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Simulation and optimization of multiple points hedging policies for operation of Cameron Highland hydropower reservoir system, Malaysia

Aida Tayebiyan[a], Thamer Ahmad Mohammad[b,*], Abdul Halim Ghazali[c], Megat Johari Megat Mohd Noor[d]

[a]*Environmental Health Engineering Research Centre, Kerman University of Medical Sciences, Kerman, Iran, Tel. +983431325435, Fax +603 8656 7129, email: ida_tayebiyan@yahoo.com (A. Tayebiyan)*
[b]*Department of Water Resources Engineering, College of Engineering, University of Baghdad, Iraq, Tel. +9647735966373, email: tthamer@gmail.com (T.A. Mohammad)*
[c]*Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia, Tel. +603 8946 6382, Fax +603 8656 7129, email: abdhalim@upm.edu.my (A.H. Ghazali)*
[d] *Ecological Engineering Research Group, Malaysia Japan International Institute of Technology (MJIIT), Unversiti Teknologi Malaysia, Kuala Lumpur, Malaysia, Tel. +603 2203 1215, Fax +603 2203 1266, email: megatjohari@hotmail.com (M.J.M.M. Noor)*

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ABSTRACT

Although hydropower generation has obvious advantages, but many of hydropower reservoir systems are still not operated efficiently and being operated based on experience. It is noticeable that even small improvement in operational rules can improve the efficiency of hydropower system. Since the output of hydropower generation depends on water release and water head, the concept of hedging and rationing can be used to minimize water release, maximize storage in the reservoir and increase water level in the reservoir. In this research, three competing hedging policies namely, one-point, two-point, and three-point are applied in order to optimize and improve the current operational policies used to generate hydropower in Cameron Highland hydropower system. The results indicate that the output of power generation in the studied system can be increased around 13% if the proposed hedging policies will be followed. Moreover, the discrepancies between highest and lowest monthly mean power generation can be reduced from 31% to 10% if the proposed hedging policies are followed in operating the studied system. This means that hedging policies will scatter the power supply in the operational period and increase stability of the system. Based on performance criteria, the best performance of the system is obtained from applying three-point hedging policy. The above results show the applicability of the proposed operational policy and improvement in power production.

Keywords: Hedging policies; hydropower; reservoir system; operation; reservoir performance indices

1. Introduction

Many reservoirs around the world have been constructed for hydropower generation because of the restriction in the use of fuels, the pollution caused by fossil fuels, and the benefits of using clean and renewable energy such as hydropower. In addition, the effective usage of hydropower resources plays a significant role in the economic development of countries such as Malaysia since hydropower stations constitute a great sector of power capacity. So, an integrated management of the hydropower resource is an essential issue in water resources utilization, which could help operators to manage systems properly and give the maximum benefit to industry [1,2]. While, the operation of a hydropower reservoir systems are so com-

*Corresponding author.

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plicated due to uncertainties of inflow, increase in water demand, limitation in water resources, and population growth [3], researchers have employed various operation rules to help the operator to forecast the amount of release in each period of operation and improve the efficacy of the system [4].

Reservoir operation rules are mathematical equations that determine the value of water release from a reservoir depending on storage volume and inflow values. As a matter of fact, previous experiences of the system are utilized to equilibrate system parameters during each operational period [5]. Research on reservoir operation rules were usually focus on two questions: "when to release?" and "how much to release?" A range of release policies were employed for operation of reservoir system. Meanwhile, standard operating policy (SOP) is the origin guideline of reservoir operation [6]. Based on SOP, if the accessible water is less than target demand, all water in the reservoir will be released in a given time period and does not impound water for future requirements. It can be summarized that SOP is a one-time operation policy and has no consideration for future requirements [7]. This is the demerit of SOP, which faces the operator with an empty reservoir. Accordingly, most water resource managers do not use SOP as an operation policy and more suitable and reliable policies are implemented. Some drawbacks and weakness of SOP can be overcome by applying hedging or rationing policy during the periods of deficit. Basically, hedging policies are an adjusted form of the SOP and often use for rationing the water supply in dry periods to decrease the severe shortage by diminishing the supply in normal periods. The principle reason of using hedging rules is to spread the predictable water shortage uniformly, which help to bring down severe deficits in the future [8]. In hydropower reservoir operation, the concept of hedging and rationing can be used to maintain and increase the water level. Since the output of hydropower generation depends upon two parameters including water release and water head, the concept of hedging and rationing can be used to improve water levels for future use. It means that when water levels are higher, the available head will increase and the required power can be produced with less water discharge. Early work by Bower et al. [9] describes a systematic economy of hedging rules for water resources management. Since then, hedging rules have become popular and described in different formulations. Bayazit and Unal [10] proposed two-point linear hedging rule. The modified form of two-point hedging rule was introduced by Shih and Revelle [11] and called one-point hedging rule. Thereafter, Srinivasan and Philipose [12] introduced three-point linear hedging rule.

In recent studies, considerable number of studies examined reservoir operation for hydropower generation [13–17], but direct application of one-point, two-point, and three-point hedging rules for operation of hydropower reservoir system have never been investigated. The innovation of this research is to simulate and optimize three operational models based on one-point, two-point, and three-point hedging rules in order to investigate the efficiency of these rules/policies in operating hydropower reservoir system. Besides using various forms of hedging policies, it seem that the application of these policies have been usually presented in terms of optimal hedging. Many metaheuristic algorithms have been used to discover the optimal operation policies of reservoir system and genetic algorithm (GA) is one of the most popular and frequent choice[18–23]. GA is a random-based algorithm that searches the decision space by using techniques inspired by natural evolution [4]. GA and its modifications have been extensively used in reservoir operation. So, real-coded genetic algorithm is used in this research to find the optimal magnitude of water release based on the hedging policies. In order to investigate the application of optimal hedging policies (one-point, two-point, and three-point) in hydropower system, Cameron Highland hydro scheme in Malaysia is selected as a case study. The performance of the hydropower reservoir system was then evaluated in terms of reliability, resilience, vulnerability, and sustainability.

2. Description and formulation for the hedging policies

The main objective of the studies concerning hydropower reservoir systems modelling is to estimate the amount of power production. In this research, the amount of hydropower production is determined by applying the multiple points hedging rules for water release. In order to investigate the efficiency of hedging rules in operating hydropower reservoir system, the operation of Cameron Highland hydro system is simulated by using Matlabvs. R2011b and optimized by using genetic algorithm. Three types of hedging policies were applied namely, one-point, two-point, and three-point hedging policies. The main difference among these hedging policies depend on the number of stages and the extent of rationing, which can be chosen based on objective function. The formulations of these policies are expressed as following:

2.1. Reservoir operation policies

2.1.1. One-point hedging policy (1PHP)

In one-point hedging policy, x-axis displays available storage and y-axis represents the sum of release and spill (Fig. 1). D_t is the target demand in time step (0.7 Mm^3), and K is the active capacity of the reservoir (2.16 Mm^3). Avail-

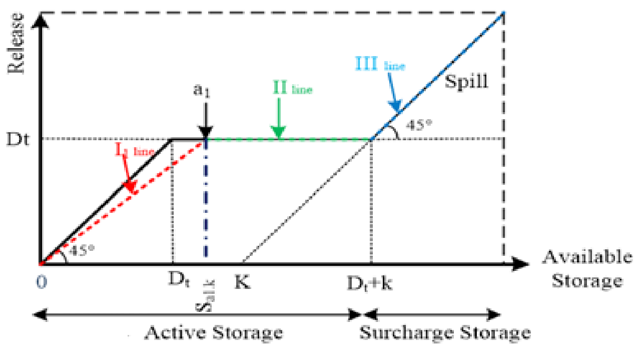

Fig. 1. Overall scheme of one-point hedging policy.

able storage is defined as the summation of initial storage (S_t) in the reservoir and inflow (I_t) minus the evaporation loss (E_t) during tth period, which is denoted by WA_t and expressed as:

$$WA_t = S_t + I_t - E_t \quad (1)$$

One-point hedging policy has only one rationing stage ($I_{1\,line}$). The angle of this sloping line is less than 45°. Therefore, the amount of water release is less than available storage and release cannot fulfill the target demand (D_t). So, water release in time step (R_t) can be determined as the fraction of D_t ($I_{1\,line}$). The fractions of D_t are presented in Eq. (2) based on the available storage and reservoir storage at a_1 point of 1PHP ($S_{a1.k}$). a_1 represents the changing point on the target. In addition, when available storage reaches a_1 in 1PHP, water release can fulfill the target demand (II_{line}) until available storage equals the target demand plus the reservoir capacity [Eq. (3)]. If the available storage exceeds $D_t + K$, spill will occur [Eq. (4)]. Furthermore, SP_t indicates spill in time step.

$$R_t = (WA_t/S_{a1.k})^*D_t \quad SP_t = 0 \quad WA_{t,} < S_{a1.k} \quad (2)$$

$$R_t = D_t \quad SP_t = 0 \quad S_{a1.k} \leq WA_{t,} < D_t + k \quad (3)$$

$$R_t = D_t \quad SP_t = WA_t - D_t - k \quad WA_{t,} \geq D_t + k \quad (4)$$

2.1.2. Two-point hedging policy (2PHP)

This strategy will reduce releases abruptly and make it less than the delivery target to preserve some water for the future use. In the case of a hydropower reservoir, this maintain and increase water levels for future use, which is one of the key factors in the operation of hydropower reservoir systems. There are two rationing stages ($I_{1\,line}$ and $I_{2\,line}$) in the two-point hedging policy (Fig. 2). The amount of water release is less than the target demand and is expressed as a fraction of D_t [Eqs. (5) and (6)]. $S_{b1.k}$ and $S_{b2.k}$ in the formula set represent the first (b_1) and second (b_2) changing points of 2PHP respectively. Whenever the available storage reaches b_2 in the 2PHP ($II_{\,line}$), water release can satisfy the target demand [Eq. (7)]. Moreover, when available storage goes beyond the sum of $D_t + K$, spill will occur [Eq. (8)]. Other parameters were defined earlier.

$$R_t = (WA_t/S_{b1.k})^*D_t \quad SP_t = 0 \quad WA_{t,} < S_{b1.k} \quad (5)$$

$$R_t = [(WA_t - S_{b1.k})/(S_{b2.k} - S_{b1.k})]^*D_t \quad SP_t = 0 \quad S_{b1.k} \leq WA_{t,} < S_{b2.k} \quad (6)$$

$$R_t = D_t \quad SP_t = 0 \quad S_{b2.k} \leq WA_{t,} < D_t + k \quad (7)$$

$$R_t = D_t \quad SP_t = WA_t - D_t - k \quad WA_{t,} \geq D_t + k \quad (8)$$

2.1.3. Three-point hedging policy (3PHP)

This policy comprises three sloping lines. Unlike 1PHP, this strategy allows a gentle decrease in releases at the time of deficit, but more dramatic reductions will occur if the drought intensifies or lengthens. Three-point hedging policy is the modified form of the two-point hedging policy (Fig. 3). So, the whole procedure is the same except the number of rationing stages, which is three lines ($I_{1\,line}$, $I_{2\,line}$, and $I_{3\,line}$). Under these conditions, water release cannot meet the target demand and is specified as a fraction of target demand [Eqs. (9)–(11)]. $S_{c1.k}$, $S_{c2.k}$, and $S_{c3.k}$ parameters in the formula set represent the first (c_1), second (c_2), and third (c_3) changing points of the 3PHP respectively. Furthermore, when the available storage reaches c_3, the water release can fully meet the target demand [Eq. (12)]. The rest of procedure is the same as in the 2PHP policy.

$$R_t = (WA_t/S_{c1.k})^*D_t \quad SP_t = 0 \quad WA_{t,} < S_{c1.k} \quad (9)$$

$$R_t = [(WA_t - S_{c1.k})/(S_{c2.k} - S_{c1.k})]^*D_t \quad SP_t = 0 \quad S_{c1.k} \leq WA_{t,} < S_{c2.k} \quad (10)$$

$$R_t = [(WA_t - S_{c2.k})/(S_{c3.k} - S_{c2.k})]^*D_t \quad SP_t = 0 \quad S_{c2.k} \leq WA_{t,} < S_{c3.k} \quad (11)$$

$$R_t = D_t \quad SP_t = 0 \quad S_{c3.k} \leq WA_{t,} < D_t + k \quad (12)$$

$$R_t = D_t \quad SP_t = WA_t - D_t - k \quad WA_{t,} \geq D_t + k \quad (13)$$

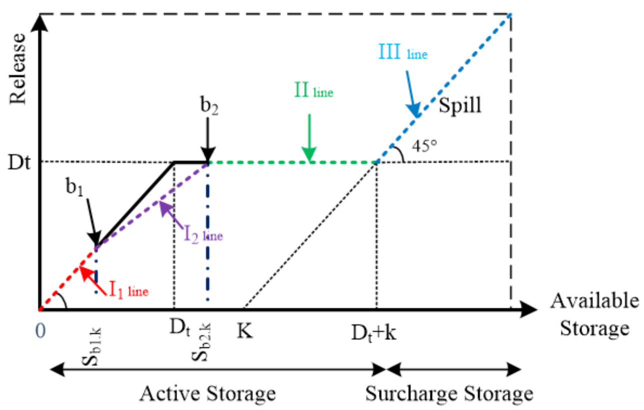

Fig. 2. Overall scheme of two-point hedging policy.

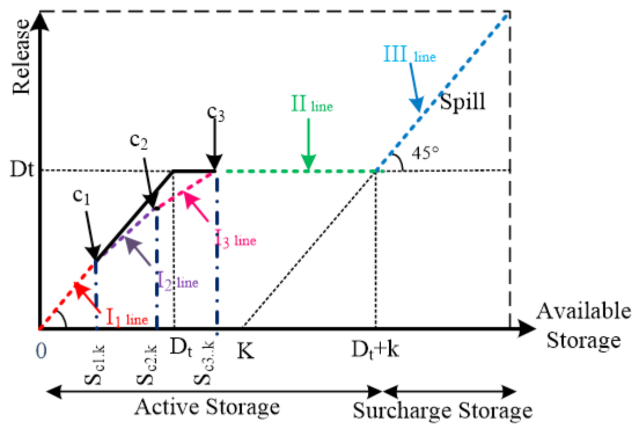

Fig. 3. Overall scheme of three-point hedging policy.

2.2. Objective function and constraints

The objective function of this research is maximization of total power generation during operational periods (2003–2012). The objective function can be expressed as a constrained nonlinear optimization problem as following:

$$Max\ G_t = \sum_{t=1}^{T} \eta_0 \gamma r_t H_t t \quad (14)$$

where G_t = power generation during the tth period (daily); η_0 = efficiency of the hydropower plant (0.85), which is taken constant during the operational period; γ = the specific weight of water (9.81 kN/m^3); r_t = the discharge during the tth period (m^3/s); H_t= the average net hydraulic head, which is determined by the difference between the level of the reservoir and the tail water during the tth period (m), t = the duration of release (h/d).

The objective function is subjected to the following constraints [17]:

2.2.1. Water balance equation

According to Shiau [18], after determining reservoir release, reservoir storage at the beginning of the second time interval should be calculated using the water balance equation.

$$S_t = S_{t-1} + I_t + P_t - E_t - R_t - SP_t \quad (15)$$

In Eq. (15), S_t = storage at time t (daily); S_{t-1} = storage at time t–1; I_t = inflow at time t; P_t, E_t = precipitation and evaporation at time t; R_t = the amount of release based on hedging policies at time t; SP_t = spill at time t.

2.2.2. Constraints on reservoir storage

Storage or water available in each time step (WA_t) is limited to reservoir storage at minimum water level (S_{min}) and storage at maximum water level (S_{max}). In this research, S_{min} and S_{max} are equalled to 3.9 Mm^3 and 6.7 Mm^3 respectively.

$$S_{min} \le S_t \le S_{max} \quad (16)$$

2.2.3. Constraints on reservoir releases

After determining the release in time step, the amount of releases (R_t) must take place in an allowable range. R_{min} is defined as the minimum permissible release and R_{max} is the maximum permissible release, which is specified according to the turbines' capacity [24].

$$R_{min} \le R_t \le R_{max} \quad (17)$$

2.2.4. Constraints on power production

The amount of power generation in each time step must be placed between the minimum (G_{min}) and the maximum (G_{max}) values of power generation [8]. These parameters are determined based on the capacity of turbines in power station. In this research, G_{min} and G_{max} are equalled to 0 and 100 MW respectively.

$$G_{min} \le G_t \le G_{max} \quad (18)$$

A water level-storage volume and water level-surface area at Ringlet reservoir can be calculated based on the shape of Ringlet reservoir (Fig. 4).

2.3. Definition of performance indices

Reservoir performance indices should be used to compare and analyze the output of operation models (1PHP, 2PHP, and 3PHP). The indices used in the current research include the following: reliability, resilience, vulnerability, and sustainability [2,25,26]. These indices are explained in detail.

2.3.1. Reliability

The reliability index illustrates the probability of success (non-failure) performance during the operational time horizon. In other words, it is an indicator to show the number of secure periods in which target demand is supplied. This metric can range between 0 and 1. Whenever the probability is closer to 1, the more likely target demand is supplied in most of periods. In this equation, *Rel* = reliability index; N_s = the number of time intervals that the reservoir can fully meet the target demands; and N = the total number of intervals in the simulation time horizon. In addition, the amount of target demands in this research is constant and equalled to 0.7 Mm^3.

$$Rel = N_s/N \qquad 0 \le Rel \le 1 \quad (19)$$

2.3.2. Resilience

Resilience is an indicator defined by how fast a reservoir will recover from a failure period. Failure periods are those periods in which demand is not satisfied. The other definition of resilience is the inverse of the average failure duration. According to Hashimoto et al. [27], φ shows the probability of success following a failure period. It is noteworthy that by using this definition, there is an exception for f_s. If f_s = 0 or in the condition of one failure, φ will be equal to unity in both cases. In this equation, φ = resilience index; f_s = the number of separate continuous sequences of failure periods; and f_d = total failure duration.

$$\varphi = f_s / f_d \qquad f_d \ne 0 \quad (20)$$

2.3.3. Vulnerability

The vulnerability index is defined by the summation of all periods of shortage in generated power. In Eq. (21), η′ = vulnerability index; S_j = maximum shortfall in each failure trails; and f_s = the number of continuous failure trials.

$$\eta = \frac{\sum_{j=1}^{f_s} \max(s_j)}{f_s} \quad (21)$$

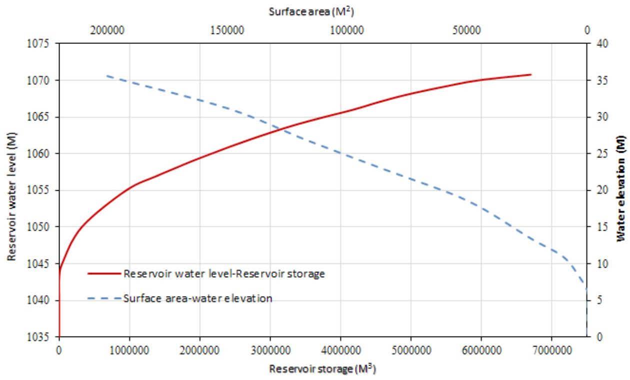

Fig. 4. Ringlet reservoir storage (M^3) corresponding to specific water level (M), Surface area (M^2) corresponding to water elevation (M).

It is essential to note that η' in Eq. (21) has volumetric units, while there is another expression of vulnerability, which has a non-dimensional formalization. In Eq. (22), η = dimensionless vulnerability; Df = the target demand during the failure (0.7 Mm^3).

$$\eta = \eta'/Df \qquad 0 < \eta < 1 \tag{22}$$

2.3.4. Sustainability

Loucks [28] synthesizes three indicators of performance such as reliability, resilience, and dimensionless vulnerability to introduce a sustainability index. In this equation, *Sus* is called the sustainability index. Other parameters are defined earlier.

$$Sus = Rel \cdot \varphi \cdot (1-\eta) \qquad 0 < Sus < 1 \tag{23}$$

2.4. Optimization procedure

The genetic algorithm (GA) is a global optimization method, which was inspired by the natural reproduction and evolution of living creatures. GA belongs in the category of artificial intelligence. It can be used to solve an optimization problem by searching for optimal or near-optimal solutions over the search domain. The capability of GA has been compared with traditional method. GA searches for a solution from multiple directions, since it inherently employs three operators: reproduction, crossover, and mutation. This increases the probability of escaping from a premature solution. However, the traditional method searches for solutions only from one single direction of the search space [29]. The known global optimum for the reservoir problem can be achieved with real-value coding [30]. Therefore, in this study, a real-coded genetic algorithm (RC-GA) is proposed for cyclic processing as an optimization technique.

The first step of cyclic processing is to create the initial population; each individual represents a candidate to the optimal solution, which is called a chromosome. Each chromosome is built as a fixed length string of symbols, and is then coded to be revealed numerically. The next step is to assign the fitness value for each individual of the population. The fitness value is a parameter to evaluate each individual that determines whether or not it can live in a subsequent population. In other words, the fitness value is a measure of the quality of an individual. The evaluation and selection of individuals that can live and transfer their genetic code to the next generation are handled by the genetic operators of selection, crossover, and mutation. These operators are performed using the decimal code. The operation is selective, i.e. the best candidates in terms of fitness are chosen as parents so that the new generation holds the best genetic heritage. A typical genetic algorithm cycle involves five major processes: fitness evaluation, selection, crossover, mutation, and the creation of a new population (Fig. 5). The success of the genetic algorithm strongly depends on problem mapping, which involves the transformation of the problem's solution to a chromosome representation. Also, the design of the fitness function determines the quality of the solution. For more details about RC-GA technique refers to [31,32].

In the present study, RC-GA is used as an optimization technique to specify the decision variables in hedging policies and maximize the total power generation throughout the time horizon (2003–2012) in the Ringlet Reservoir. The number of decision variables in each policy is determined based on the number of rationing stages (sloping lines) in each form of hedging policy. Accordingly, ($S_{a1.k}$) in 1PHP, ($S_{b1.k}$ and $S_{b2.k}$) in 2PHP and ($S_{c1.k}$, $S_{c2.k}$, and $S_{c3.k}$) in 3PHP are variables that should be optimized by RC-GA.

3. Case study

In order to evaluate the efficiency of multiple point hedging policy in hydropower reservoir system, Sultan Abu Bakar dam is selected as study area. The Sultan Abu Bakar dam was constructed on the Bertam River in the district of Cameron Highlands, Malaysia. The lake has been created as a result of the dam construction and it is known as Ringlet reservoir. It forms an integral part of the Cameron Highlands Hydroelectric Scheme (CHHS) of the National Electricity Board. The dam impounds the waters of Bertam River and its tributaries and also those of the Telom River and its tributaries, which have been diverted from their original course and now pass through the Telom tunnel into the Bertam catchment. From Ringlet reservoir, the water is led through the `Bertam tunnel (6.8 km in length) to the high pressure penstocks of the Sultan Yusuf Power Station (SYPS), which has a total installed capacity of 100 MW. After leaving the SYPS, the water is carried through a tail race tunnel into the Jor reservoir of the Batang Padang Hydro Scheme. The systematic diagram of hydropower reservoir system is shown in Fig. 6.

Ringlet reservoir impounds the inflow of Bertam River and Telom River, which is passed through the Telom tunnel. The inflow of these two sources measure based on the output of power generation in Sultan Yussuf power station. The average monthly inflow of Ringlet reservoir is shown in Fig. 7.

A recent study by Tenaga Nasional Berhad Research Centre (TNBR) in 2004 declared that an average of 102,000 (m^3/year) of sediment coming into Ringlet reservoir, which has resulted in a reduction of storage from 4.7 Mm^3 to

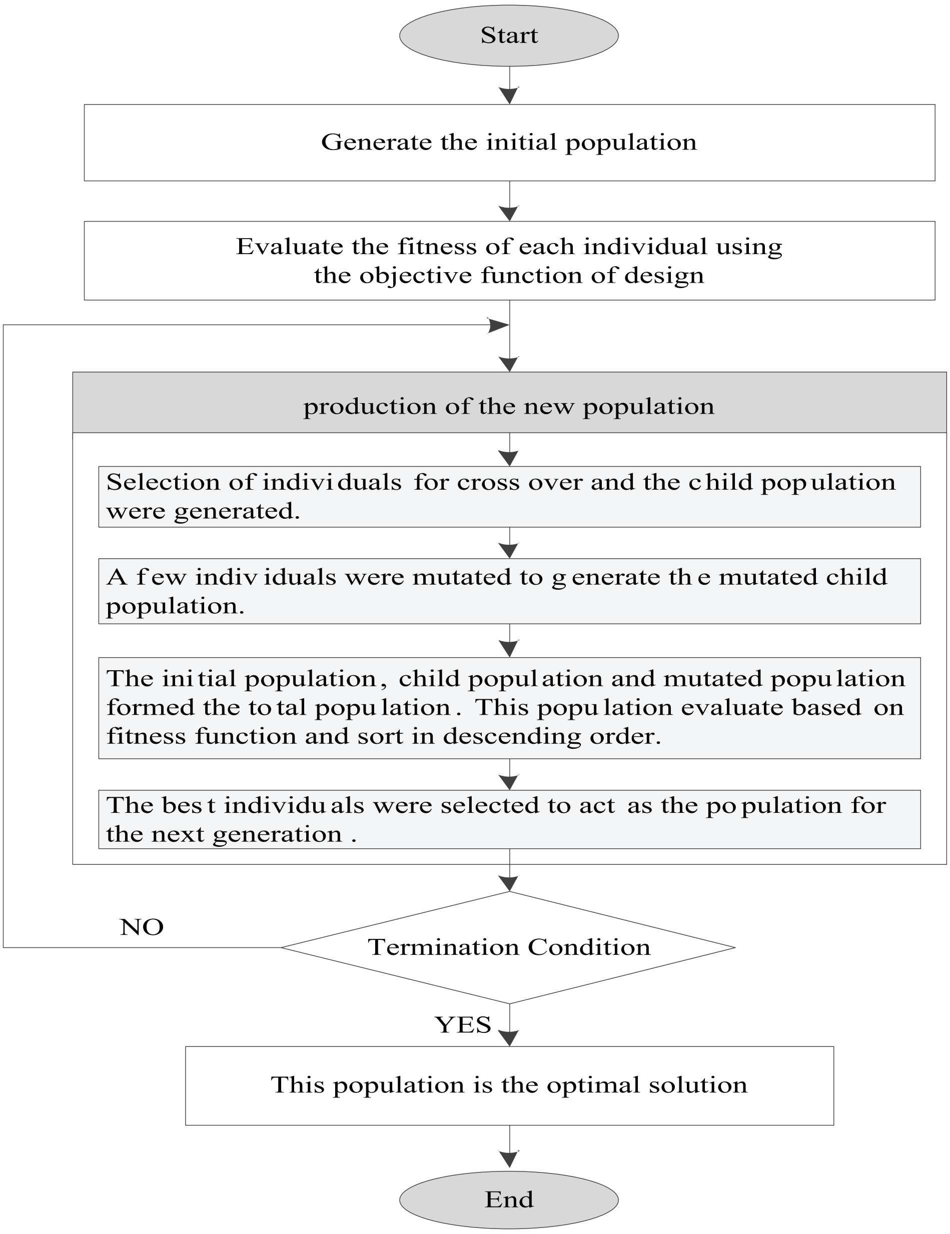

Fig. 5. Real coded genetic algorithm flowchart.

almost less than 2 Mm^3. Maximum beneficial reservoir level is 1070.8 m and minimum water level varies due to sedimentation. Due to sediment, the reservoir lost more active storage every year, but managers try to keep the active storage by dredging and recover some storage. In present years, TNB manager kept the minimum water level at 1065.3 m above sea level by continues dredging. However, the minimum draw down level is EL 1058.8 m. Water level currently is permitted to vary just 5.5 m, which makes the operation more difficult.

From Ringlet Reservoir, the water is led through the Bertam Tunnel to the high pressure penstocks of the Sultan Yussuf Power Station (SYPS). This is an underground power station, which lies 573 m below the level of the reservoir. The SYPS is located in the state of Perak near the 19th milestone on the Tapah-Cameron Highlands road. The total installed capacity of SYPS is 100 MW, which is produced by 4 Pelton turbines. The Cameron Highland hydro scheme is operated by Malaysia's TNB utility company. The system comprises the Ringlet Reservoir and SYPS, which has certain characteristics (Table 1).

4. Results and discussion

This research was conducted to compare the applicability of multiple points hedging policies in operating hydropower systems with the main objective to maximize the

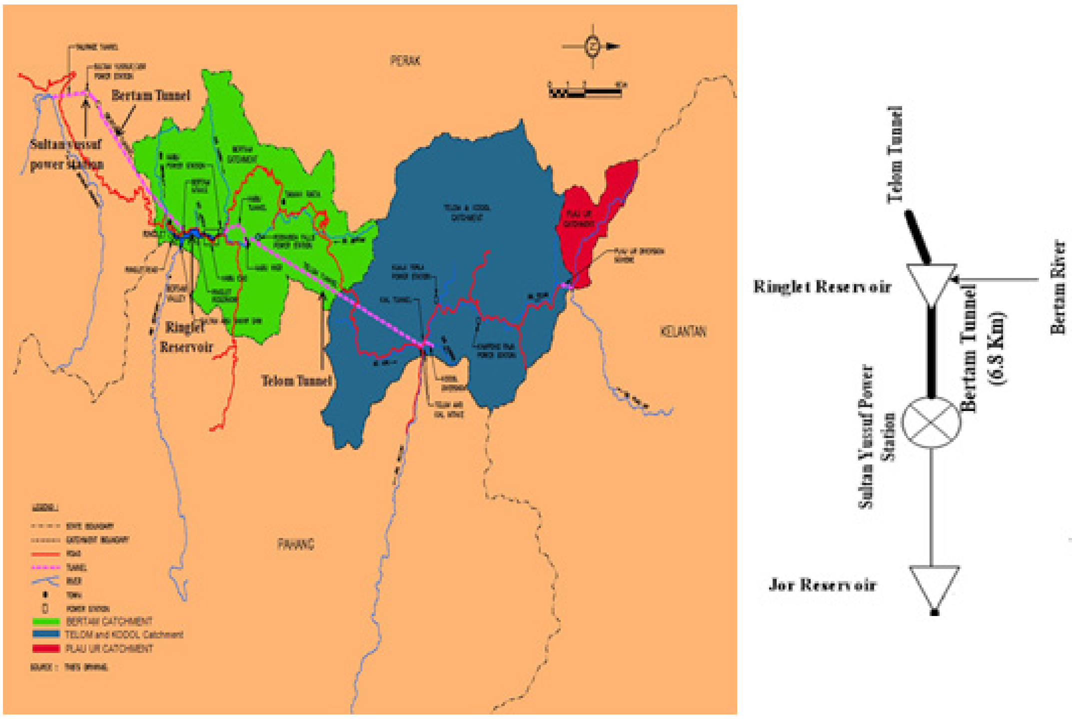

Fig. 6. Schematic diagram of Cameron Highland hydropower reservoir system.

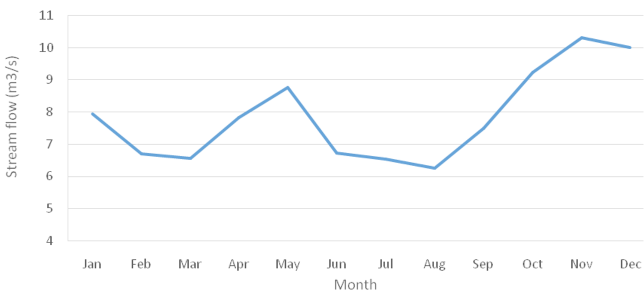

Fig. 7. Monthly mean inflow coming into Ringlet reservoir (Reference: TNB).

total power generation during the selected period (2003–2012). In order to achieve this objective, it was necessary to apply an optimization algorithm to find the best solution. The objective function should be formulated to reflect the above target. Meanwhile, the daily data of stream flow, evaporation, water demand, and water level-storage curve were collected from 2003–2012 in order to use in constructing the operational models namely 1PHP, 2PHP, and 3PHP. Accordingly, the whole procedure of this research could be summarized in five main processes: data collection, reservoir operation, optimization processing, output results, and analysis of output results, which is shown in Fig. 8.

MATLAB code gives full control on genetic operators such as population, mutation, cross over, and more decisions in developing constraints [33]. So, the user can specify population size. Initial population is generated randomly. In the current research, because of the nature of problem, real-coded is used. The number of decision variables in each model depends on the number of changing points in the specific hedging policy. The characteristics of GA are summarized in Table 2. For getting more information about the types of selection, crossover, and mutation it is recommended to refer to Whitley [34].

The constructed GA programme did not give the similar results in each iteration because of the difference in initial population since GA creates initial population randomly. In this research, different size of population is selected such as 50, 100, 200, were taken and 50 was selected by trial and error. Evolutionary algorithm in general and the proposed algorithm are random based optimization methods which do not converge to a specific and unique solution even in subsequent runes. By conducting about 20 runs, the results together with the calculated objective function are shown in Table 3. Because of the maximization nature of the objective function, only largest value is considered as the best solution in 20 runs, optimum values for the three hedging polices were found and shown in Table 3 and the value of objective function in 1000 iteration for each policy is shown in Fig. 9.

The number of decision variables in each form of hedging policy depends on the number of rationing stages. $S_{a1.K}$ in 1PHP, $S_{b1.K}$, $S_{b2.K}$ in 2PHP, and $S_{c1.K}$, $S_{c2.K}$, $S_{c3.K}$ in 3PHP are the decision variables, which were optimized using the RC-GA technique. These variables were determine as a coefficient of active storage (K) such as a_1 in 1PHP, b_1, b_2 in 2PHP, and c_1, c_2, c_3 in 3PHP. Afterwards, these coefficients were optimized to determine the pattern operational policies (Table 4). Based on these patterns, mean and total output of power generation from 2003–2012 were determined. According to the given results, the output of power generation increased by 13% compared with the mean output of present operation policy (2895.89 GWh). In addition, by

Table 1
Characteristics of Cameron Highland hydro scheme

Description		Description	
Gross storage	6.7 Mm^3	Max discharge capacity	963 m^3/s
Usable storage	4.7 Mm^3	Catchment area	183.4 km^2
Active storage	2 Mm^3	Gross head	587.3 m
Reservoir surface area	0.5 km^2 at EL. 1071.1 m	Max discharge	5.493 m^3/s
Max operating level	EL. 1070.8 m	Annual generation	320 GWh
Min operating level	EL. 1065.2 m	Rated head	573 m
Catchment area	183.4 km^2	Installed capacity	100 MW

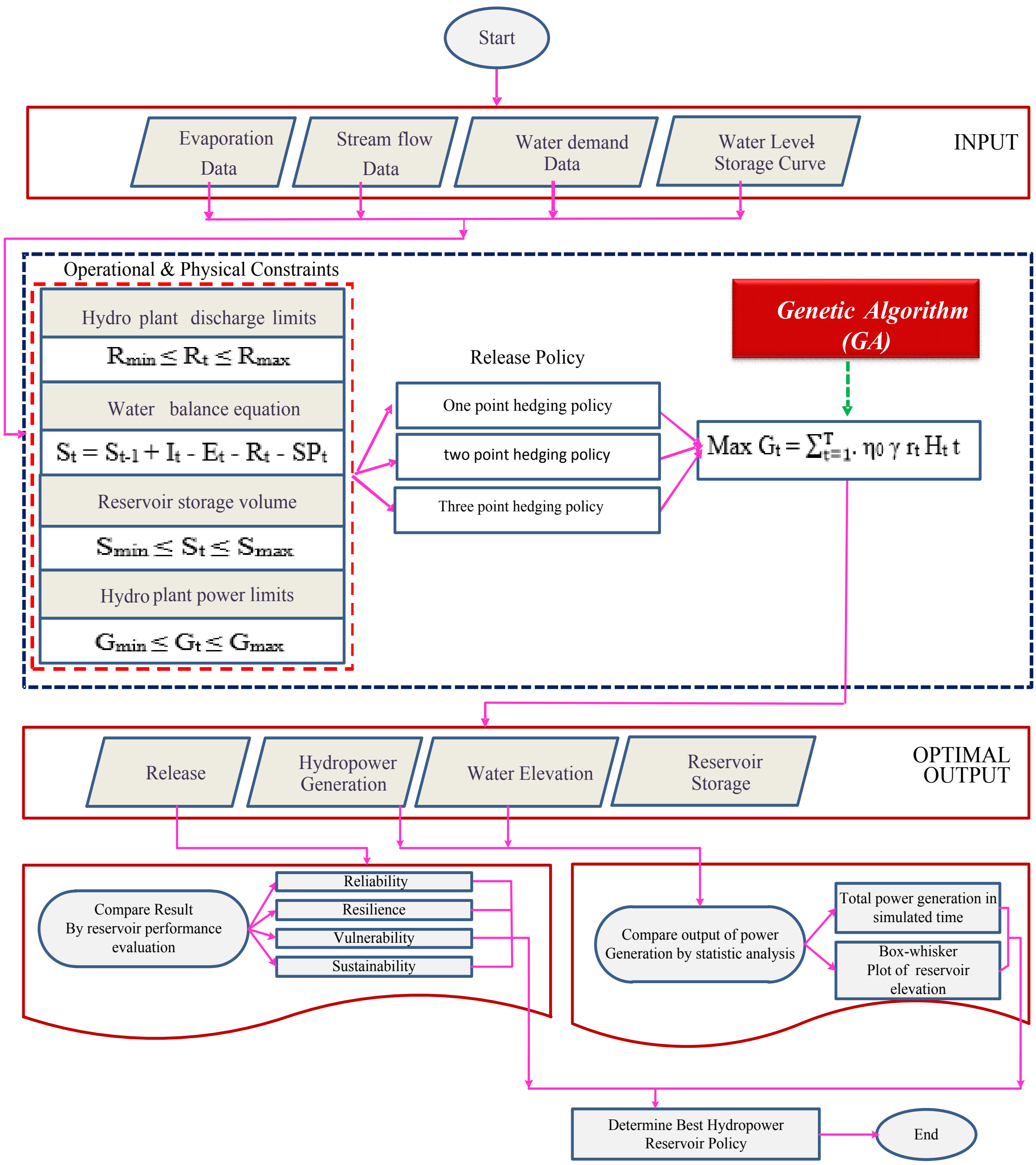

Fig. 8. Flow diagram of methodology.

Table 2
Characteristics of RC-GA in operational models

Characteristics	1PHP	2PHP	3PHP
Decision variables	1	2	3
Population	50	50	50
Iteration	1000	1000	1000
Selection type	Roulette wheel	Roulette wheel	Roulette wheel
Crossover type	Two-points	Two-points	Two-points
Mutation type	Uniform	Uniform	Uniform
*P*c	0.2	0.2	0.2
*P*m	0.02	0.02	0.02

*P*c: probability of crossover, *P*m: probability of mutation

Table 3
Statistical measures for 20 runs in 1PHP, 2PHP, and 3PHP respectively

Runs	1PHP	2PHP	3PHP
1	3284218098	3284242722	3285313608
2	3284218098	3284242722	3285313608
3	3284217600	3284242722	3285313608
4	3284218098	3284242722	3285313608
5	3284208537	3283475143	3285121461
6	3284218098	3283341183	3284673529
7	3284218098	3284242722	3285159253
8	3284218098	3284242722	3285313608
9	3284217600	3284242722	3284950196
10	3284217998	3284242722	3285313608
11	3284218098	3283819201	3285313608
12	3284218098	3284242722	3285076357
13	3284012753	3284242722	3285313608
14	3284217998	3283403340	3285313608
15	3284217998	3284242722	3285313608
16	3284217998	3284242722	3285165414
17	3284217998	3283546699	3285178687
18	3284216504	3283577351	3284976683
19	3284167099	3283600274	3284376763
20	3284167000	3283521918	3284933617
Min	3284012753	3283341183	3284376763
Max (best solution*)	3284218098	3284242722	3285313608
Average	3284202093	3283959889	3285137402
Standard deviation	47211.75775	366020.6639	252731.0889

analysing the output of total power generation during the simulated period (2003–2012), the highest amount of power generation can be obtained by using 3PHP. According to the given results, 3PHP, 1PHP, and 2PHP give the maximum power generation respectively (Table 4).

The given results also can be proven by analysing the water head. As it mentioned earlier, in operating hydropower reservoir system, two parameters are affecting power production output and these parameters are water release

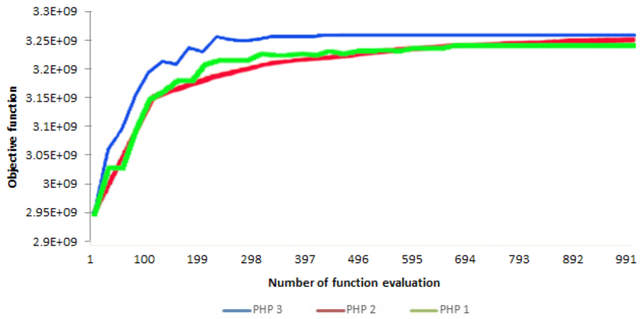

Fig. 9. The amount of objective functionin 1000 iteration for each policy.

and water head. When storage in the reservoir is increase the head is increase too. Hence, a smaller discharge from a reservoir may be sufficient to produce the required power. Thus, water level play a significant role in power generation output. The highest water level has more benefit in power production. Therefore, statistical analysis of reservoir elevation for developed operation policies were done and summarized by using box plot of reservoir elevation (Fig. 10). In descriptive statistics, a box plot is a convenient way to depict groups of numerical data graphically through their quartiles. Box plots may also have lines extending vertically from the boxes (whiskers) indicating variability outside the upper and lower quartiles, hence the terms box-and-whisker plot. The vertical lines illustrate the variation of water level, and the second horizontal lines (Q2) represent the mean water level in the reservoir by using each policy. The skeletal box plot consists of a box extending from the first quartile (Q1) to the third quartile (Q3).The schematic box plot divides the data based on four invisible boundaries namely, two inner fences and two outer fences. As usual, we define the interquartile range (IQR) to be Q3–Q1. The inner fences are Q1 – 1.5 IQR and Q3 + 1.5 IQR, while the outer fences are Q1 – 3 IQR and Q3 + 3 IQR. Outliers may be plotted as individual points. Here the 'o' symbol represents the inner outlier.

Based on the given results, it is very clear that the highest mean water level can produce more power generation. The highest mean water elevation is given by 3PHP, 1PHP, and 2PHP respectively. This result provides an evidence for the output of total power generation (Fig. 10), which was discussed earlier. The second aspect to point out is whenever the optimal operating policies can be applied water storage in the reservoir is strictly limited and did not exceed the surcharge storage and inactive zones are in critical draw down and fulfilled the periods. Although, the maximum operating level is at the elevation of 1070.8 m, all types of operating policies try to maintain some storage in a whole year for flood control.

Further research was also conducted on the mean monthly live storage from 2003 to 2012. The impacts of constructed policies on mean monthly live storage (as a fraction of maximum storage) were compared with TNB operation (Fig. 11). The dash line shows the mean monthly of live storage from 2003–2012by using TNB operation. While the mean monthly live storage in TNB operation varies around 5% annually, the mean monthly storage does not change significantly by using constructed policies and is almost constant

Table 4
Optimization of decision variables in release policies based on operational policies

Parameters	Point	Point	Optimized variables	Storage (m^3)	Total power generation (GWh)
1PHP					3284.22
a_1	$S_{a1.K}$	$a_1{*}k$	0.500	5287282	
2PHP					3283.38
b_1	$S_{b1.K}$	$b_1{*}k$	0.358	4886070	
b_2	$S_{b2.K}$	$b_2{*}k$	0.418	5055596	
3PHP					3285.22
c_1	$S_{c1.K}$	$c_1{*}k$	0.312	4756100	
c_2	$S_{c2.K}$	$c_2{*}k$	0.398	4999088	
c_3	$S_{c3.K}$	$c_3{*}k$	0.427	5081025	

$S_{a1.K}$; $S_{b1.K}$, $S_{b2.K}$; and $S_{c1.K}$, $S_{c2.K}$, $S_{c3.K}$ represent the changing points on target demand specified as decision variables of 1PHP, 2PHP and 3PHP respectively. *K* is an active reservoir capacity of the reservoir (2,158,200 m^3).

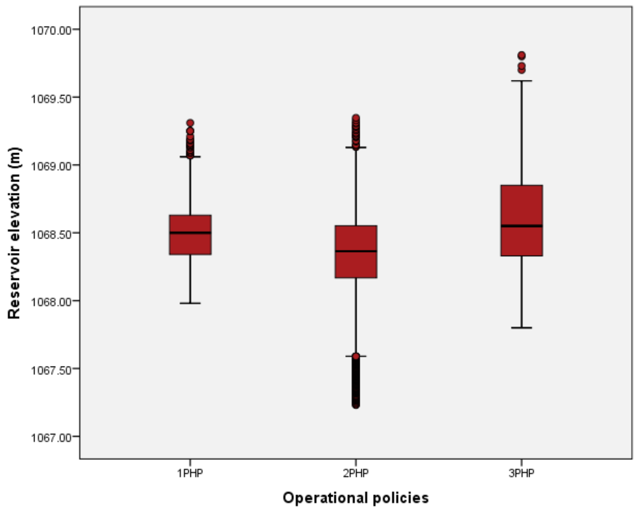

Fig. 10. Reservoir elevation box plot for different forms of operational policies.

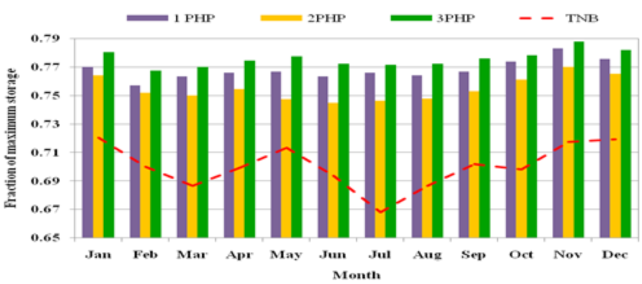

Fig. 11. Mean monthly live storage (as a fraction of maximum) at the Ringlet reservoir using optimized operational policies from 2003–2012.

in a whole year. This result shows the stability of the reservoir system while using optimal operational policies.

The impacts of using optimal operating policies on mean monthly power generation (2003–2012) were also investigated and compared with TNB operation (Fig. 12).

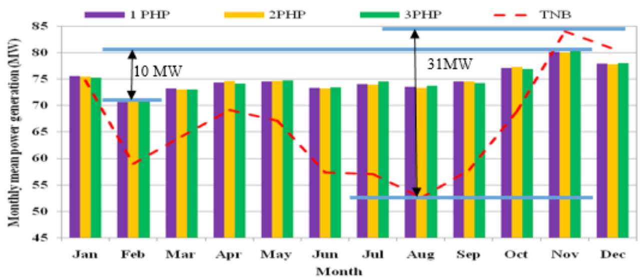

Fig. 12. Mean monthly power generation using optimized operational policies from 2003–2012.

According to constructed policies, the discrepancies of mean monthly power generation between the highest and lowest months are found to be around 10 (70–80 MW), while this variation is found to beabout 31 (53–84 MW) for TNB operation. These results also show that by using optimized hedging policies it increase the stability of the system's power generation. Results show that although there is no significant difference in mean monthly power generation among optimal hedging policies but the discrepancy in mean monthly output between the hedging policies and TNB operation policy is considerable.

Reservoir performance indices were used to select the most accurate operational policies. Several criteria were applied to evaluate the reservoir system such as reliability, sustainability, dimension vulnerability, and sustainability (Fig. 13). It is remarkable to note that the target demand for calculating these indices was taken 0.7 Mm^3. Based on the given results, the reliability value of 1PHP was extremely low, while the reliability of 3PHP was around 0.7, which means that the system could provide the target demand in 70% of the simulation period (2003–2012). Another criterion was the resilience index, which shows how fast a reservoir will recover from a failure period. The system attained the highest resilience value by using 1PHP operation. The next index of performance was system vulnerability, where the lowest value gives the better system performance. The lowest vulnerability was 10% by using 1PHP and the highest value was about 0.5 (50%) by using 3PHP. The given

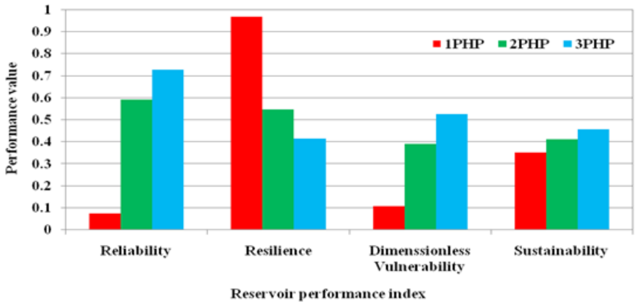

Fig. 13. Reservoir performance indices for different operational release policies.

results can be summarized in one criterion, which is called the sustainability index. Since, it is incorporated reliability, resilience, and vulnerability in its formula and used to determine the best system performance. Based on the given results, 3PHP gave the highest sustainability value, which means 3PHP generally is the most suitable policy among the constructed policies.

5. Conclusion

In this research, three competing hedging policies were formulated and applied to investigate whether these policies can be used in operating a selected hydropower system. The applied policies are one-point, two-point, and three-point hedging policies. The policies were constructed, optimized and applied in order to evaluate the performance of hydropower reservoir system. The reservoir system operation models were formulated to maximize the total hydropower generation during operational periods (2003–2012) at a daily time scale which is subjected to various physical and operational constraints. The genetic algorithm was applied to identify the optimal daily reservoir operational models. The optimized results show that the examined hedging policies could increase the hydropower by 13% compared with the planned hydropower production during operational periods. Also, results show that the application of these policies does not change the mean monthly storage significantly (almost constant) throughout the year. This result shows that hedging policies could increase the stability of the system power production. The performance of various hedging policies was evaluated using various measures such as reliability, resilience, vulnerability, and sustainability. Generally results showed that the best performance of the system resulted from the application of the three-point hedging policy. Multiple points hedging policies were strongly recommended to be used as operational procedures in hydropower reservoir systems.

Symbols

WA_t	—	Water availability at time t (m^3)
S_t	—	Water stored in the reservoir at the beginning of time t (m^3)
I_t	—	Reservoir inflow at time t (m^3)
E_t	—	Evaporation loss at time t (m^3)
R_t	—	Release at time t (m^3)
D_t	—	Target demand in time t (m^3)
SP_t	—	Spill at time t (m^3)
K	—	Active storage (m^3)
$S_{a1.k}$	—	Reservoir storage at the point of one-point hedging policy (1PHP)
$S_{b1.k}$, $S_{b21.k}$	—	Reservoir storage at first and second point of two-point hedging policy (2PHP) respectively.
$S_{c1.k}$, $S_{c2.k}$, and $S_{c3.k}$	—	Reservoir storage at first, second and third point of three-point hedging policy (3PHP) respectively
TNB	—	Tenga Nasional Berhad
η_0	—	Efficiency of the hydropower plants
γ	—	The specific weight of water (9.81 kg/m^3)
H_t	—	Defined as the difference between the level of the reservoir and the tail water in time interval t
r_t	—	Release at time t (m^3/sec)
t	—	The duration of release (h)
S_{max}	—	Storage volume at normal water level
S_{min}	—	Storage volume at minimum water level
S_{t-1}	—	Storage at time t–1
G_t	—	Hydropower generation in time t
G_{max}	—	Maximum capacity of hydro plants
G_{min}	—	Minimum capacity of hydro plants
R_{max}	—	Maximum permissible release
R_{min}	—	Minimum permissible release
Rel	—	Time-based reliability index
N_s	—	The number of time intervals that reservoir can fully meet the target demands
N	—	The total number of intervals in simulation time horizon
β	—	Resilience index
f_s	—	The number of separate continuous sequences of failure periods
f_d	—	Total failure duration
η	—	Vulnerability index
S_j	—	Maximum shortfall in each of failure trails
η	—	Dimensionless vulnerability
Df	—	Target demand during the failure
k	—	Sustainability index

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