages for scenario 1 can be achieved through Fmincon optimization by increasing +12.48% and +5.23% of water storages for BB and SK Dams, respectively. Considering potential side flow for scenario 2 and scenario 3 can help reduce the volume of yearly water released from two main dams of –1,025 and –1,505 MCM, respectively. This indicates the capability in increasing the reservoir water storages at the end of wet season. Consequently, the water storage of BB Dam for the scenario 2 and scenario 3 can be increased by +29.01% and +36.07% higher than the current operation. Similarly, the water storage of SK Dam can be raised up by +17.38% and 21.39% for the scenario 2 and scenario 3, respectively. The water sharing between BB and SK Dams performed by Fmincon optimization for three scenarios was also explored to see the behavior of joint operation of these two reservoirs in supplying water to the water demand nodes. It is revealed that there is not much difference in term of water sharing ratio between BB and SK Dams for all scenarios and current operation when the long–term average values of optimal water sharing ratio were evaluated. Water allocation between BB and SK Dams from 2000 to 2020 was shared in the existing 0.44:0.56 ratio for scenario 1 and current operation and 0.45:0.55 ratio for scenario 2 and scenario 3. It seems to be insubstantial differences in long–term average values of optimal water sharing ratio among these scenarios compared with the current operation. However, high variability in daily water sharing ratio between BB and SK Dams could be predominantly reduced when Fmincon optimization was implemented as illustrated in Fig. 9(a), Fig. 9(b), Fig. 9(c), and Fig. 9(d). The proportion of water released from SK Dam in dry and normal years is still higher than BB Dam for all scenarios and higher than the current operation particularly in normal years. However, the Fmincon optimization proposes to supply water from BB Dam higher than SK Dam specially in dry season (Jan–May) of wet years with the average yearly water sharing ratio of 0.54:0.46, 0.55:0.45, and 0.55:0.45 for scenario 1, scenario 2, and scenario 3, respectively. As a result, the average monthly release schemes in dry years, normal years, and wet years are accordingly established and presented in Table 4. This leads to the increase in water storages of two main storage dams in a long–term operation if reservoir operating tool is changed. It can be drawn that altering the operational strategy by considering potential side flow and applying the new tools for dam re–operation is necessarily essential to achieve the operational goal in coping with water scarcity in this region.

4.2.4. Reservoir operation performance

The reservoir operation performance implemented by the Fmincon optimization for the multi–reservoir re–operation system in GCPYRB was assessed through three indices; (1) reliability, (2) vulnerability, and (3) resiliency as shown the results in Fig. 10. The reliability index was used to describe the capability of the operational system accomplished by the Fmincon optimization to satisfy target water demand in GCPYRB. It is appeared that applying Fmincon optimization together with considering the potential side flow for the determination of dam releases can handle well in solving the water scarcity problem in GCPYRB. The reliability index reaches up to 97%, 100%, and 100% for scenario 1, scenario 2, and scenario 3, respectively which is much higher than that quantified with reliability of 55% for current operation and above the acceptable level at 80% reliability [33]. Moreover, there is higher possibility to recover the operational system from water stress into satisfaction when the Fmincon optimization was employed. It is illustrated that the resiliency index accomplished by the Fmincon optimization lies from 80% to 100% for all

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scenarios which indicates potential low–risk in term of reservoir operation. The resiliency index for the current operation drops to 14% signifying that possibility to recover from water deficit situation in the region is harder particularly in critical dry years. In addition, the potential low–risk for all scenarios performed by the Fmincon operation is also found when vulnerability index was analyzed. The vulnerability index is accounted to 10% for the current operation and dropped to 0.1% for scenario 1 and 0% for scenario 2 and scenario 3, respectively. It is reassured that the severity level of water deficit occurred in this region can be solved at some extent by the optimization–based solution when optimal water sharing between BB and SK Dams is accordingly derived.

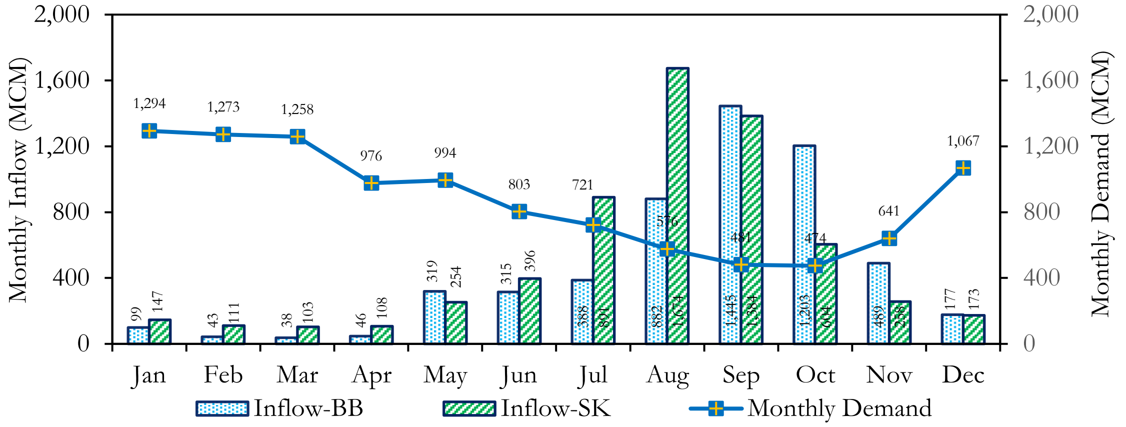


Fig. 3. Average monthly observed inflows of BB and SK Dams and target water demand from 2000 to 2020.

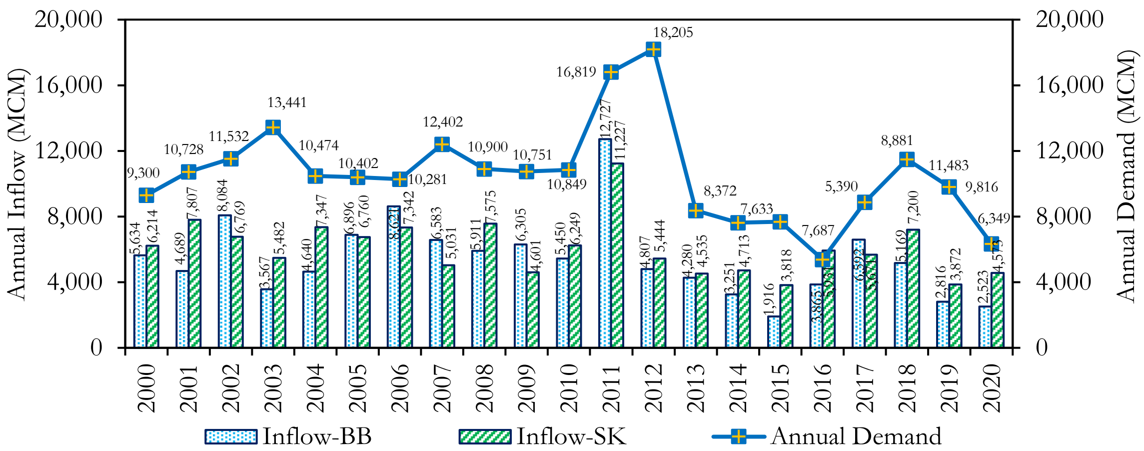


Fig. 4. Annual observed inflows of BB and SK Dams and target water demand from 2000 to 2020.

Table 1. Current Status of water supply and target water demand in GCPYRB from 2000 to 2020.

Water Supply and Water Demand	Dry Season (Nov–Apr)	Wet Season (May–Oct)	Yearly
Total reservoir inflows of BB and SK Dams (MCM)	1,792	9,755	11,547
Potential side flow from tributaries (W.4A, Y.17, N.22A) (MCM)	1,375	2,538	3,913
Target water demand in GCPYRB (MCM)	6,508	4,089	10,557
Δ_1 = Total reservoir inflows – Target water demand (%)	–72.46	+140.94	+9.38
Δ_2 = Total reservoir inflows + Potential side flow – Target water demand (%)	–51.33	+203.63	+46.45
Total reservoir outflows of BB and SK Dams (MCM)	7,110	4,065	11,175
Sharing ratio of water release ratio of BB:SK	0.46:0.54	0.43:0.57	0.44:0.56

Table 2. The comparison of total water supply and water deficit accomplished by Fmincon optimization.

Total Water Supply	Dry Season	Wet Season	Yearly
TWS for current operation (MCM, Δ%)	7,110 (+9.25)	4,065 (+0.40)	11,175 (+5.86)
TWS for scenario 1 (MCM, Δ%)	6,593 (+1.30)	4,202 (+3.78)	10,794 (+2.25)
TWS for scenario 2 (MCM, Δ%)	6,711 (+3.11)	4,418 (+9.12)	11,129 (+5.42)
TWS for scenario 3 (MCM, Δ%)	6,850 (+5.25)	4,777 (+17.99)	11,627 (+10.13)
Water Deficit (WD)	**Dry Season**	**Wet Season**	**Yearly**
WD for current operation (MCM)	0	73.71	73.71
WD for scenario 1 (MCM)	0	0	0
WD for scenario 2 (MCM)	0	0	0
WD for scenario 3 (MCM)	0	0	0

Remark: Δ is the different values compared to the target water demand

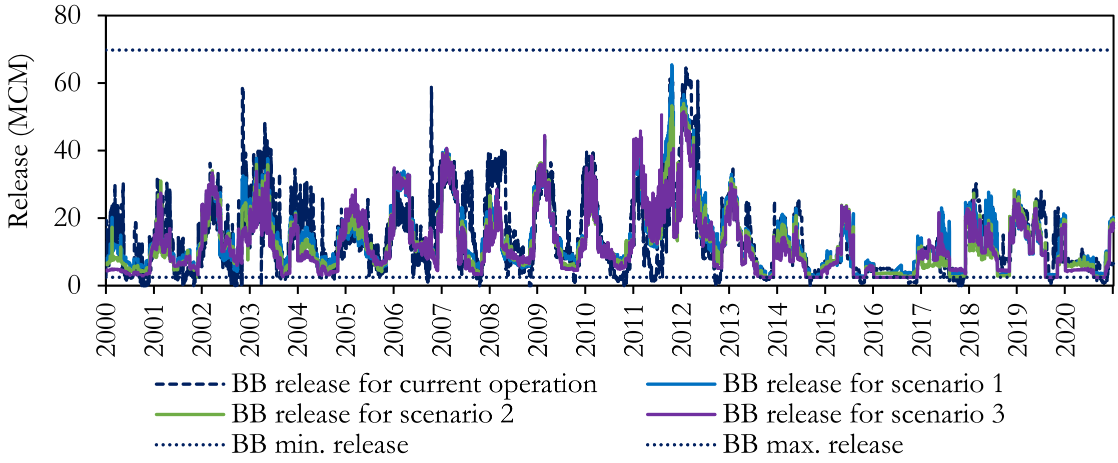
Table 3. Potential of increasing reservoir water storages.

Scenarios	Dam Release (MCM)						Increase in Water Storage (Δ %)					
	BB			SK			BB			SK		
	DS	WS	Yearly	DS	WS	Yearly	DS	WS	Yearly	DS	WS	Yearly
Current operation	3,424	1,780	5,203	3,687	2,285	5,972	–	–	–	–	–	–
Scenario 1	3,170	1,870	5,040	3,423	2,331	5,754	+11.03	+14.19	+12.48	+5.09	+5.40	+5.23
Scenario 2	2,996	1,666	4,662	3,371	2,118	5,488	+26.25	+32.26	+29.01	+16.83	+18.02	+17.38
Scenario 3	2,879	1,550	4,429	3,283	1,958	5,241	+32.97	+39.72	+36.07	+20.78	+22.10	+21.39

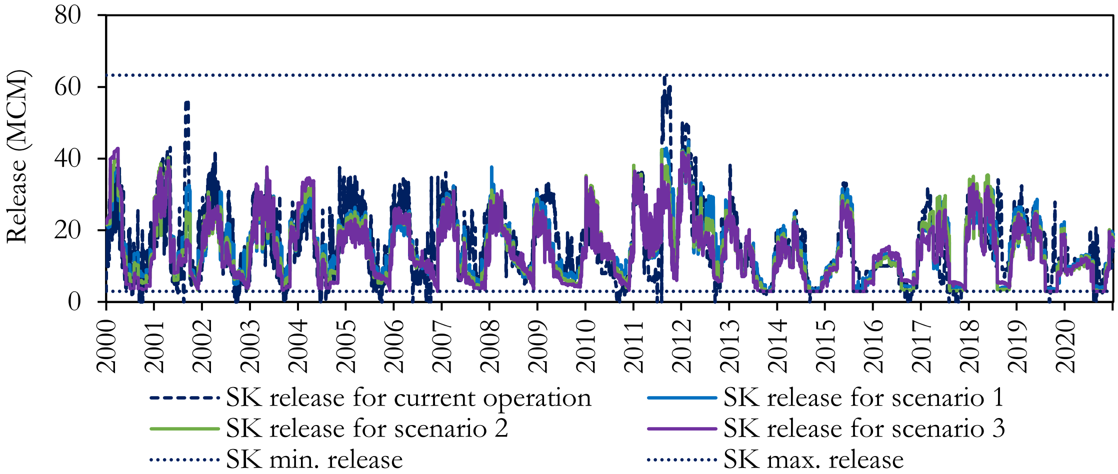
Remark: Δ is the different values compared to the current operation

Table 4. Average monthly release schemes of Bhumibol and Sirikit Dams (BB:SK ratio).

Month	Average Monthly Release Scheme from 2000 to 2020				Average Monthly Release Scheme in Dry Years				Average Monthly Release Scheme in Normal Years				Average Monthly Release Scheme in Wet Years			
	Current Operation	Scenario 1	Scenario 2	Scenario 3	Current Operation	Scenario 1	Scenario 2	Scenario 3	Current Operation	Scenario 1	Scenario 2	Scenario 3	Current Operation	Scenario 1	Scenario 2	Scenario 3
Jan	46:54	46:54	44:56	43:57	45:55	45:55	45:55	41:59	47:53	43:57	41:59	41:59	45:55	57:43	55:45	55:45
Feb	46:54	45:55	44:56	43:57	45:55	44:56	45:55	41:59	47:53	44:56	41:59	41:59	43:57	55:45	55:45	55:45
Mar	45:55	45:55	43:57	42:58	42:58	43:57	44:56	40:60	47:53	43:57	40:60	40:60	41:59	55:45	56:44	56:44
Apr	45:55	43:57	42:58	42:58	40:60	41:59	43:57	40:60	47:53	41:59	39:61	39:61	42:58	53:47	55:45	55:45
May	45:55	43:57	42:58	42:58	45:55	41:59	43:57	40:60	46:54	42:58	39:61	40:60	42:58	50:50	51:49	51:49
Jun	44:56	43:57	42:58	42:58	44:56	39:61	40:60	39:61	44:56	43:57	41:59	41:59	42:58	46:54	50:50	50:50
Jul	42:58	41:59	42:58	42:58	37:63	39:61	41:59	40:60	44:56	41:59	40:60	41:59	42:58	44:56	47:53	50:50
Aug	44:56	44:56	45:55	45:55	47:53	46:54	46:54	45:55	44:56	43:57	44:56	43:57	40:60	47:53	50:50	50:50
Sep	45:55	46:54	46:54	45:55	37:63	46:54	45:55	45:55	48:52	44:56	44:56	44:56	44:56	50:50	51:49	50:50
Oct	40:60	48:52	49:51	48:52	33:67	46:54	46:54	45:55	37:63	46:54	44:56	46:54	64:36	61:39	61:39	61:39
Nov	44:56	52:48	53:47	53:47	42:58	49:51	46:54	46:54	40:60	49:51	52:48	52:48	64:36	66:34	67:33	66:34
Dec	48:52	50:50	50:50	50:50	41:59	48:52	49:51	48:52	47:53	49:51	49:51	50:50	61:39	58:42	58:42	57:43

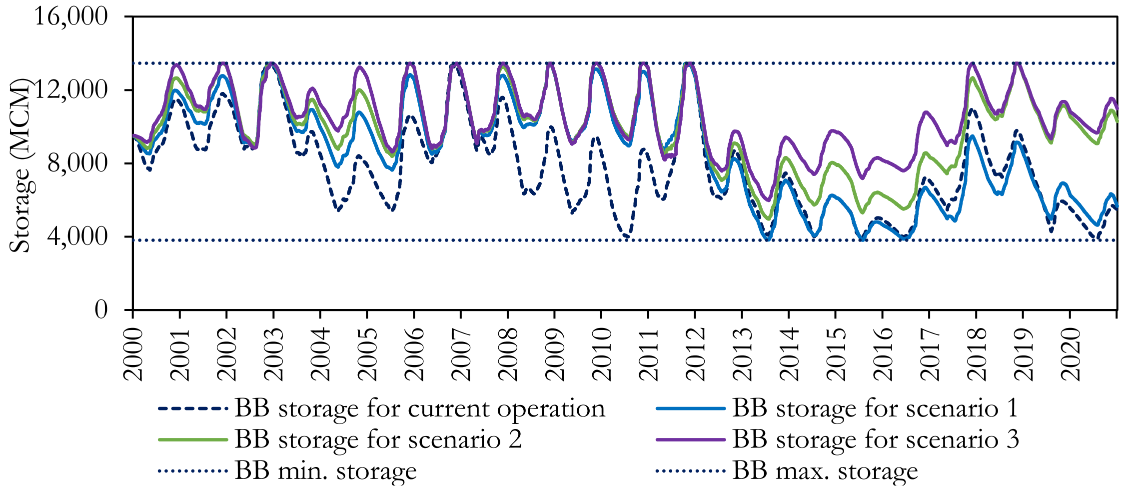


(a) BB Dam

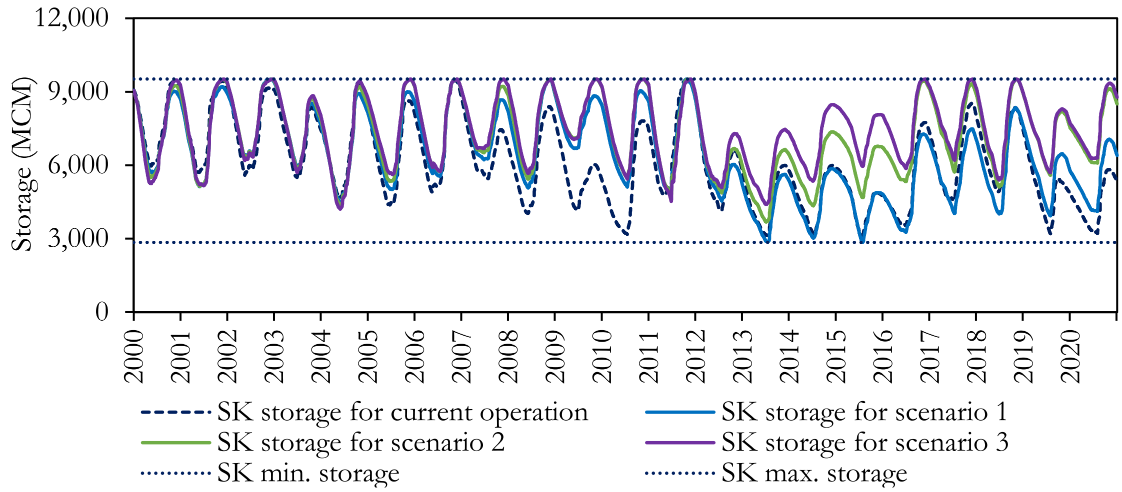


(b) SK Dam

Fig. 5. Optimal daily dam releases accomplished by Fmincon optimization and observations.



(a) BB Dam



(b) SK Dam

Fig. 6. Daily reservoir water storages accomplished by Fmincon optimization.

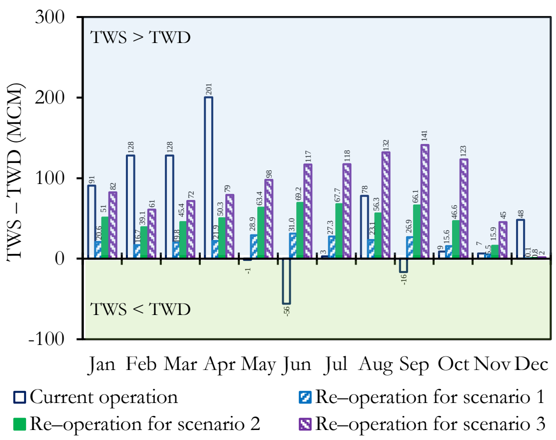


Fig. 7. Monthly water deficit when re–operating with Fmincon optimization from 2000 to 2020.

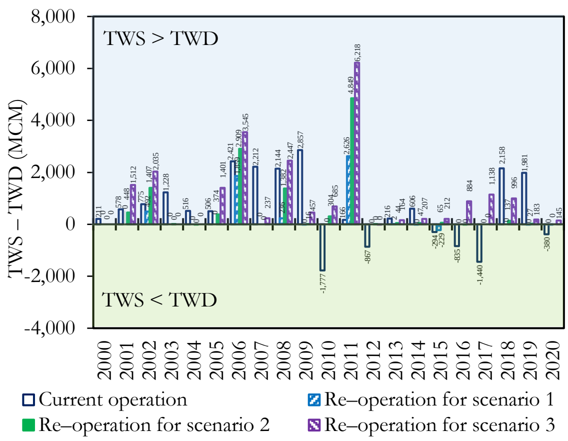


Fig. 8. Yearly water deficit when re–operating with Fmincon optimization from 2000 to 2020.

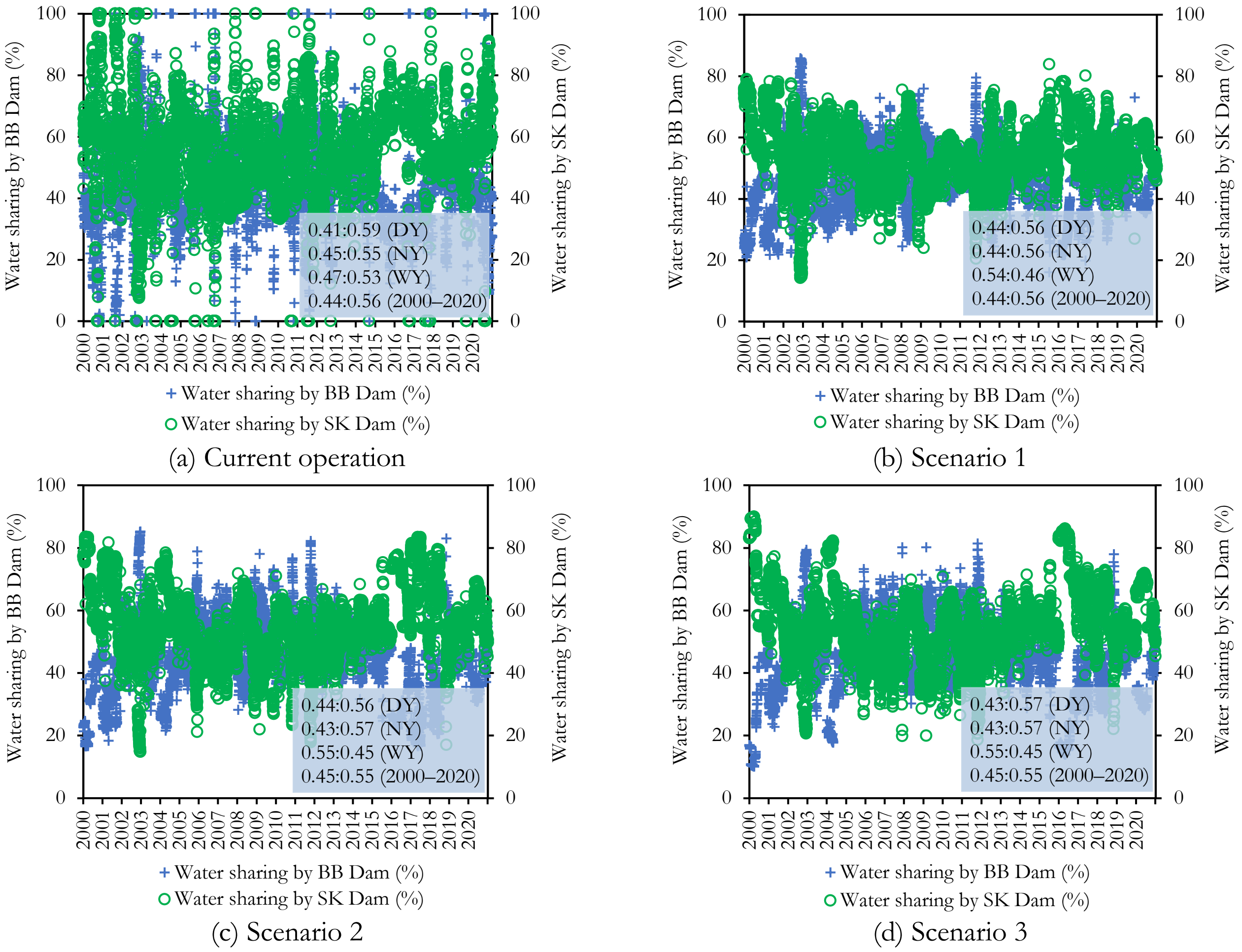


Fig. 9. Daily and average water sharing ratio between BB and SK Dams.

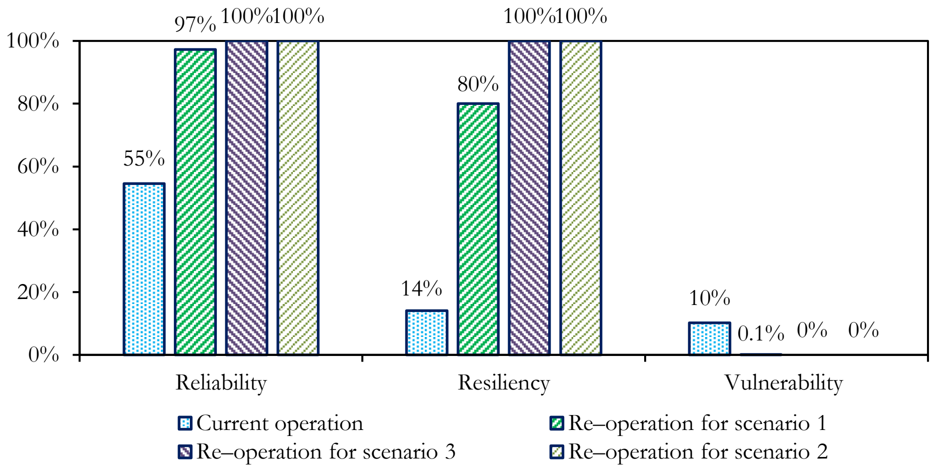


Fig. 10. Reservoir performance indices accomplished by Fmincon optimization.

5. Conclusion

It can be drawn that water scarcity can be reduced by the implementation of Fmincon optimization as it can derive the optimal water sharing between BB and SK Dams effectively corresponding to potential water supply in each reservoir and potential side flow at downstream gauged stations. Based on the optimality of long–term daily dam release proportionally shared by these two main dams, consequently, the dam operators can determine monthly and seasonal release schemes to represent flow regulation by reservoirs for substantial and robust improvement in solving water scarcity problem. In addition, applying Fmincon optimization can help increase the potential water storages of BB and SK Dams at the end of wet season significantly which indicates higher possibility in satisfying the rising needs of water over the dry season in this region.

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