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An adaptive surrogate-based, multi-pollutant, and multi-objective optimization for river-reservoir system management

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ABSTRACT

Integrated management of quality and quantity of river-reservoir water can provide comprehensive information to manage river-reservoir water resources. However, high computational bottlenecks have prevented such management from being applicable in real-world systems. Accordingly, in the present study, we proposed a multi-objective optimization algorithm based on modular support vector regression (SVR) in which several small sub-SVR modules trained through an efficient adaptive procedure cooperate to solve a large-scale problem related to integrated management of quality and quantity of river-reservoir. The performance of the proposed approach was evaluated through an adaptive surrogate-based simulation-optimization (ASBSO) framework under reservoir selective withdrawal scheme (SWS) in Ilam integrated River-Reservoir. The ASBSO framework provided a set of non-dominated optimal solutions to alleviate Ilam River water quality standard violations, enhance Ilam Reservoir outflow water quality, and maximize the downstream water supply satisfaction. The analysis of the Pareto-front indicated that the implementation of MPWLA (multi-pollutant waste load allocation) programs at any level could alleviate the water quality problems in Ilam Reservoir. Furthermore, the reservoir water storage in the regular patterns to meet downstream water demands have resulted in water quality deteriorations in Ilam Reservoir. The results obtained from examining the proposed approach, showed that integrated river-reservoir system management improved water quality in the range from 7 to 28% at the checkpoints of the Gol-Gol Branch of Ilam River and in the range from 5 to 21% at Ilam Reservoir outflow.

1. Introduction

Comprehensive management of the quality, as well as quantity of water, could promote the coordinated development of water resources to increase economic and social welfare without compromising on the sustainability of valuable ecosystems. Development of an integrated approach to characterize waterways at different temporal–spatial scales can provide knowledge for improving and redesigning the nation's water resource infrastructures to meet multiple objectives. Moreover, the development agricultural, industrial, and livestock activities at river basin scales and the construction of large dams may change hydrological, biological, and chemical features in the water bodies. However, reservoirs are operated to support anthropogenic activities are susceptible to water quality deterioration and ecosystem health threats (Kuriqi et al., 2020).

Numerous research works have been conducted on restoring water quality and/or preventing the hypoxic condition in the receiving water bodies. For instance, Meng et al. (2017) developed a waste load allocation (WLA) program in four main pollution units (industry, municipal, livestock breeding, and agriculture) in the Yitong River, China. Furthermore, Xu et al. (2018) proposed an integrated water and multi-pollutant WLA (MPWLA) model to derive the trade-offs between economic growth, resource acquisition, and environmental conservation of coal chemical industries. An efficient WLA program was also designed to

Abbreviations: SVR, Support Vector Machine; ASBSO, Adaptive Surrogate-based Simulation-Optimization; SWS, Selective Withdrawal Scheme; MPWLA, Multi-Pollutant Waste Load Allocation; WLA, Waste Load Allocation; ANN, Artificial Neural Network; TGR, Three Gorges Reservoir; WQSM, Water Quality Simulation Model; MCM, Million Cube Meter; MGCE, Mahab-Ghodss Consulting Engineering; 2-D, Two Dimensional; CPU, Central Processing Unit; MOPSO, Multi-Objective Particle Swarm Optimization; DOE, Design of Experiments; WQI, Water Quality Index; BOD, Biological Oxygen Demand; WSE, Water Surface Elevation.

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provide an optimization approach in which the objectives of the environmental regulators as well as the pollutant dischargers to the Tuojiang River basin were thoroughly considered (Zhang et al., 2018). On the other hand, Saadatpour et al. (2019) developed MPWLA programs in Gheshlagh River, Iran, to enhance the water quality index at control points, equity measures, and economic costs of wastewater treatment plant units. All the previous studies on WLA were limited to a specific condition, regardless of the dynamic waste assimilative capacities in the water bodies. Besides, most of the recent studies have assumed rivers as only receiving water bodies, so that they have not taken the water bodies with complex hydrodynamic as well as water quality characteristics such as reservoirs into account. However, focusing on specific conditions and overlooking the temporal and spatial dynamics of natural forcing functions and human interventions may lead to conservative and/or improper water resources management (Afshar et al., 2018; Hasanzadeh et al., 2020).

In addition to upstream WLA programs, reservoir operation strategy with selective withdrawal scheme (SWS) has been argued to have a significant impact on enhancing/improving water quality aspects. In reservoir operation management, water quantity and quality joint operation give rise to water pollution alleviation, ecological restoration in ambient water bodies, and sustainable social-economic livelihood improvement. Extensive studies have been conducted on reservoirs operation management to consider the quality and quantity aspects of their water (Khan et al., 2012; Hu et al., 2014; Li and Qiu, 2015; Shaw et al., 2017; Yu et al., 2018; Saadatpour et al., 2020) Hu et al. (2014) illustrated a self-adaptive GA-aided multi-objective ecological reservoir operation model to manage the quality and quantity of water in the Xiangxi River near to the "Three Gorges" Reservoir (TGR), China. Considering the environmental issues, a model to optimize the hydropower reservoir operation was developed by Shaw et al. (2017) for a reservoir in Tennessee, USA. The dynamic ANN model has been trained to emulate the hydrodynamic and water quality responses of the CE-QUAL-W2 model according to various reservoir operating strategies. Moreover, Yu et al. (2018) developed optimal reservoir operation strategies in the TGR system to manage the eutrophication challenges in downstream estuarine and maximize hydropower energy generation. Saadatpour et al. (2020) also proposed a novel methodology to develop reservoir operating rules considering water quality enhancements, maximization of downstream water supply, and hydropower energy generation in the Karkheh Reservoir, Iran.

A profound review of the related literature could indicate the scarcity of research works simultaneously studied the upstream MPWLA programs and reservoir operations in SWS concerning the water resources quantity and quality aspects. On this account, the current study presented a comprehensive approach to overcome the challenges of large-scale water resources on the river-reservoir scale. In the proposed approach, the capabilities of (a) the numerical hydrodynamic and WQSM (water quality simulation model) in the depiction of the eutrophication complex processes at temporal and spatial scales, (b) Adaptive WQSM surrogate models in drawing water quality responses, and (c) evolutionary algorithm (EA) to intelligently guide the search space and find optimal solutions were applied in Ilam River-Reservoir system.

The remaining part of this paper is organized as follows; Section 2 introduces the study area and the integrated river-reservoir model and explains the numerical hydrodynamic and WQSM experiments. Section 3 introduces the SVR module and adaptive surrogate-based simulation-optimization approach and formulates the mathematical problem statements. Section 4 demonstrates the results and discussion, and Section 5 concludes this study.

2. Case study

2.1. Study area

Ilam Dam River-basin is in the southeast of Ilam province and consists of three sub-basins, Gol–Gol, Chaviz, and Ema. This dam has been impounded since 2000 on the Konjancham River after a confluence of three tributaries, Gol–Gol, Chaviz, and Ema (Fig. 1a). The reservoir is morphologically complex, relatively narrow, and dendritic. Ilam Reservoir is an essential source of drinking water annually supplying 16.8 MCM to people dwelling in Ilam City. It also provides irrigation water for 6800 ha. agricultural areas.

The widespread algae growth and undesirable taste and odor of water in the Ilam Reservoir have led to concerns about public health and the reservoir operation objectives. The extensive and uneven development of traditional and modern industrial, agricultural, and animal husbandry activities in the upstream catchment of the Ilam Dam have also been identified as the main sources of threats to water resources. Gol-Gol River, the main branch of the Ilam Reservoir, has been recognized as an important source of nutrient pollutants in the waterbody. The Gol-Gol catchment consists of six sub-catchments, G1 to G6, which are all affected by anthropogenic activities (Fig. 1a). Furthermore, the use of fertilizers and pesticides in the agricultural fields, animal manure, wastes of animal husbandry and poultry activities, etc. have increased the nutrients and Iron (Fe) concentrations in the water resources of the Gol-Gol sub-basin. Also, the accumulation and stagnation of high-nutrient water resources in Ilam Dam have provided favorable conditions for algal blooms and reservoir water resources deteriorations.

Additionally, the continuing deterioration of water quality in the last several decades and a serious threat to local water security in the Ilam River basin have necessitated comprehensive water resources management considering spatial and temporal aspects, water quality and quantity issues, and detailed analyses of hydrological and water quality processes in the upstream and downstream water bodies.

2.2. Ilam reservoir hydrodynamic and WQSM, CE-QUAL-W2

Models have long been applied in water resources management to guide decision-making and enhance the knowledge of the system. The comprehensive representation of the Ilam River-Reservoir system consisting of Gol-Gol River and Ilam Reservoir is modeled in 2D hydrodynamic and WQSM, CE-QUAL-W2 (Fig. 1b). As shown, the domain of the Gol-Gol River is from G6 sub-catchment inflow as the headwaters to G1 sub-catchment inflow as the downstream point, 20 km in length. In this figure, the river is represented as a waterbody with one branch, consists of 42 longitudinal segments with 500 m length, five tributaries as pollutant sources originated from sub-catchments G1 to G5. Ilam Reservoir is also located right below the Gol-Gol River. Moreover, Fig. 1b illustrates that the Ilam Reservoir CE-QUAL-W2 model domain is split into 20 longitudinal segments and 43 vertical layers with varying spaces. We can also observe that this reservoir comprises three separate branches (Gol-Gol, Chaviz, and Ema). Branch 1 (Gol-Gol reach) is defined as the main branch receiving inflow from the Gol-Gol River, while branches 2 and 3 receive inflow from the Chaviz and Ema Rivers, respectively.

Ilam Reservoir is equipped with two middle and upper intakes at the altitude range from 928 to 942 m above sea level, respectively. The hydrodynamic and water quality model of the Ilam River-Reservoir model was calibrated and validated based on the monitored data in the Ilam River basin. Further, the data on the historical reservoir operation strategies in Ilam Reservoir was taken from the Iran Dams website. Meanwhile, the meteorological data of the Ilam synoptic station were collected from the Iran National Meteorological website. Besides, the geometric, hydrologic, and water quality data in the CE-QUAL-W2 model setup were provided based on comprehensive hydrological and environmental studies, conducted in the Ilam River basin (MGCE, 2009).

3. Methodology

For simultaneous MPWLA programs and reservoir operations in SWS, considering water resources quantity and quality aspects,

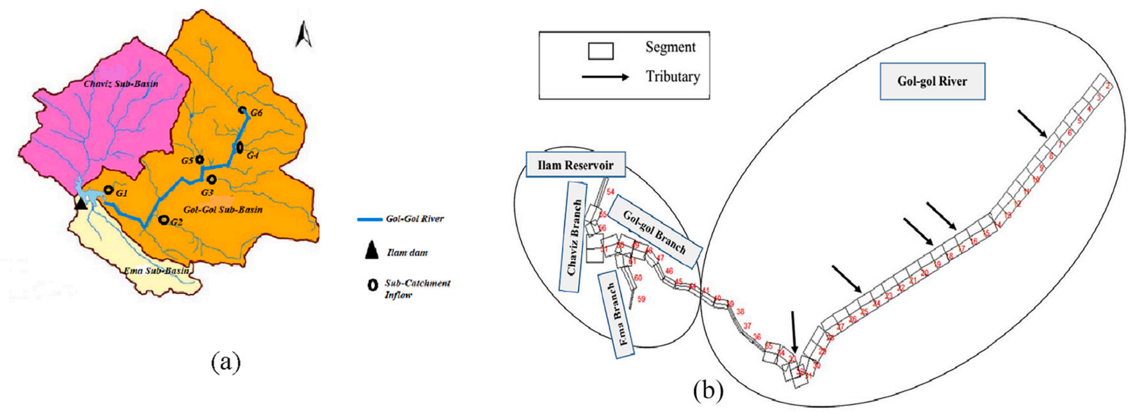

Fig. 1. (a) The Schematic Representation of Ilam Dam River Basin and the Gol-Gol Sub-Catchments' Inflows, (b) The Numerical Representation of Ilam River-Reservoir System in CE-QUAL-W2.

simulation models are often coupled to optimization algorithms. Although some applications of 2-D numerical hydrodynamic and WQSMs have been reported, the development and implementation of the comprehensive approach outlined in this research are quite novel. The main reason for employing such a novel approach can be associated with a great deal of CPU time required to find and report solutions for each alternative to 2-D numerical hydrodynamic and WQSMs. According to the pre-determined application in which a model will be applied, WQSMs may require to be executed hundreds or thousands of times, in which the computational burden could become quickly prohibitive (Razavi et al., 2012). Moreover, to overcome the challenge of the tremendous amount of CPU time required to run hydrodynamic and WQSM, a cheaper-to-run surrogate model was employed.

Support Vector Regression (SVR) can be applied as surrogate models to emulate complex numerical hydrodynamic and WQSMs. Due to their complexity, large-scale spatial and temporal characteristics, and multiplicity of decision variables in the comprehensive management of the integrated river-reservoir, a network of surrogate models are required to approximate different state variables at temporal and spatial scales. In this regard, adaptive modular SVR WQSMs were linked to the multi-objective particle swarm optimization (MOPSO) algorithm (Saadatpour, 2012) with the idea of search interval adaptation. In the following, more details about each component of the proposed methodology are described.

3.1. Support vector regression (SVR)

Traditional/statistical regression methods are described as the procedure acquiring a function *f(x),* which has the least deviation between estimated and real data responses for all training samples (Basak et al., 2007). The main objective of the SVR is to define a regression function as below;

$$f : R^D \rightarrow R$$

$$y = f(x) = \omega^T \phi(x) + b \tag{1}$$

Where $\phi(x)$ is a function, which maps data x from low to high dimensional feature space, ω is a weight vector, ω^T is a transpose of vector ω, and b is a numeric value that can be either up or down (Wang and Xu, 2017). Meanwhile, the ε-insensitive function is adjusted in standard SVR. It is supposed that the training data set are fitted with a linear function in the accuracy of ε. Then, the problem is defined as an optimization problem, in which the objective function should be optimized (Wang and Xu, 2017).

3.2. Surrogate models

A surrogate model of a time-consuming numerical function may be represented as $M = M(p,x)$ explained by a set of parameters (p) and a vector of input variables (x). It intends to provide acceptable estimation with a rather low computational burden. The proper function, $y = G(x)$, over the input variables space, can be presented as Eq. (2), where ε is the error related to the surrogate model approximation (Gaspar et al., 2017).

$$y = M(p,x) + \varepsilon(x) \tag{2}$$

The set of parameters (p), which describes the surrogate model, can be determined based on experimentally observed samples. Observational data is also generated based on random basic variable vectors (x) and the corresponding function values (Gaspar et., 2017) determined with direct execution of the time-consuming numerical WQSM.

$$\chi = \left\{ \left(x^{(k)}, y^{(k)} = G\left(x^{(k)}\right) \right), k = 1,2,\dots,m \right\} \tag{3}$$

In Eq. (3), the generated $x^{(k)}$, as the vector k of basic random variables, defines a so-called DOE (Design of Experiments) (Gaspar et al., 2017). DOE, indeed, puts an initial set of sample points in the feasible parameter space (Wang et al., 2014) to maximize the amount of information gained from a limited number of sample points.

3.2.1. Surrogate WQSMs

In this research, the water quality index (WQI), which integrated dissolved oxygen (DO), nitrate (NO_3), phosphate (PO_4), Iron (Fe), and BOD represented the water quality condition in the reservoir waterbody. In the Gol-Gol river system, PO_4 and Fe concentrations are water quality indicators studied in this research. The physical, chemical, and biological processes describing the water quality fate and transport in the monitoring points have been illustrated in authentic references with details (Saadatpour, 2012; Cole and Wells, 2018). Moreover, the sources of nutrients and Iron in the upstream flow (main branches and/or tributaries) and the reservoir operation strategies in SWS could affect the water quality responses in the river-reservoir system. In the current work, the water quality parameters (DO, NO_3, PO_4, Fe, and BOD) were checked at one control point in the reservoir outflow and Fe and PO_4 were monitored at two control points along the river. Therefore, five state variables in the Ilam Reservoir outflow and four state variables in the Gol-Gol River defined the water quality conditions in the river-reservoir system and/or objective functions in the optimization procedure. In the present study, we also developed the surrogate modular SVR model in which several small sub-SVRs cooperated to solve the large-scale problem related to integrated management of quality and quantity of river-reservoir. These small sub-SVRs, as surrogate WQSMs, were specified by a series of simpler SVRs in which each sub-model worked as a module and operated on separate inputs to accomplish some sub-tasks. The output data of each sub-SVR, as surrogate WQSM, also emulated specific water quality parameters at the specified monitoring point.

The main difference in the surrogate WQSMs of any reservoir is the inclusion of time delays between the input and output data. Realizing the significant reservoir detention time and long travel time between the headwater and/or tributaries and the reservoir outlets, the time delays affecting downstream water quality responses should be included in the water quality approximation model. However, in this research, no time delays were included in the surrogate WQSMs to depict the water quality responses in the Gol-Gol river due to the dominance of the transportation process in this river, which could result in insignificant lags between system loading and responses. Fig. 2a represents the input parameters included in PO_4 sub-SVR module to approximate PO4 concentration in the Gol-Gol branch (river), checkpoint 2. In the surrogate WQSM, we considered all the parameters and pollutant sources affecting PO_4 concentration at checkpoint 2 in the Gol-Gol Branch in PO_4 sub-SVR framework.

The input structure of the PO_4 sub-SVR module, which depicts PO_4 concentration in Ilam Reservoir outflow, is shown in Fig. 2 (b). Based on this figure, the time delays due to pollutant sources located at a significant spatial distance away from Ilam Reservoir outflow are also included in the PO_4 sub-SVR module of the reservoir. Moreover, the reason for regardless of time delays of pollutant inflowing flux of Ema and Chaviz branches was due to their proximity to the reservoir outflow. Furthermore, the input data of each sub-SVR WQSM has been selected based on PMI (Partial Mutual Information) index, reference to reputable sources, and extensive sensitivity analysis (Saadatpour et al., 2020).

3.3. *Adaptive surrogate- based simulation-optimization approach (ASBSO)*

Surrogate-based optimization techniques are promising for computationally high fidelity numerical WQSMs. The generalized framework, illustrated in the adaptive surrogate WQSMs, conducts simultaneous local searches on separate ensembles while updating the surrogate models. In the present work, in the adaptive surrogate-based simulation-optimization framework (ASBSO), the initial generations of optimization were used for collecting the first training sample, and the SVR

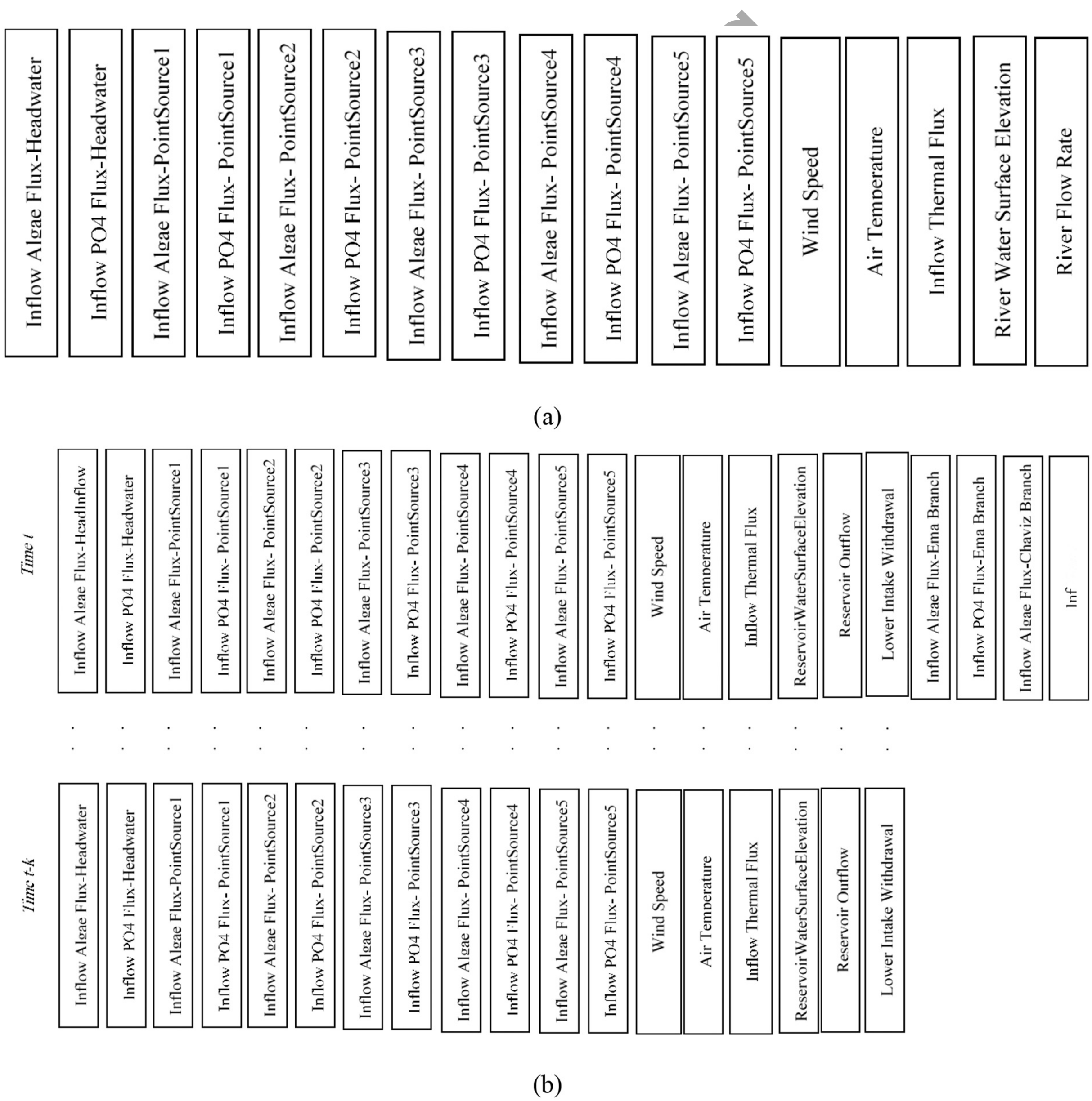

Fig. 2. Input Data of PO4 sub-SVR Modules, Approximate PO4 Concentration in **(a)** Gol-Gol Branch, Check Point 2; **(b)** Ilam Reservoir Outflow.

module was trained for the first time. In subsequent optimization iterations, the SVR module was applied instead of the numerical WQSM for function evaluation in the optimization procedure. Since the SVR module was trained with finite training samples, the initial SVR may not have appropriately fulfilled the approximation accuracy criteria. Therefore, as the optimization algorithm (MOPSO) progresses, new points in the neighborhood of the optimal solutions were assessed with the numerical WQSM and added to the training samples. Then, the SVR module was re-trained based on the updated training samples, and the efficiency of the network was enhanced.

3.4. Water quality index (WQI)

The physical, chemical, and biological characteristics of water resources indicate their suitability for a specific use. A water quality index (WQI) also aggregates various sub-indices representing different water quality parameters (Saadatpour et al., 2019). Each water quality parameter belongs to a specific sub- index, whose score (s_i) is calculated based on a known mathematical formula. To aggregate various sub-indices, an aggregative index introduced in Eq. (4) is applied:

$$I = \left(1 - N + \sum_{i=1}^{N} s_i^{-1/k}\right)^{-k} \tag{4}$$

Where k is a positive constant, sensitive to the variation of sub-indices. The value of 0.4 is recommended for k. In this research, BOD, DO, NO_3-N, PO_4-P, and Iron, as water quality variables, were first converted to sub-indices according to the corresponding equations. Then, the index formulated in Eq. (4), I, aggregated various sub-indices. The WQI could vary between zero and one, so that the higher the WQI's value, the better the quality.

3.5. Model statement and formulations

Derivation of optimal reservoir operating strategies in a SWS and pollutant control by appropriate MPWLA is a multi-period and multi-objective optimization issue. In the current research work, due to computational bottlenecks, combinations of various surrogate WQSMs (SVR module) in river and reservoir waterbodies were proposed to estimate the proper behavior of the waterbodies' responses to any operation strategy and/or upstream MPWLA program. In this research, regarding the optimization, three different qualitative and quantitative objectives were considered as follows: (1) enhance the WQI in reservoir outflow, (2) minimize the sum of PO_4-P and Iron violations from a pre-set standard values at various checkpoints in the Gol-Gol Branch over the multi-period operation time horizon (Eqs. (5) to (8)):

$$Max \quad WQI_{ReservoirOutflow} \tag{5}$$

$$Min \quad Max\left(\sum_{t=1}^{T} F^{Viol}_{PO_{4j,t}} + F^{Viol}_{Fe^{j,t}}\right) \quad \forall j = 1, 2 \tag{6}$$

$$F^{Viol}_{PO_4^{j,t}} = \begin{cases} \dfrac{PO_4^{j,t} - PO_4^{Standard}}{Max\left(PO_4^{j,t}\right)} & PO_4^{Standard} < PO_4^{j,t} \\ 0 & Otherwise \end{cases} \tag{7}$$

$$F^{Viol}_{Fe^{j,t}} = \begin{cases} \dfrac{\left(Fe^{j,t} - Fe^{Standard}\right.}{Max\left(Fe^{j,t}\right)} & Fe^{Standard} < Fe^{j,t} \\ 0 & Otherwise \end{cases} \tag{8}$$

In Eq. (6), T is the total simulation time step and $WQI_{ReservoirOutflow}$ is water quality index in reservoir outflow. In Eqs. (7) and (8), $PO_4{}^{Standard}$ and $Fe^{Standard}$ address the phosphate and iron standard values in the surface water body, respectively (Iran Department of Environment (IR DoE) 2015). Furthermore, $Max(PO_{4j,\,t})$ and $Max(Fe^{j,\,t})$ are the maximum reported values of phosphate and Iron at checkpoints in the river, respectively. In these two equations, $Fe^{j,t}$ and $PO_4{}^{j,t}$ are simulated Iron and phosphate concentration at time step t in control point j, respectively. $F_{PO_{4j,\,t}}{}^{Viol}$ and $F_{Fe^{j,\,t}}{}^{Viol}$ in Eqs. (7) & (8) are PO_4 and Fe violation functions at time step t and control point j in river. In this research, Fe and PO_4 concentrations were checked at 5-day time intervals. Additionally, water quality in the Gol-Gol River was controlled in terms of PO_4-P and Fe to ameliorate the problem related to the undesirable water quality, such as eutrophication and unfavorable taste and odor of water in Ilam Reservoir, which is a drinking water resource. (3) The quantity objective also aimed to enhance the downstream water demand satisfaction by minimizing the sum of downstream water demand deficits (Eq. (9)):

$$Min \quad F_{AgriculturalDemandDeficit} = \sum_{t=1}^{NDay}\left(\frac{Demand^t - Release^t}{Demand^t}\right)^2 \tag{9}$$

where $Demand^{\,t}$ and $Release^t$ are the downstream water demands and the allocated water to the downstream demand at day t, respectively. $NDay$ is the end day of simulation period in the current study. In this research, the quantity objective function is checked at daily time step.

4. Results and discussion

4.1. CE-QUAL-W2 model setup

In this research, the calibration process consisted of the comparisons of the predicted river and in-reservoir hydrodynamic and water quality concentrations with those observed during the monitoring period, which was from July 2008 to December 2008. The verification process also lasted from January 2009 to April 2009. Further, the CE-QUAL-W2 model calibration was provided by adjusting parameter values within the specified ranges, so that model predictions could emulate the observed data. Model calibration consisted of a three-step process: (1) water balance calibration, (2) hydrodynamic/thermal calibration, and (3) water quality calibration. The water surface elevation (WSE) in the Gol-Gol River and Ilam Reservoir was compared with the recorded data in hydrometric stations. This comparison indicated a mean absolute error (MAE) as 4.5 and 21 cm in the river and reservoir, respectively. On the other hand, the calibration results of the temperature profile in the reservoir matched with the field data, appropriately (MAE less than 0.47 °C). The comparison results of the CE-QUAL-W2 model and the observed data of some water quality parameters, in segment 51, are presented in Fig. 3. The CE-QUAL-W2 model was set up to depict the hydrodynamics, nutrients, and Iron water quality parameter in the Ilam River-Reservoir system.

4.2. Surrogate modular SVR WQSM

In eutrophication processes, the interactions and feedbacks among various water quality parameters (nutrients, dissolved oxygen, etc.) are formulated based on mathematical governing equations (Cole and Wells, 2018). On this account, in this study, the effective forcing functions of each water quality parameter were considered as input data to the data-driven, SVR module.

In the WQSM application considered here, a modular SVR was developed with N sub-modules, in which N was the number of water quality parameters in various monitoring points. In other words, rather than training one large SVR module, N small sub-SVR modules were trained, each of which was associated with only one output parameter.

Moreover, the candidate input of sub-SVR WQSM modules consisted of 15-day averaging meteorological, hydrological, hydraulic, and inflowing water quality flux data. The water bodies' responses (concentration of water quality variables in the monitoring point) derived from CE-QUAL-W2 executions, were also regarded as the output columns in each sub-SVR WQSM module. For instance, the input vector

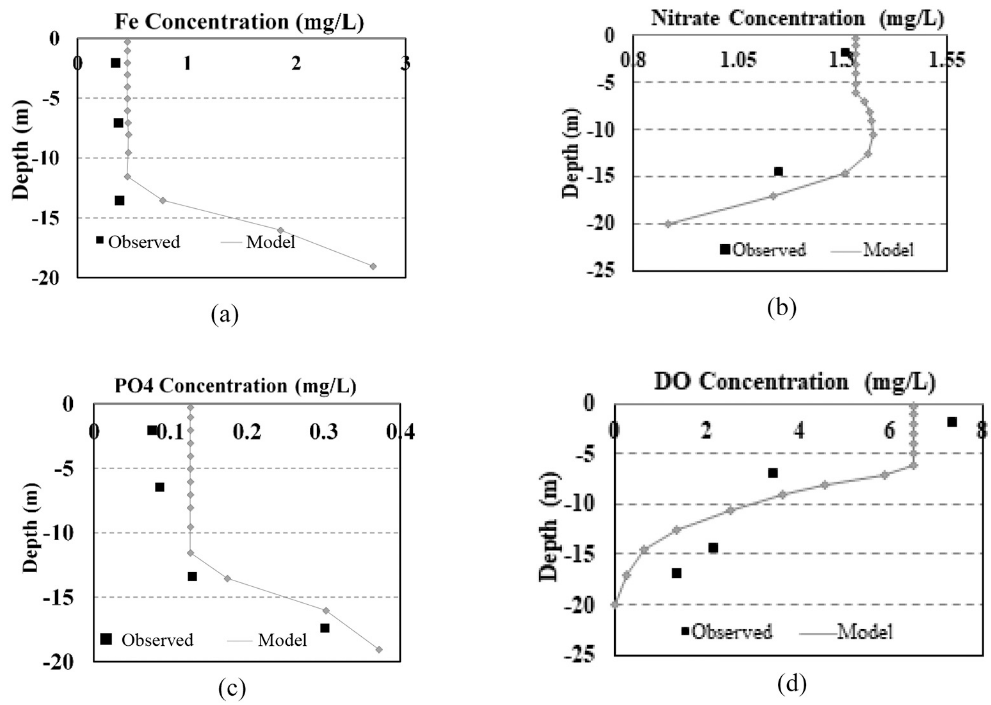

Fig. 3. The Comparison Results of CE-QUAL-W2 and Field Data in Ilam Reservoir **a)** Fe Concentration on September, **b)** Nitrate Concentration on August, **c)** Phosphate concentration on September, **d)** DO Concentration in August

considered for dissolved oxygen approximation consisted of nitrate, ammonia, phosphate, CBOD, and DO inflow fluxes from headwaters (three branches: Chaviz, Ema, and Gol-Gol) and tributaries (five pollutant point source units), WSE, outflow rate, wind speed, air temperature, thermal inflow flux from headwaters, and tributaries for the simulation period. For each water quality parameter in Ilam Reservoir outflow, two-month delays were considered for inflow fluxes of Gol-Gol headwater and five pollutant point sources. No delay was assumed for inflow fluxes of the two headwaters; Ema and Chaviz headwater. The input data of each sub-SVR module was also determined based on sensitivity analysis and PMI.

Fig. 4 and the statistical analysis of approximation error demonstrate a very good performance of the SVM modules as surrogate WQSMs took the place of the CE-QUAL-W2 model. Based on test data, the approximation error of each sub-SVR WQSM at each checkpoint was less than 10% depicting its acceptable accuracy in showing the approximation of the water quality status according to various MPWLA programs and/or reservoir operation strategies in SWS.

4.3. Comprehensive river-reservoir water resources management

In this research, a novel methodology was examined for the multi-objective river-reservoir system management focusing on the extraction of integrated optimal MPWLA programs and reservoir operation strategies in SWS. The current study focused on enhancing the downstream water supply satisfactions, whilst minimizing the environmental impacts in an interconnected river-reservoir system. In other words, control of nutrient and iron inflows to the Gol-Gol River and management of mass and energy circulations in the reservoir were pursued through the implementation of appropriate MPWLA programs and reservoir operation strategies in SWS, respectively. Results were assessed in two steps; 1- the 3D Pareto-front (Fig. 5) was analyzed to represent the trade-offs, conflicts, and correlations among the objectives. 2- the extreme points of the Pareto-front, i.e., the best solution in each objective, were studied to separately evaluate the MPWLA program and SWS operation strategies.

The Pareto-front analysis revealed that in the low-order MPWLA programs, the ASBSO framework intelligently set scenarios to provide suitable circulation patterns of the mass and energy processes in the reservoir and improve the released water quality status. Furthermore, the implementation of MPWLA programs at any level alleviated the water quality problems in Ilam Reservoir. However, in the alternatives to the low-order MPWLA programs, the recommended reservoir operation strategies enhanced the released downstream water quality status. Furthermore, the results show that balancing the reservoir storages to meet downstream water demands could result in water quality

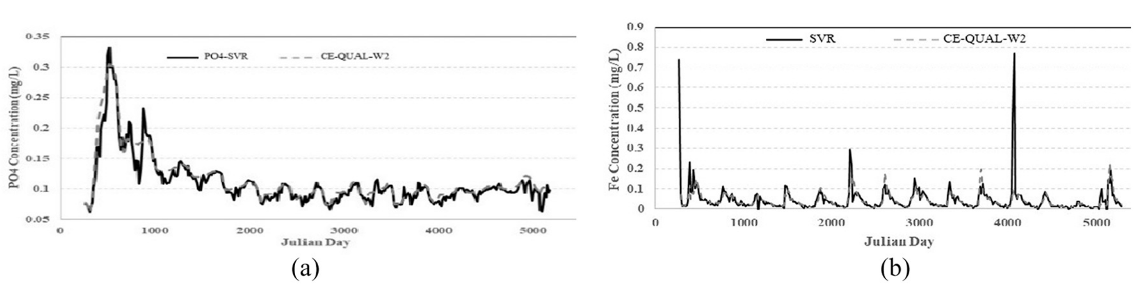

Fig. 4. Comparison the Performances of (a) PO4 sub-SVR Module in Ilam Reservoir Outlet and (b) Fe sub-SVR Module in Gol-Gol River; Checkpoint 1, with CE-QUAL-W2

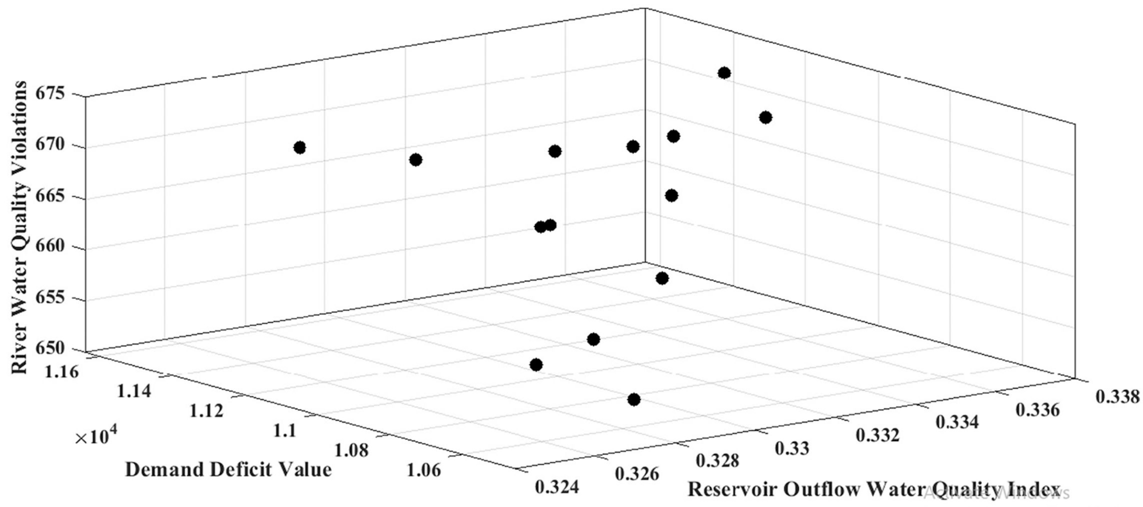

Fig. 5. Pareto front derived in river-reservoir system management problem, considering quality and quantity objectives.

deteriorations in Ilam Reservoir. The water quality deterioration was due to the impediments to the outflows of unfavorable water and/or water mixing in the reservoir at specific time steps.

The objective function values in the extreme members of Pareto-front in comparison to "focusing only on reservoir management" scenario (Only Ilam Reservoir operation management in SWS, with no MPWLA program in Gol-Gol Branch), are illustrated in Table 1. According to this table, solution II, which aimed at minimizing the deficit of water needs in Ilam Reservoir, has amended the water delivery to downstream by 7% in comparison to another extreme solution that intended to enhance water quality in reservoir release as much as possible. Additionally, the analysis and observation of the long- term results (release from the reservoir) demonstrated that 90% of downstream demands were satisfied through various optimal reservoir operation strategies (all members of Pareto-front). This approved that sufficient attention had been paid to the quantitative objective of Ilam Reservoir. Results also confirmed that addressing the reservoir operation based on specific storage and release rules, which attempt to meet downstream water demands, is in conflict with the water quality objective in the reservoir, because increasing the supply of downstream consumption requires more water storage in the reservoir, which in turn increases the pollutant detention times in the reservoir. Therefore, we can claim that putting focus only on one objective in the integrated river-reservoir system management might undermine the achievement of sustainable development objectives.

Additionally, sustainable water resources management in the study area, focusing only on Ilam Reservoir management considering water quality and quantity aspects in comparison to the extreme members of the Pareto-front (Fig. 5), was examined. The results demonstrated that water resources management in an integrated river-reservoir perspective could be more achievable to obtain the best environmentally friendly performance than focusing only on the reservoir management perspective. Closer examination of results also indicated that in comparison to various extreme scenarios of Pareto-front members, "focusing only on reservoir management" and/or failure to implement MPWLA programs in the Gol-Gol River had increased undesirable water quality parameters (NO_3, BOD, PO_4, and Fe) by 7 to 20% in Ilam Reservoir. To provide more relevant evidence, the Phosphate concentrations in Ilam Reservoir outflow in various extreme Pareto-front scenarios and "focusing only on reservoir management" scenario are presented in Fig. 6.

In addition, focusing on the results showed that all the members of Pareto-front had experienced less nutrient and Fe loads in the reservoir due to the implementation of the MPWLA program in the Gol-Gol branch. Furthermore, all the members attempted to alleviate the reservoir water quality deterioration through reservoir operation strategies in SWS. More analyses of the results demonstrated that most of the water quality parameters in Ilam Reservoir outflow in the "Best Water Quality in Reservoir Outflow" scenario had more suitable conditions than other scenarios, including the scenario, which aimed at minimizing the "Water Quality Violations in the River". This could be explained by the use of more appropriate reservoir operation strategies in SWS in the "Best Water Quality in Reservoir Outflow" scenario in comparison to the "Less Water Quality Violations in River" scenario. In other words, the mass and energy circulations in the reservoir in the "Best Water Quality in Reservoir Outflow" scenario were planned in such a way to release the proper amount of contaminations from the relevant intake in the appropriate time steps.

To understand how integrated river-reservoir management could be beneficial, results from various extreme scenarios of Pareto-front were compared with the No MPWLA scenario at checkpoint number 2 of the Gol-Gol River (Fig. 7). As can be seen, improvements with the "Less Water Quality Violations in River" scenario become more pronounced with high-order MPWLA programs in Gol-Gol River.

Results also showed that implementing MPWLA programs in the form of integrated river-reservoir systems in various extreme scenarios of Pareto-front could improve water quality in the range of 7 to 28% at checkpoint 2 of the Gol-Gol River. A similar water quality enhancement at checkpoint 1 of Gol-Gol River was perceived in the range of 5 to 21% for different monitored water quality parameters compared to the No MPWLA scenario. The average and maximum concentrations of Fe at checkpoint 2 in various extreme scenarios of Pareto-front in comparison

Table 1
Comparison to "Focusing Only on Reservoir Management" Scenario.

	WQI in Reservoir Outflow	Downstream Demand Deficit (Eq. (9))	River Water Quality Violation (Eq. (6))
Scenario I	0.3464	11,234.8	219.43
Scenario II	0.3259	10,455.1	215.47
Scenario III	0.3273	10,491.9	213.13
Scenario IV	0.3035	10,455.7	231.81

Solution I: Best Water Quality in Reservoir Outflow.
Solution II: Minimum Agricultural Deficit.
Solution III: Minimum Water Quality Violations in the River.
Solution IV: Focusing only on Reservoir Management.

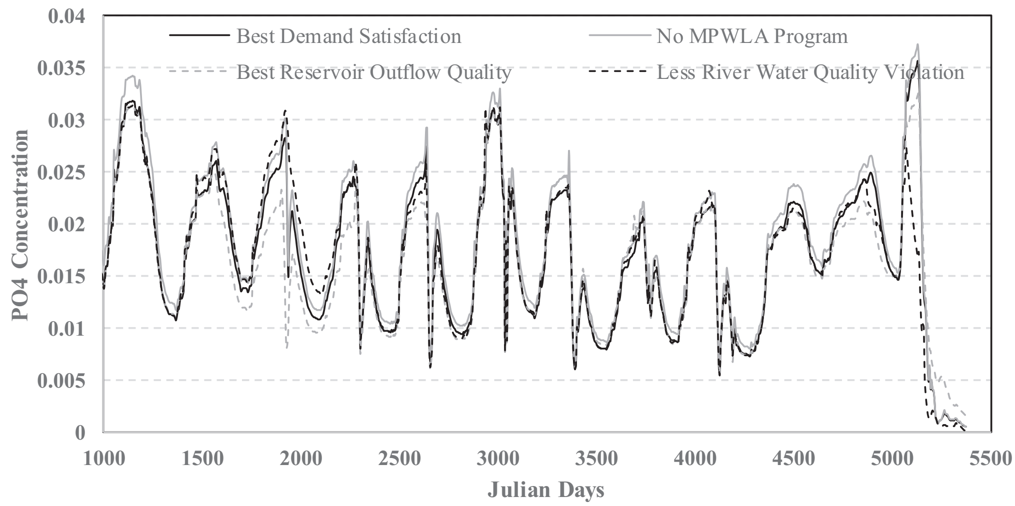

Fig. 6. Time Series of PO4 Concentration in Ilam Reservoir Outflow for the Four Solutions Presented in Table 1.

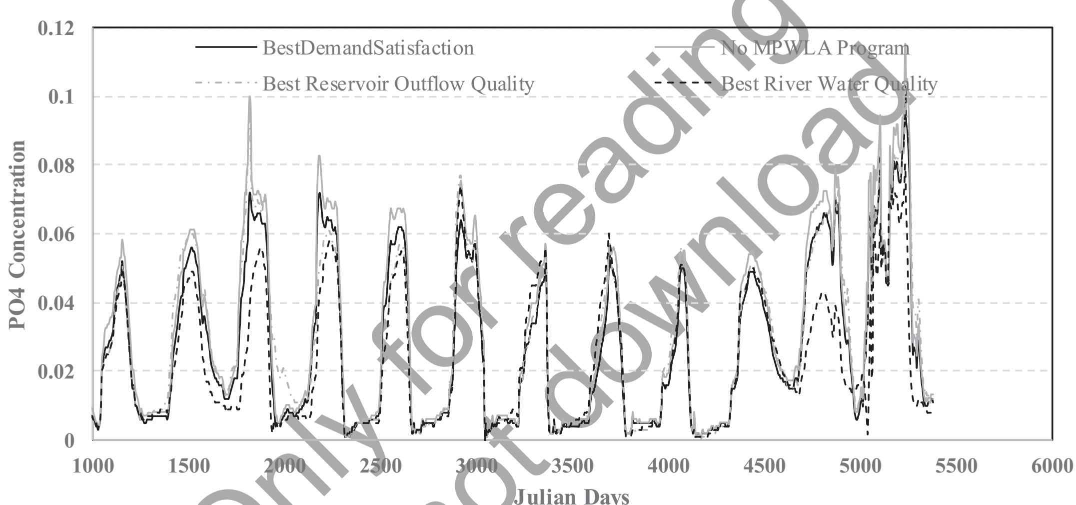

Fig. 7. Time series of PO4 Concentration in Various Extreme Scenarios and No MPWLA Program at CheckPoint 2 of Gol-Gol River.

to the No MPWLA program are also depicted in Fig. 8. Like Fe, better water quality conditions were reported for other parameters in the integrated river-reservoir system management scenarios. According to this figure, the implementing the MPWLA program in the Gol-Gol River has resulted in an average improvement of 28% and 20% in the average and maximum concentrations of Fe at checkpoint 2, respectively.

On the other side, analysis of the optimal MPWLA programs of the Pareto-front in the Gol-Gol Branch indicated that due to higher nutrient and Iron (Fe) flux in G2 and G3 sub-catchments, more stringent WLA programs had been assigned to these tributaries. Furthermore, low-order MPWLA programs had been assigned to the more upstream tributaries with lower nutrient flux, such as G4 and G5.

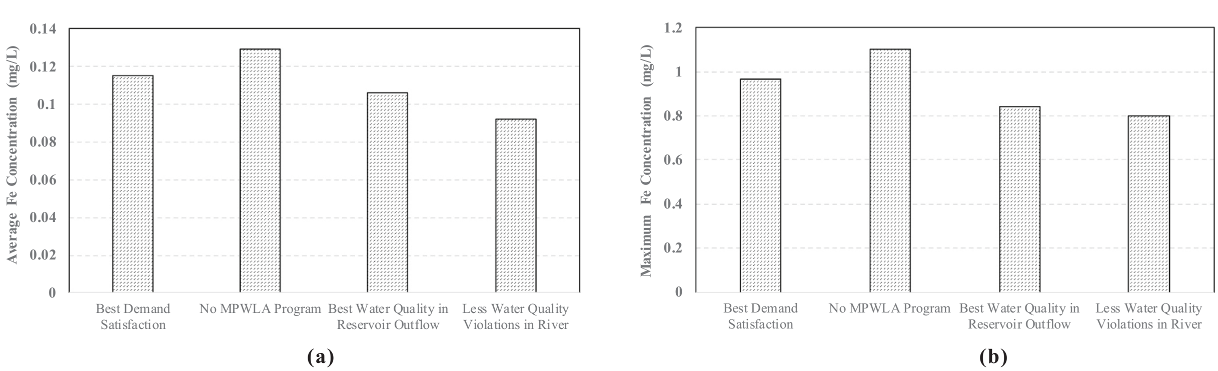

Fig. 8. The (a) Average and (b) Maximum Fe Concentration at Checkpoint 2 of Gol-Gol Branch in Various Scenarios.

5. Concluding remarks

This study developed a new surrogate-based approach to optimizing the quality as well as quantity aspects of water in a large-scale problem, integrated river-reservoir system. The proposed methodology applied a complex numerical hydrodynamic and WQSM of river-reservoir system, surrogate SVR module of WQSMs, and MOPSO algorithm. The applicability and advantages of ASBSO were evaluated through a case study in the Ilam River-Reservoir system, which is threatened with the pollution sources of the upstream sub-basins. Furthermore, this study demonstrated the benefits of using a 2D hydrodynamic and WQSM, instead of a lump and/or 1D WQSMs, to address complex real-world eutrophication management issues of the dendritic river-reservoir system. The surrogate SVR modular WQSMs comprehensively approximated various state variables in the basin-scale water cycle with appropriate spatial and temporal resolutions.

The proposed methodology also provided a Pareto-front, whose members represented an integrated MPWLA program with reservoir operation strategy in SWS in the river-reservoir system. The developed model also provided information, based on which we can learn how water quality and quantity aspects in the river-reservoir system would be impacted by optimized MPWLA programs and reservoir operation strategies in SWS. It also makes our results more interpretable and confirmable.

Although, the proposed methodology was applied for integrated river-reservoir water quality and quantity models, it could be potentially applicable to other complex systems, such as integrated ground and surface water resources systems, basin-scale surface water systems consisting of multiple rivers, and reservoir networks, etc. Future studies could take other parameters, such as ecological health, economic costs, and social issues into consideration.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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