Optimizing Selective Withdrawal System in Reservoir to Manage Downstream Water Quality and Hydropower Energy Generation

Motahareh Saadatpour[1], Shima Javaheri[2]
1- Assistant Professor, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
2- M. Sc. Graduated Student of Civil and Environmental Engineering, College of Environment, Karaj, Alborz, Iran

Email: msaadatpour@iust.ac.ir

Abstract

The integrated water quality and quantity management in reservoir design and operation is the key to meet sustainable development goals while maintain ecological services and economic benefits. Selective withdrawal systems (SWS) can help adapt reservoir operation to manage and enhance downstream water quality. This research develops a surrogate based simulation-optimization approach (SBSOA) to release water from different intakes in reservoir to minimize deviations from standard dissolved oxygen (DO) concentration and maximize annual hydro power peak energy generation. ANN is developed to act as surrogate of time consuming CE-QUAL-W2 model in approximation reservoir outflow DO concentration. The developed surrogate model is coupled with multi-objective particle swarm optimization (MOPSO) to derive optimal SWS (locations and withdrawal ratio) in Karkheh reservoir. Optimization results for water quality and quantity management with SWS are compared to historical release model. The results show optimal SWS can help enhance release water quality compared with historical scenario.

Keywords: ANN, CE-QUAL-W2, Karkheh reservoir, MOPSO, Selective Withdrawal System.

1. INTRODUCTION

Dams as man-made structures, whose effects, besides the obvious change from a stream to a lake environment in the reservoir itself, are related to the spatial and temporal changes of in-stream flow, downstream nutrients and sediment flow reductions, vertical and longitudinal changes of water temperatures and water quality profiles, and impeding fish and wildlife migration [1]. Historically, in many countries over the worlds, water reservoir planning, management, and designs have aimed to satisfy quantity and/or economic objectives. As a result, a lot of water-related problems have arisen. This has caused the need for better and more comprehensive viewpoints in planning and management process. Nowadays, water quality has become increasingly more important in reservoir design, planning, and management due to intense multi-objective demands on limited resources, its effects on other environmental interests, such as fish and wildlife, impact or impairing water use. Therefore, laws and regulations require consideration of water quality for new reservoir construction and structural or operational modifications of existing reservoirs [2].

Natural conditions and human interventions affect the reservoir hydrodynamic and water quality parameters. The effects of natural events (hydrological and meteorological conditions) couldn't be considered directly into the realm of reservoir design and/or management process. But human interventions can influence/enhance water quality through a) pre-treatment or control of reservoir inflows; b) in-pool management or treatment techniques; and c) management of reservoir outflows [2]. Reservoir outflow management is the most common method which affects reservoir in-pool and release water quality. Outflow management can consist of controlling the outflow rate, outlet location and timing of releases, and treating the release. In this paper, third alternative is considered on the case which the outflow is controlled through equipping the reservoir with multilevel outlets. The aforementioned selective withdrawal system (SWS) provides water releasing at different elevation with various physical, chemical, and biological characteristic [3]. In this regards, the reservoir is outfitted with SWS in order to meet downstream water quality objectives and also the quantity objective (hydropower peak energy 2 generation). The main objectives of the problem are to reduce downstream water quality deterioration and increase hydropower peak energy generation through SWS application in reservoir.

In this study simulation-optimization (SO) approach has been developed to determine optimal SWS design in hypothetical case study (Karkheh reservoir, Khuzestan, Iran) with sufficient, known, and complete hydrological, meteorological, hydraulic, and water quality data. The calibrated and verified 2D hydrodynamic and water quality simulation model of Karkheh reservoir has been applied to assist the design and evaluation process of the outlet structures in order to predict the effects on water quality and designing water quality targeted operation in new and existing reservoirs. Due to high computational burden of numerical hydrodynamic and water quality simulation model (WQSM), CE-QUAL-W2, a surrogate model is developed to overcome the computational obstacles. The surrogate model has been coupled with Multi-objective particle swarm optimization (MOPSO) algorithm to derive optimal SWS (the outlet locations and withdrawal ratio) in reservoir.

2. METHODOLOGY

Proper SWS designing and deriving optimal reservoir operation strategies in selective withdrawal framework are efficient and effective approaches help achieve quantity objectives and also prevent and/or reduces water quality deterioration. In this point, social, economic, and environmental objectives are achievable. Coupled numerical WQSM and evolutionary algorithm (EA), as SO approach, are effective tools to solve this high complicated, inter-related, non-linear, and large scale problems. Unfortunately, EA requires plenty of numerical WQSM calls to converge near- optimal and/or optimal solutions and therefore considering water quality issues in water resources planning and management problems results in higher computational intensity. To reduce the computational burden in highly expensive SO model, approximation model is often suggested. These approximation models are initially developed as the “surrogates” of the expensive simulation models in order to improve the overall computational performance. The details about applied tools and approaches of this research are discussed below.

2.1. MODEL DEVELOPMENT

In this research, MOPSO algorithm has been developed to be coupled with CE-QUAL-W2 as 2D hydrodynamic and water quality simulation model. The applied WQSM is capable to simulate the effective factors on mass and energy circulation, transportation, and fate process in the reservoir, temporally and spatially. Due to extensive WQSM call requirement in SO approach and also expensive time and computational costs CE-QUAL-W2 model, surrogate based SO approach (SBSOA) has been applied. The proposed approximation model, as a surrogate of numerical WQSM in this research, has the ability to quickly and inexpensively respond to various SWS design in reservoir. The interaction between various applied tools in this research is presented in Figure 1.

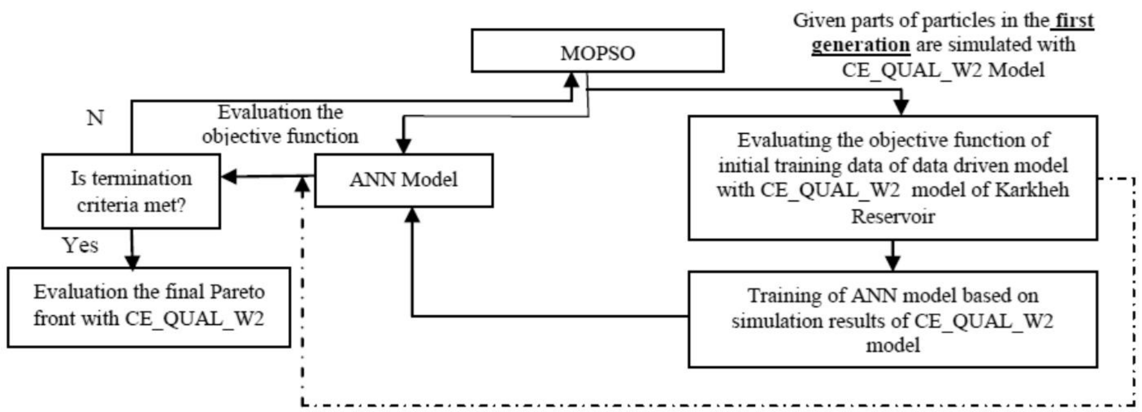

Figure 1. The structure of SBSOA in optimal SWS design in reservoir

The considered SWS in this research have been located vertically in dam structure. The intake type, elevation of location, and the corresponding layer numbers of each intake in CE-QUAL-W2 model have presented in Table 1. The last two lines present current intake elevations in Karkheh reservoir. In this study, up to five intakes could be selected in SWS design process in the reservoir in SBSOA.

Table 1- Intake elevations and locations corresponding to computational layers of CE-QUAL-W2 model

Intake Number	Intake type	Intake Elevation, masl	Intake top layer number	Intake bottom layer number
1	Point	212	7	9
2	Point	206	10	12
3	Point	200	13	15
4	Point	196	15	17
5	Point	192	17	19
6	Point	188	19	21
7	Point	182	22	24
8	Point	176	25	27
9	Point	170	28	30
10	Point	162	32	34
Main 1	Point	180	23	25
Main 2	Point	161.5	32	34

2.2. SIMULATION MODELS

Process based WQSMs are useful tools which depict the transportation and fate mechanism, physical, chemical, and biological inter-relations in water bodies explicitly, spatially and temporally. To model the complicated and inter-connected physical, chemical, and biological mechanisms, massive hydrological, meteorological, hydraulic, water quality data is required and extensive model parameters should be set. In contrast, data-driven models, discarding the aforementioned mechanisms and processes, approximate the water quality responses in water bodies quickly and inexpensively. In this study, ANN model, as data-driven model, has been trained and tested according to numerical and process based WQSM, CE-QUAL-W2 model.

2.2.1. CE-QUAL-W2 MODEL

CE-QUAL-W2 as 2D hydrodynamic and WQSM has been applied in this study. This model has the capability to simulate the spatial and temporal hydrodynamic and water quality variations in reservoirs. The reservoir geometry is gridded vertically and longitudinally as computational elements which mass and transport equations are solved in each element with finite difference method. The elements connections have been considered through settling and diffusion processes. Water surface elevation, velocity, flow rates, as important hydrodynamic variables, affect the mass transportation in water body. The 2D advection-diffusion-reaction equations have been solved to simulate water quality concentration in each computational grid. The model has the ability to simulate the mechanisms affect temperature, nitrate, phosphate, algae, dissolved oxygen, organic and inorganic matters, sediments, total dissolved solids, coliforms, and etc. in reservoir [4].

2.2.2. ANN AS SURROGATE WQSM

Surrogate models have been developed to approximate the partial behaviors of complicated, multi variant model based on limited data originated from the expensive and more fidelity simulation models [5]. Proper and correct relevance definitions between decision variables (intake elevation and outflow rate of each intake in this research; SWS) and state variables (reservoir outflow DO concentration) are main and significant step in surrogate model 4 development. ANN has been recognized as a useful and efficient tool in surrogate model development process. The mathematical function of ANN could be written as:

$$Y=f(X,W)+\varepsilon \qquad (1)$$

Y, *f*, *X*, *W* and *ε* are output vector, input vector, ANN model parameter vector, connecting vector among system input and output, and ANN model error vector, respectively. Successful and proper ANN input data selection lead to increasing the accuracy of surrogate model in design and planning problem through enhancing the approximation precision. To achieve the aforementioned aims in developing ANN model as reservoir outflow DO concentration, it is required to acquire profound knowledge and understanding on the mass transport and fate mechanism, the cause and effect relations among various water quality parameters, among water quality and quantity parameters, temporal and spatial dynamics of system responses, and delays and their main reasons.

2.2.2.1. ANN MODEL DEVELOPEMENT IN DO CONCENTRATION APPROXIMATION

DO is significant water quality parameters in water-bodies and is essential element in aquatic lives. The simplification of mathematical equations describing DO fate and transport in reservoir is required in surrogate model development process. Reviewing the mathematical equations (2) shows algae growth rate (AG), phosphorous half-saturation coefficient (p_s), nitrate half-saturation coefficient (n_t), solar radiation half-saturation coefficient (I), algae respiration coefficient (k_{ra}), algae concentration (V_a), flow area ($A_{Surface}$), reaeration coefficient (K_L), DO saturated concentration (O_{sat}), DO concentration (O), nitrification coefficient (K_{NH4}), de-nitrification coefficient (K_{NO3}), organic matter decay rate (K_{POM}), nitrate concentration (V_{ni}), NH_4 concentration (V_{NH4}), sediment organic matter decay rate (K_s), sediment concentration (V_{sed}), bottom sediment oxygen demand (SOD), bottom sediment area (A_{Sed}), required oxygen to decay organic matter (γ_{OM}), and required oxygen to decay NH_4 (γ_{NH4}) [4].

$$V\frac{\partial O}{\partial t} = (AG(T, n_t, p_s, I) - k_{ra})V_a\gamma_{OM} + A_{Surface}K_L(O_{sat} - O) \quad (2)$$

$$+ K_{NO_3}(T)V_{ni}\gamma_{NH_4} - K_{POM}(T)V_{c_{POM}}\gamma_{OM} - K_{NH_4}V_{NH_4}\gamma_{NH_4} - \gamma_{OM}K_s(T)V_{Sed} - SOD(T)\times A_{Sed}$$

Furthermore, understanding the thermal energy transportation and modeling is required due to temperature (T) effects the reservoir water quality parameters. The mathematical equations prove that inflow water temperature, the exchanged heat flux with atmosphere, inflow and outflow rates, flow area, and water body volume have more effects on water temperature in water-bodies. Meteorological parameters such as air temperature, dew point temperature, wind speed and direction, … affect the exchanged heat fluxes with atmosphere.

Due to spatial distribution and extension of reservoir water body, various mass and energy diffusion and advection process, the role of wind speed and gravity, reservoir geometry, the withdrawal locations in reservoir, and etc. there are vertical thermal and quality gradients in deep reservoirs. Furthermore, in long reservoirs due to effective fate and transport processes, there are longitudinal thermal and quality gradient, too. In this regards, the longitudinal gradient leads to delays between outflow and inflow water temperature and quality in reservoir.

Considering the above concepts and mathematical equations describing the DO concentration in water bodies, water temperature, transportation and circulation processes in reservoir, NH4 inflow flux, NO3 inflow flux, TSS inflow flux, BOD inflow flux, PO4 inflow flux, DO inflow flux, algae inflow flux, thermal inflow flux, air temperature, wind speed, outflow rate, water surface elevation (WSE), and outflow ratio from each outlet (10 outlets are considered in this study) have been considered as ANN input data to model reservoir outflow DO concentration (Figure 2).

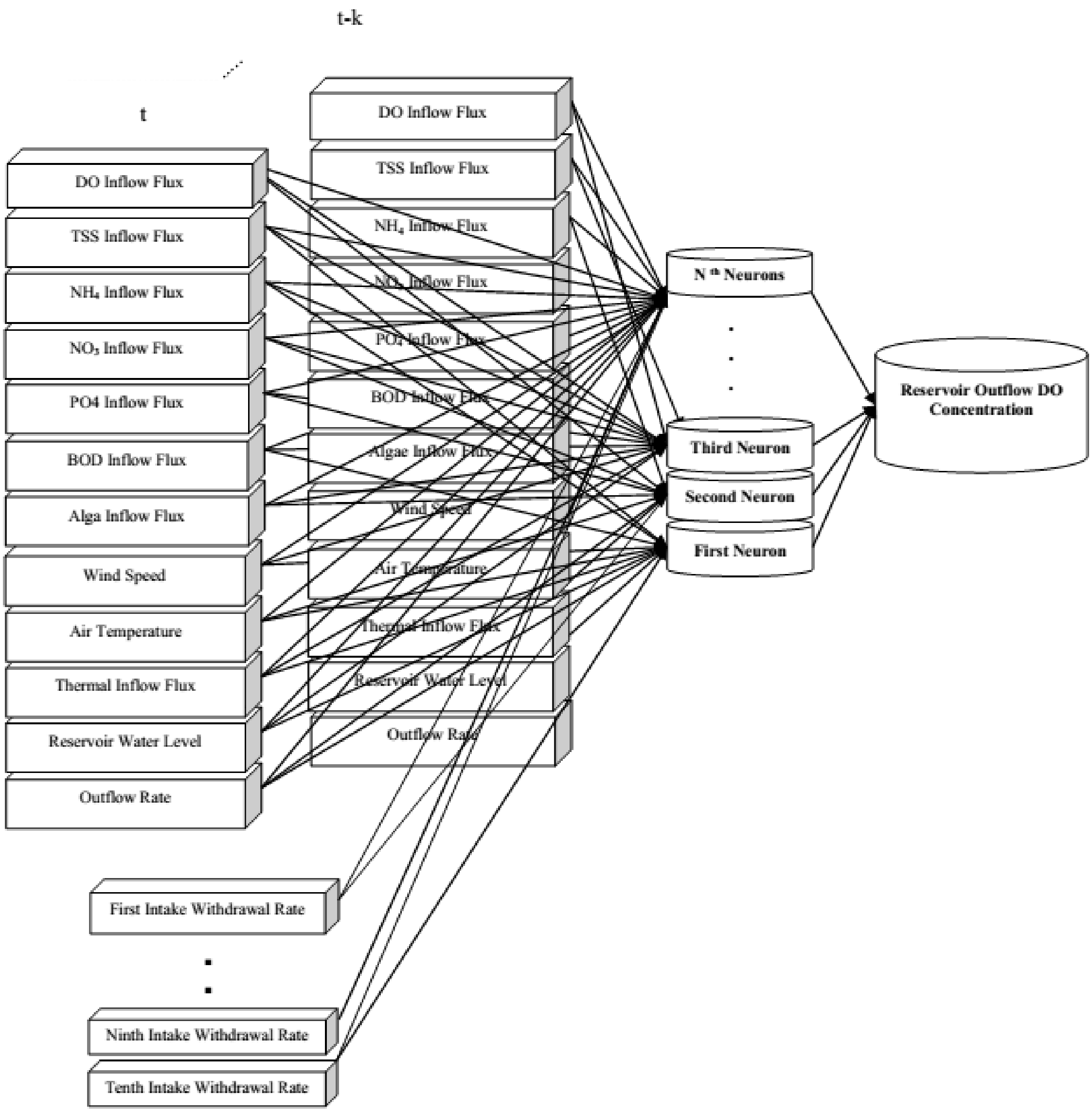

Figure 2. Input data in neural network model of reservoir outflow dissolved oxygen [6]

The studies on Karkheh reservoir show system responses in time step *t* are affected by meteorological, hydrological, water quality, and reservoir operation strategy in time step *t-k*. As a result, the time delays of input data except the withdrawal ratio of each outlet are considered. In this regards, various water quality inflow fluxes, thermal inflow fluxes, outflow rates, WSE, and the meteorological data are introduced with three months delays. All aforementioned data are arranged as 15-day averaging time steps. Reservoir outflow DO concentration is approximated in each 10-day time step. CE-QUAL-W2 model has been applied to train ANN DO approximation model. 20 various reservoir operation scenarios in selective withdrawal scheme during 15 years have been simulated with CE-QUAL-W2 model. 80% of scenarios have been implemented for ANN training and the remaining scenarios have been applied as ANN model test.

2.3. MODEL STRUCTURE

The developed surrogate model has been coupled with MOPSO to determine the optimal SWS (design problem). In this study, minimizing the number of DO concentration violation from standard value and maximizing the average annual peak energy generation have been considered as objective functions. ANN DO approximation model, simulate reservoir outflow DO concentration, is coupled with MOPSO. The simulation model (surrogate WQSM and hydropower simulation model) and optimization algorithm have coupled sequentially (Figure 1).

The final derived Pareto front, derived in SBSOA, have been simulated and evaluated with CE-QUAL-W2 model.

2.4. WATER QUALITY AND QUANTITY OBJECTIVE FUNCTIONS

DO as water quality index is considered in this study. Minimizing the number of DO violation from standard value in each 10-day is defined as water quality objective function in this research. In equation (3) and equation (4), $DO_{standard}$ and $DOConcentration_i$ are standard DO value (5 mg/L) and reservoir outflow DO concentration in time step i, respectively.

$$Min \quad f_{quality} == (NumberofDOViolationDay) \tag{3}$$

$$DOConcentration \begin{cases} DO_{standard} & DOConcentration \geq DO_{standard} \\ DOConcentration & else \end{cases} \tag{4}$$

Maximizing average annual hydropower peak energy generation is defined as water quantity objective in Karkheh reservoir (equation (5) to equation (7)).

$$DesignFlow = (IC \times 1000 / (9.81 \times Eff \times DesignHead)) \tag{5}$$

$$Q_{in} = Outflow_t \times (Y_{1_t} + Y_{2_t} + Y_{3_t} + Y_{4_t} + Y_{5_t} + Y_{6_t} + Y_{7_t}) \tag{6}$$

DesignFlow, Q_{in}, $Outflow_t$, Y_{it}, *IC*, *Eff*, *DesignHead*, $plantInflow_t$ are power plant design flow, available flow in power plant, Karkheh reservoir outflow rate in time step t, withdrawal ratio of outlet i at time step t, power plant installed capacity, and design head, respectively. In equation (7), $plantInflow_t$ and $NetHead_t$ are water inflow rate to power plant and net head water in system. *peaktime* and *Energy* are power plant operation in peak time (hourly) and average annual peak energy generation, respectively.

$$Energy = ((\sum_{t-1}^{TotalContolDay} 9.81 \times plantInflow_t \times NetHead_t \times Eff \times peaktime \times 10/1000000)/5310) \times 365) \tag{7}$$

2.5. CASE STUDY AREA

The proposed methodology in this research has been applied in hypothetical case study with complete and comprehensive calibrated and verified 2D hydrodynamic and water quality model, Karkheh reservoir. Karkheh reservoir is constructed on Karkheh River, Khuzestan, Iran. The dam crest and maximum depth are 3030 m and 117 m, respectively. With 5346.2 MCM capacity, 162 km^2 surface areas, and 60 km length in normal water level, 220 masl, this reservoir is the largest reservoir in Iran. Supplying agricultural water demand for approximately 50000 km^2 of irrigation area, 934 GW annual hydropower energy generation, and flood control are the main objectives of this large scale hydraulic structure.

3. METHODOLOGY APPLICATION IN CASE STUDY WITH SUFFICIENT DATA; RESULTS AND DISSCUSION

The developed ANN model to approximate reservoir outflow DO concentration has been trained and tested with CE-QUAL-W2 model results. Then SBSOA has been applied to derive optimal decision variables in SWS problem. Finally, the Pareto front derived in SBSOA has been evaluated with CE-QUAL-W2 model to revise the derived Pareto front. The results are presented below.

3.1. SURROGATE MODEL DEVELOPMENT TO APPROXIMATE RESERVOIR OUTFLOW DO CONCENTRATION 7

The performance of ANN model in approximation reservoir outflow DO concentration has been evaluated with four various SWS. The approximated values with ANN model have been compared with CE-QUAL-W2 model results. The intensive sensitivity analysis have been done on learning and training functions and also the neuron numbers in hidden layer of ANN model. Then the network with higher performance has been chosen to simulate system responses according to various reservoir operation strategies in selective withdrawal framework. The comparison results have been presented in Figure 3. The statistical criteria represent suitable convergences between ANN model predictions compared with CE-QUAL-W2 model.

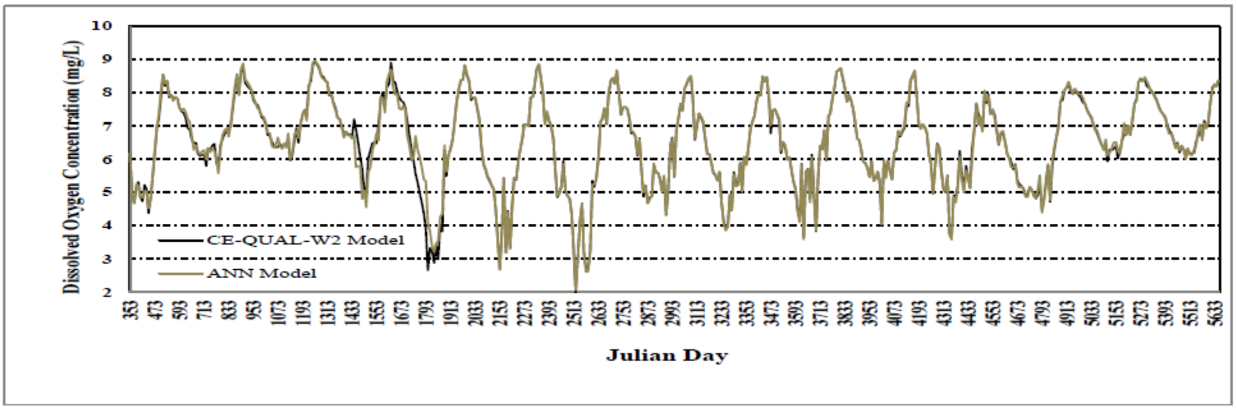

Figure 3. Comparison the performance of DO neural network model with CE-QUAL-W2

3.2. SWS Design Problem and Reservoir Operation Strategy in Selective Withdrawal Framework

Maximizing average annual peak energy generation and minimizing number of DO violation from standard value have been defined as two main objectives of this problem. The Pareto front evaluated with CE-QUAL-W2 model is presented in Table 2. The optimal outlet locations, withdrawal ratio, and the objective function values corresponding to each of Pareto front are presented. The number of DO violation from standard value in the best water quality scenario and best water quantity scenario are 16 and 52 days, respectively. The results show water quality objective conflicts with hydropower energy generation objective.

Table 2- The Final Pareto Front Evaluated with CE-QUAL-W2 Model

Pareto Front No	Scenario Characteristic	Characteristic					Water Quality Objective (day)	Water Quantity Objective (GWh)
1	Intake No.	5	6	7	9	10	52	409.19
	Withdrawal ratio	0.96	0	0.04	0	0		
2	Intake No.	1	5	7	9	10	16	405.52
	Withdrawal Ratio	0.81	0.09	0.08	0.01	0.01		

Time series of reservoir outflow DO concentration in best water quantity scenario is compared with historical operation based on one hydropower intake. The comparison results are presented in Figure 4 . The studies show the number of DO violation in historical operation scenario is 94 days which is more than the worst water quality scenario derived with SBSOA.

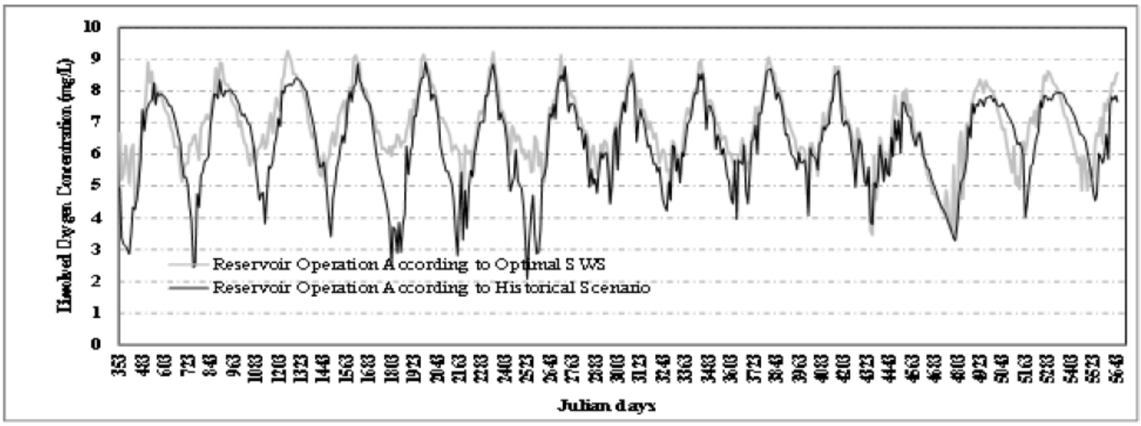

Figure 4. Comparison reservoir outflow DO concentration in optimal and current intake designing scenarios

4. CONCLUSIONS

In this study a new methodology was applied to design SWS in reservoir which could be equipped with multiple outlet release schemes. Water quantity and quality objectives (minimizing number of DO violation from standard value and maximizing average annual hydropower peak energy generation) have been considered as objective functions in this study. Static ANN model is trained and tested to approximate reservoir outflow DO concentration based on dynamic simulation results of CE-QUAL-W2 model according to various SWS. MOPSO has been coupled to ANN DO approximation model sequentially to derive optimal SWS. The derived Pareto front of SBSSA has been evaluated with CE-QUAL-W2. The comparison results show reservoir outflow DO concentration in optimal SWS is more adapted to standard value compared with historical operation system in reservoir. Future research will concentrate on deriving optimal reservoir operation rules in selective withdrawal framework considering quantity and quality issues, adaptive SBSOA, and broaden the range of quality and quantity objectives such as temperature, turbidity, salinity, environmental flow, and etc.

5. REFERENCES

1. Olivares, M. A. (2008), "*Optimal Hydropower Reservoir Operation with Environmental Requirements,*" Ph. D. Thesis, University of California, Davis.
2. Dortch, M., 1997, "*Water Quality Consideration in Reservoir Management,*" Water Resources Update, 108: 32-42.
3. Rheinheimer, D. E., Null, S. E., Lund, J. R. (2014), "*Optimizing Selective Withdrawal from Reservoirs to Manage Downstream Temperatures with Climate Warming,*" Journal of Water Resources Management (ASCE), DOI: 10.1061/(ASCE)WR.1943-5452.0000447.
4. Cole, T.M. and Wells, S.A. (2013), "*User's Guide for CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.71,*" Washington, DC: U.S. Army Corps of Eng, Draft File report, 20314-1000.
5. Solomatine, D. (2015), "*Surrogate Modelling in Model-Based Optimization. An Introduction,*" The UNESCO-IHE Institute for Water Education, Delft, Netherland.
6. Javaheri, S. and Saadatpour, M. (2017), "*Deriving Hydropower Reservoir Operation Rules in Selective Withdrawal Framework Considering Quality and Quantity Objectives; Simulation-Optimization Approach Based on Meta-Modelling,*" Journal of Iran Water Resources Research, http://www.iwrr.ir/article_45175_0.html.