EVALUATION OF OPTIMIZATION MODELS FOR RESERVOIR OPERATION : FROM RULE-CURVE TO MANY-OBJECTIVE OPERATION

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ABSTRACT

Quantitative comparison between different models of reservoir operation can provide valuable suggestions to decision-making and help to promote new planning tools under changing environment. A full spectrum of the models for reservoir operation range from rule-based model (RBM), single-objective optimization (SOM), bi-objective optimization (BOM) to many-objective optimization (MOM) models are considered. The Qinshitan Reservoir, a large reservoir in the southwest of China, is used as a case and the four models of reservoir operation are established accordingly and are evaluated quantitatively under typical hydrological years. Amongst the models, the MOM provides a comprehensive perspective on reservoir operation and achieved the best performance for offering the most options to the decision making. The MOM also discovers a step-wise operational scheme that has not been captured by the RBM, the SOM and the BOM.

Keywords *Reservoir Operation; rule-based operation; optimization model; Many-objective;*

1. INTRODUCTION

To adapt to the changing environment, the way of operating reservoirs has been slowly but gradually transferred from simple rule-based operations that are based on simulation model, to optimal reservoir operation that are based on optimization models. As purposes of reservoir operation increase, new objectives are considered in the optimization model and formulate the model from single objective to multiple-objective (2~3 objectives) to even many objectives (more than 3 objectives).

Although the concept of operating reservoir has been adapted quickly, the gap between research and practice are still large (Simonovic, 1992; Brown et al., 2015). Most of the reservoirs worldwide are still practicing rule curve based operation (ICOLD, 2016). Therefore, a systematic comparison between the different ways of reservoir operation can illustrate a full scope of options, which helps to narrow the gap between researchers and practitioners. This study used Qinshitan Reservoir, a large reservoir in southwest of China, as a case to evaluate four different operation modes ranging from rules curve model to many-objective optimization. The major contribution of the study is (1) evaluation of a full range of operational models that are currently in the practice and (2) identification of the many-objective optimization (MOM) models as a screening tool for prioritizing multiple objectives of reservoir operation.

2. STUDY CASE

The Qinshitan Reservoir is a major hydraulic facility of the Lijiang River basin in the southwest of China. It is located at the upstream of the Gantang River, which is the largest tributary of the Lijiang River. The schematic of water distribution from the Qinshitan Reservoir is presented in Fig. 1. Q_{Gn}^{t} denotes the upstream natural flow of the Gantang River at time t , i.e. the inflow to the Qinshitan Reservoir. Q_{tb}^{t} and Q_{sw}^{t} are the outflow through turbines and spillways at time t, respectively, A bypass channel is located in the downstream of the reservoir and provides water for irrigation, i.e. Q_{i}^{t} in Fig.1. Some of the Q_{i}^{t} return to the Gantang River due to soil drainage and is denoted as Q_{ir}^{t}. Q_{d}^{t} is the flow extracted for domestic use in the Guilin city at time t; Q_{Ln}^{t} is the flow from upstream of the Lijiang River and were joined by the total flow of the Gantang River Q_{GR}^{t} at the city of Guilin. Q_{LR}^{t} denotes the total flow of downstream of the Lijiang Rivers at time t.

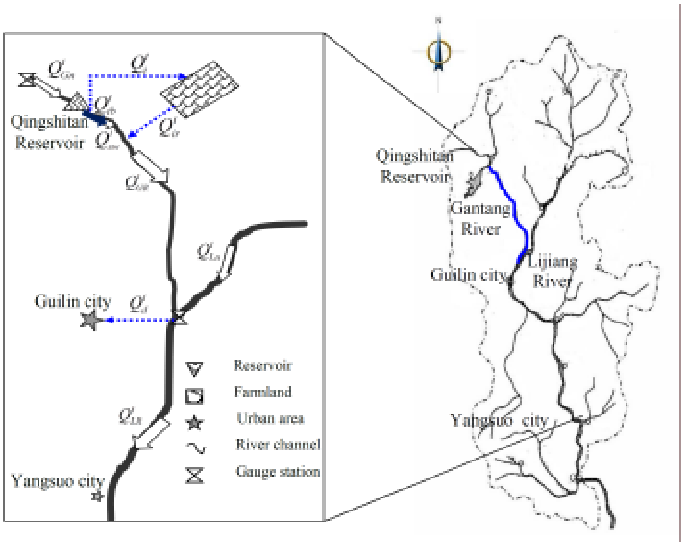

Fig. 1 : Schematic of water distribution from the Qinshitan Reservoir (Adapted from Chen et al., 2012).

The Qinshitan Reservoir serves seven purposes in total: irrigation, power generation, domestic water supply, navigation, water quality, flow maintenance of Gangtang River and flow maintenance of Lijiang River, respectively.

The functions of these purposes can be written in the following:

$$index\_I = \sum_{t=1}^{n}(\frac{Q_i^t}{Q_{i\_target}^t})/n \qquad (1)$$

$$index\_D = \sum_{t=1}^{n}(\frac{Q_d^t}{Q_{d\_target}^t})/n \qquad (2)$$

$$index\_PG = \sum_{t=1}^{n}(\frac{P^t}{P_{capacity}})/n , P^t = \eta * g * H^t * Q_{tb}^t * \Delta t \qquad (3)$$

$$index\_N = \sum_{t=1}^{n}(\frac{\min(Q_{LR}^t, Q_{n\_target})}{Q_{n\_target}})/n,\ Q_{LR}^t = Q_d^t + Q_{sw}^t + Q_{ir}^t + Q_{LN}^t - Q_d^t \qquad (4)$$

$$index\_WQ = \sum_{t=1}^{n}(\frac{\min(Q_{LR}^t, Q_{wq_{target}})}{Q_{wq\_target}})/n \qquad (5)$$

where *ex_I* , *index_D*, *index_PG* , *index_N, index_WQ* are indexes for quantification of the purposes for irrigation, domestic, power generation, navigation and water quality. n is the total number of time step t. $Q^t_{i\_target}$, $Q^t_{d\_target}$, Q_{n_target} and Q_{wq_target} are target flow(m^3/s) for irrigation, domestic, navigation and water quality, respectively. P^t is power generated during each time step. $P_{capacity}$ is the power generated under full capacity. η is the efficiency coefficient. g is the gravitational acceleration (m/s^2). H^t is water head (m) at time t, which can be computed by reservoir water surface elevation(WSE) and downstream WSE.

The other two purposes, namely flow maintenance of Gangtang River and flow maintenance of Lijiang River, are measured using Indicators of Hydrologic Alteration (IHA). In this case, the IHA is used for measuing the alteration of the flow regime in both the Lijiang River and the Gantang River. The inflow to Qinshitan Reservoir, i.e., Q_{Gn} is treated as nature flow of the Gantang River and compared with total flow of the Gantang River downstream, i.e., Q_{GR} , which is altered by the reservoir operation. Since there is no record for the nature flow of Lijiang River downstream, the total flow combined by the Q_{Gn} and Q_{Ln} is treated as nature flow of Lijiang River downstream and compared with Q_{LR}, the altered flow of Lijiang River downstream. Because altering streamflow within-year variability has the potential to modify critical aspects of the physical habitat (Kiesling, 2003; Suen, 2010), it is expected to minimize the flow alteration in both the rivers. Therefore, the two purposes are formulated in the following:

$$index\_FG = 1 - \sum_{i=1}^{m} \mathrm{IHA}_i(\ Q_{Gn},\ Q_{GR})/m \qquad (6)$$

$$index\_FL = 1 - \sum_{i=1}^{m} \mathrm{IHA}_i(\ Q_{Gn} +\ Q_{Ln},\ Q_{LR})/m \qquad (7)$$

where *index_FG*, *index_FL* are indexes for quantification of the purposes for minimizing the flow alteration of the Gantang and the Lijiang River, respectively. The IHA is a model to calculate the 32 indicators (m=32) between two flow regimes. A Matlab version of the IHA model is developed by the authors and is incorporated in the operation models.

3. OPERATION MODELS

The operational horizon is one year since the Qingshitang reservoir is annually regulated. A daily time step is considered and the daily outflow from the reservoir are the decision variables. Due to varied considerations, the objectives and constraints are described in each proposed model, respectively.

3.1 Rule curve based model (RBM)

The RBM is essentially a simulation model based on the predetermined rule curves. The rule curves for Qinshitan Reservoir operation were calculated using typical historical inflow scenarios and are shown in Fig. 2.

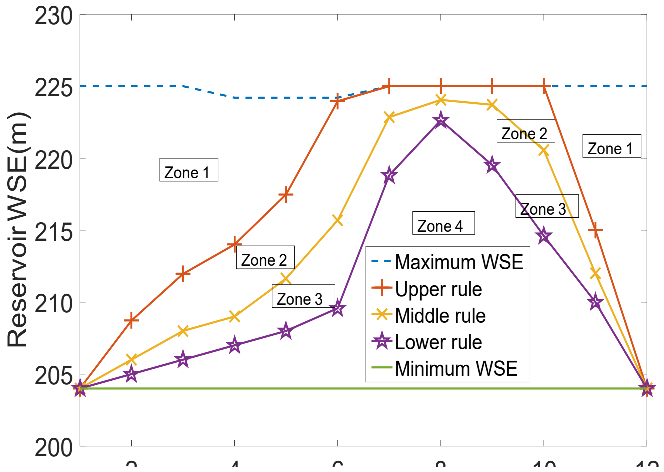

Fig. 2 : Illustration of Rule curve for Qingshitan reservoir operation.

The curves in Fig. 2 divided the reservoir operation into a few zones, in which different operational guidance on outflow release is provided. For example, if the reservoir WSE is in Zone 1, then the outflow should be equal to the *Maximum turbine flow* (67.4 m^3/s for the case) and the water for irrigation should be always guaranteed. The RBM is built according to the rule curves and has what-if procedures to formulate a function in the following:

[reservoir_WSE (t), Outflow]=f (rules curve, reservoir_WSE (t-1)) (8)

The pseudo code for the RBM is written as:

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If reservoir_WSE(t-1) is in Zone n (n=1, 2, 3, 4), Then
    Outflow=rules curve (zone n)
    Reservoir_storage(t)=(inflow-outflow)*operation time step+Reservoir_storage(t-1)
    reservoir_WSE (t)=f(Reservoir_storage(t))
end
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The restrictions on reservoir WSE (such as maximum reservoir WSE and dead water level) and on flows (such as maximum turbine flow) are implicitly considered in the RBM and can be satisfied accordingly. Since the RBM is a simulation model, the objectives are not considered. However, with the obtained outflow and WSE from RBM, the performance of the reservoir operation, namely the index on the seven purposes can be evaluated based on Equation (1) ~ (7).

3.2 Single-objective optimization (SOM)

The SOM is an optimization model of reservoir operation with single objective. The navigation purpose, which has been emphasized recently for Qinshitan Reservoir, is selected as the objective. Other purposes of reservoir operation such as power generation are treated as constraints in the SOM and are restrained no less than the corresponding values from the RBM. The goal of the SOM is to obtain better navigation objective without suffering other purposes of reservoir operation. Therefore, the SOM is formulated as:

Maximize index_Navigation (9)

Subject to:

$$index\_I \geq RBM(index\_I); \qquad (10)$$

$$index\_D \geq RBM(index\_D); \quad (11)$$

$$index\_PG \geq RBM(index\_PG); \quad (12)$$

$$index\_WQ \geq RBM(index\_WQ); \quad (13)$$

$$index\_FG \geq RBM(index\_FG); \quad (14)$$

$$index\_FL \geq RBM(index\_FL); \quad (15)$$

Other operational constraints:

Continuity constraints, WSE constraints, turbine flow constraints and ending WSE constraints are included as other operational constraints and are written in the following:

$$Reservoir\_storage(t) - Reservoir\_storage(t-1) = (Q_{Gn}^{t} - outflow(t)) * \Delta t \quad (16)$$

$$reservoir\_dead\_WSE \leq reservoir\_WSE(t) \leq maximum\_reservoir\_WSE \quad (17)$$

$$0 \leq Q_{tb}^{t} \leq Maximum\_turbine\_flow \quad (18)$$

$$reservoir\_WSE(end) \geq \mathrm{RBM}(reservoir\_WSE(end)) \quad (19)$$

Where $reservoir\_WSE(end)$ is the ending WSE. This is to ensure that the ending WSE from the SOM are no less than that from the RBM.

The outflows from the reservoir are the decision variables. Since the model is daily-based for a year, there are 365 decision variables in total. The optimization model is solved by Genetic Algorithm (GA) that is built in Matlab.

3.3 Bi-objective optimization (BOM)

The BOM is a typical multi-objective optimization model for reservoir operation. Similar to other researches (Reddy & Kumar, 2006; Chang & Chang, 2009), the BOM consider two aggregated objectives: one is for human interests and another is for ecological purposes. For the case study, irrigation, power generation, domestic water supply, navigation and water quality requires strong regulation of reservoir operation and are aggregated as the first objective. This objective is obviously conflicting to maintain the nature flow regime of both the Gangtang and Lijiang River, which are aggregated as the second objective. All the purposes are assigned with equal weights to avoid human prejudice. The BOM model is formulated as:

$$Maximize\ (index\_N + index\_I + index\_D + index\_PG + index\_WQ)/n\_h \quad (20)$$

$$Maximize\ (index\_FG + index\_FL)/n\_e \quad (21)$$

Subject to:

Operational constraints: Continuity constraints, WSE constraints, turbine flow constraints, ending WSE constraints

where *n_h* is number of objectives concerning human interest and has a value of 5 in this case. Correspondingly, *n_e* is number of objectives concerning ecological interest and has a value of 2. The operational constraints are the same with the SOM, so are the decision variables. The model is solved by Non-dominated Sorting Genetic Algorithm (NSGA-II), a widely used multi-objective optimization algorithm (Deb et al., 2002). The NSGA-II is available in the Matlab and can be implemented using "gamultiobj", a built-in function for multi-objective optimization.

3.4 Many-objective optimization (MOM)

The MOM can be thought as an extension of the BOM. However, all the purposes of reservoir operation are explicitly considered as objectives without aggregation. The model formulation is written as:

Maximize (index_PG) (22)
Maximize (index_I) (23)
Maximize (index_D) (24)
Maximize (index_N) (25)
Maximize (index_WQ) (26)
Maximize (index_FG) (27)
Maximize (index_FL) (28)

Subject to:

Operational constraints: Continuity constraints, WSE constraints, turbine flow constraints and ending WSE constraints

The decision variables and the operational constraints are the same as the MOM and the SOM model. A reference point-based optimization algorithm called NSGA-III (Deb & Jain, 2014), is used for solving the MOM.

4 DATA AND EXPERIMENTS

Annual inflows of three typical years (wet, normal, and dry) to Qinshitan Reservoir are considered (Fig.3). These years are corresponding to the year of 1993, the year of 1999 and the year of 2004. The recorded flow in the upstream Lijiang River i.e., Q^{t}_{LN} is also shown in Fig 3. Other data used for the operation models include reservoir storage-WSE relation, flow-WSE relations for the river channel.

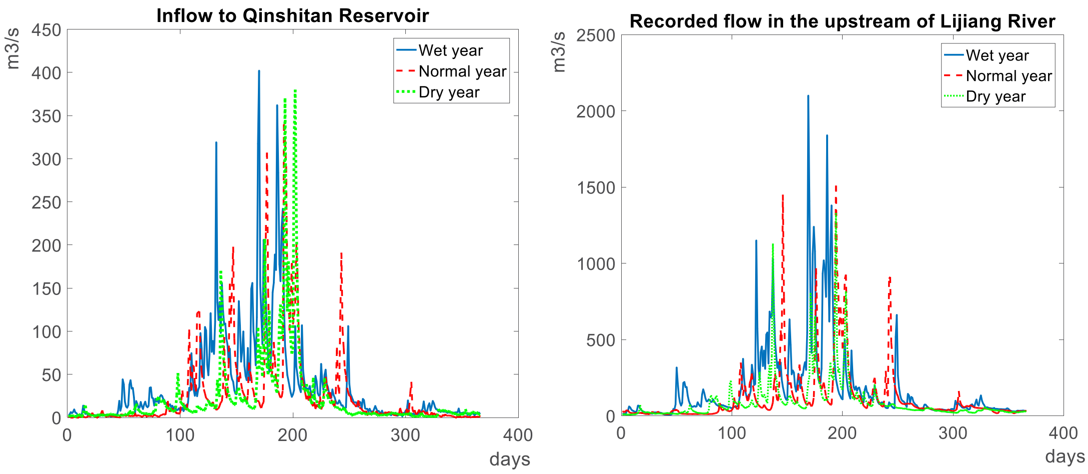

Fig. 3 : Typical annual Inflow to Qingshitan reservoir and recorded flow in the upstream Lijiang River

For each operation model, three experiments are conducted using the three years of hydrological data. Due to the randomness of the optimization algorithm, 30 runs are repeated for each experiment under the same setting and the average results are reported. Even different optimization algorithm (GA, NSGA-II and NSGA-III) are used for the SOM, BOM and MOM, the core operators of those algorithms are the same i.e., crossover and mutation. Therefore, all the models adopt the same settings. The crossover is a two-point type with a rate of 0.9, and the mutation operator is uniform type with a rate of 0.01. The population size is 500 and the number of generation is 5000; the stopping criteria are function tolerance (the average relative change in the best fitness function value) less than 10E-6.

5. RESULTS AND DISCUSSIONS

Since the historical operation of Qinshitan Reservoir was carried out based on rule curve, the historical records on reservoir WSE and on the outflow are used to represent the results from the RBM. The index for the seven purposes are calculated using RBM and Equations (1)~(7). The results for the three typical years are shown in Fig.4. The reservoir operation under wet year has the best performances for the entire seven indexes because of relative abundant inflow (see Fig.3). The indexes under normal year are not much different from that under dry year except for the index of power generation. The index result from other operation models i.e., SOM, BOM and MOM are shown in Fig. 5. Since the results of RBM represent the historical operation, it is treated as a benchmark for comparison and is included in Fig. 5.

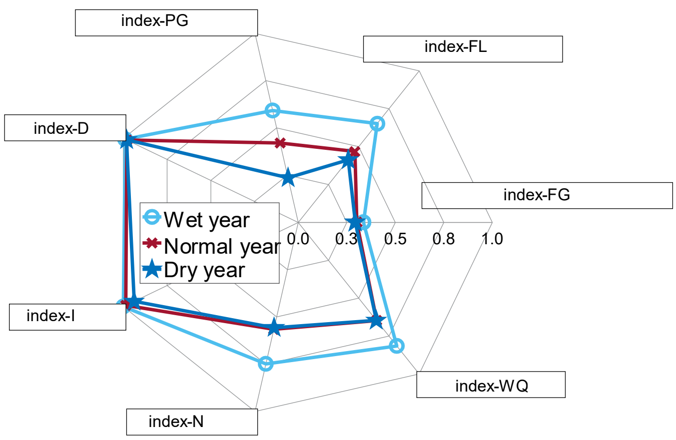

Fig. 4 : Index results of Qinshitan Reservoir under RBM for the three typical years

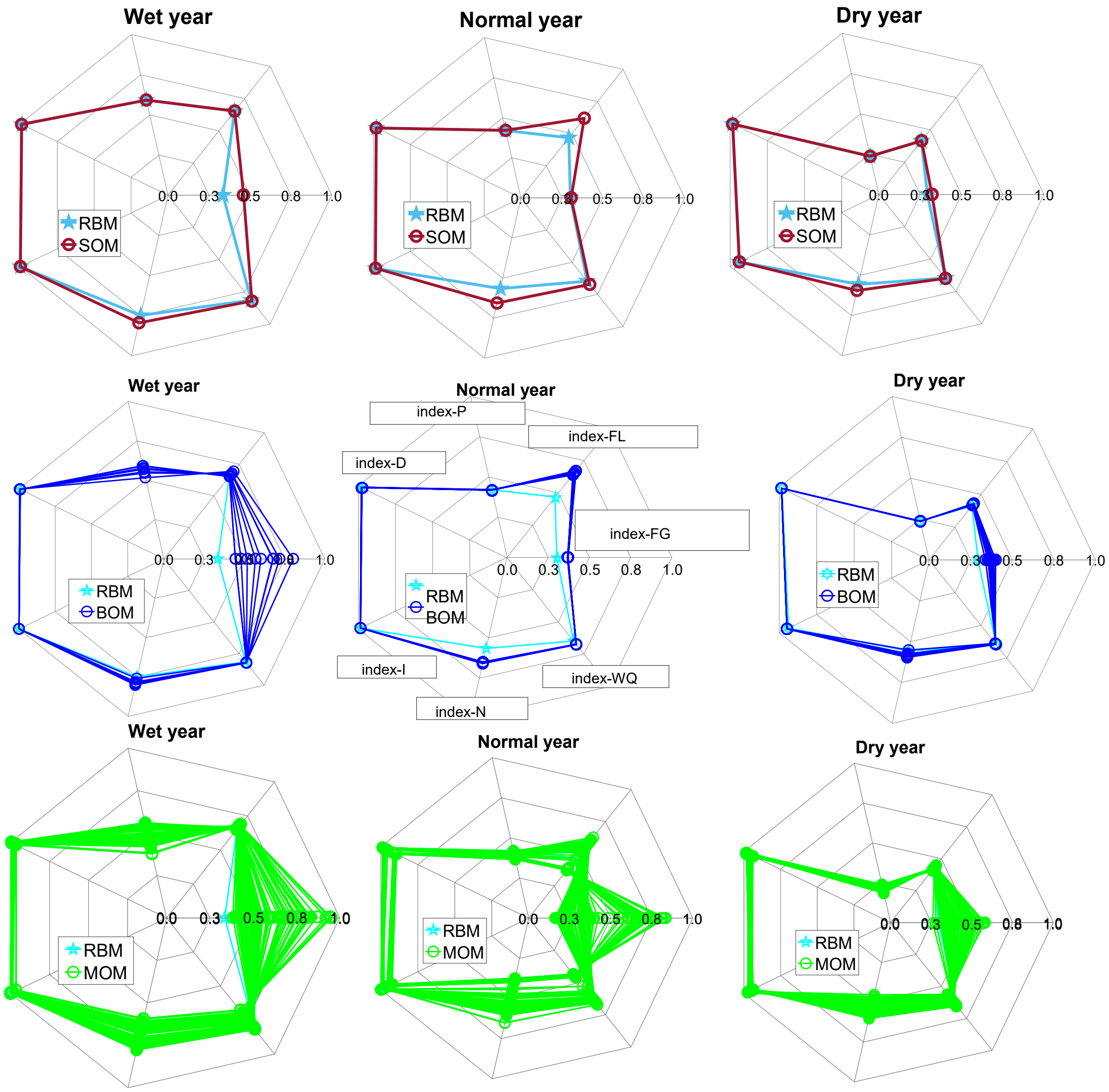

Fig. 5 Compare Index results of Qinshitan Reservoir for the three typical years

The SOM acquire better *index_N*, (the objective for the SOM) under all the three typical years, compared to that of the RBM. Other indexes from the SOM are no less than those from the RBM as they were constrained in the SOM. Some of the index such as *index_FG*, and *index_FL* has been even improved. This means reservoir operation under the RBM can be improved by using optimization techniques under the same condition.

The results of the BOM are a group of solutions which represent trade-off between the two aggregated objectives. All of the solutions show better results than the RBM. Moreover, the result of the SOM has been included in the results of the BOM, as shown in Table 1~3. This means that the BOM provide more options for reservoir operation by having different combinations on the objectives. It is particularly obvious for the wet year, in which *index_FG* can have a range from 0.44 to 0.80 and *index_PG* vary from 0.52 to 0.59. In such context, the decision maker can consider different scenarios, for example, a scenario with higher hydropower production but more serious impact on the river flow regime, or another scenario with less impact on the river flow regime but lower hydropower production.

The results of the MOM almost cover all the results from other three operation models (Fig. 6 and Table 1~3). Much wider range on the index can be observed from the MOM. Among them, the *index_FG* has shown the most flexible result, ranging from 0.16 to 0.95, if consider all the values for the three typical years. Other index varied accordingly with a smaller range. Since the Qinshitan Reservoir is on the Gantangjiang River, the reservoir operation is essentially the regulation for that river. The more the river has been regulated, the more human interests would be satisfied; however, result in a stronger alteration on the nature flow regime.

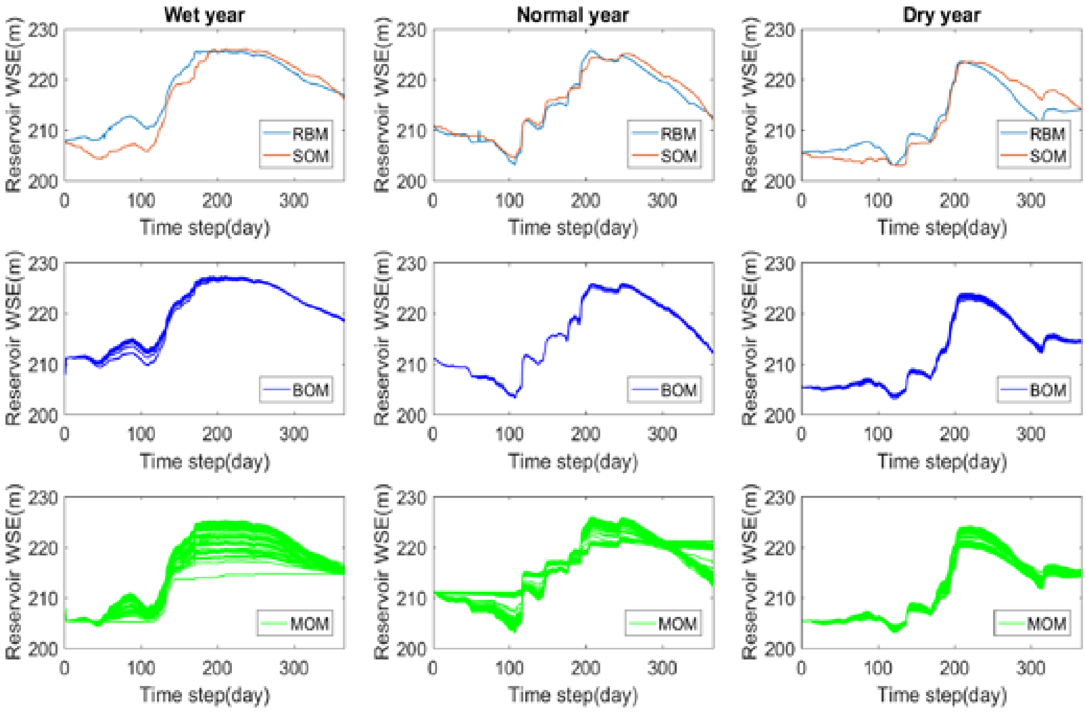

Fig. 6 : WSE results of Qinshitan Reservoir under RBM for the three typical years

The comparison showed that the optimization models i.e., SOM, BOM and MOM obtains better index for the objectives than that from RBM, the simulation model. It should be noted that all the optimization models are deterministic, namely all the inflow information are known in advance and has no uncertainty. This is not a practical situation where large uncertainty is associated with the inflow forecast, particular for the middle- and long-term. The optimization models may not always be better than the RBM, which is more robust under different inflow conditions, as many historical inflow scenarios have been considered. However, the optimization techniques can be used to derive better rule curves, which in turn result in a better RBM.

The step-wise pattern discovered by the MOM may not be practical for reservoir operation in the real-world. Under this pattern, the reservoir regulation capacity is not fully explored, which are not expected by the original design and planning. However, it provides another option for new hydro-projects that are being planned. Given the increasing awareness of ecological protection, the MOM can serve as an emerging planning tool, in which a no-reservoir designing scheme may be an option.

6. CONCLUSIONS

The MOM demonstrates the best performances among the four operation models for providing the most options to decision making. Assigning weights to aggregate objectives can be avoided in the MOM as it explicitly considers all the operational purposes as objectives. This consideration is helpful for exploring the complicated relations between the many objectives. Therefore, the MOM can also be served as a screening tool when priorities of the objectives are not directly available. A step-wise pattern for operating WSE of reservoirs is discovered by the MOM, which is not captured by the other operation models. This pattern may not be practical for the present, but provides a new perspective for reservoir operation in future scenarios.

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